5 Water Use in Agroecosystems

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Abstract

The integrated role of water in ecosystems and, in particular, in agroecosystems, as well as the multiple uses of water – across various sectors that have increasing demands, have been widely recognized. But regions and institutions are still struggling to resolve issues around water – be it scarcity, accessibility or degradation. Mostly, they are caught in conventional institutional and policy frameworks that have been set up based more on sectoral than on cross-sectoral principles, thus preventing them from achieving the ultimate goal of sustainability. This chapter analyses the current and future challenges related to water availability and water use for agriculture from this perspective. It looks at water quantity and quality, water infrastructure, and related governance and institutional aspects, using case studies from basins in different geographic regions.

Background

Agriculture uses about 70–72% of the total water that is withdrawn from surface and groundwater around the world (Molden, 2007; Wisser *et al*., 2008), and as much as about 90% in developing countries (Cai and Rosegrant, 2002). Shortages of water, and the means by which they can have a major effect on food production, are discussed by Strzepek and Boehlert (2010). It is estimated that food production needs to increase by at least 50%, and probably almost double, by 2050 in order to meet the needs of a growing population and changing consumer preferences for more water-intensive crops (Molden, 2007). Based on current practices, this implies almost a doubling of water use by agriculture worldwide.

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However, the environmental sustainability of water use and, in many places, the limits to its absolute availability, have already been reached globally – while locally, they have even been surpassed (Molden, 2007). Many important river basins no longer have enough water for all of the human users of the resource, let alone for the environmental needs of the resource base itself, and one third of the world's population lives with physical or economic water scarcity (Molden, 2007). Furthermore, water limits have already been stretched to breaking point in important food-producing regions. For example, groundwater levels are declining rapidly in several major breadbasket and rice-bowl regions, such as the North China Plains, the Indian Punjab, and the Ogallala in Western USA (Giordano and Villholth, 2007; Shah, 2009).

Water scarcity, for both people and the environment, is related to accessibility: in regions of physical water scarcity, water is over-allocated, leaving little or none for uses that are currently given a lower priority, such as the environment. In economically water-scarce regions, water is available for use, but access is difficult, most often because of limited investment in water infrastructure (Mulligan *et al.*, 2011). When there is institutional water scarcity, both water and infrastructure are present, but national or local institutions and norms prevent some social groups or individuals from accessing water. In all cases, although in very different ways, lack of access to water is a threat to future food production and environmental sustainability, and this needs to be addressed using different approaches.

Water Availability for Agriculture

Water availability differs naturally according to agroecological zones: it is abundant in humid and sub-humid zones but is scarce in arid zones and drylands. Its availability for use is further determined by its accessibility and by the quantity that is being withdrawn, as well as by how efficiently it is being used. Estimates of the global freshwater supply are subject to high uncertainties owing to lack of available data, lack of data conformity and difficulties in data access. Even at the basin level, available water resources are difficult to assess in detail as there are major gaps in sufficient high-quality, high-resolution and long-term hydrological data (Mulligan *et al.*, 2011). This situation is further complicated by climate change, which constitutes an additional challenge to the amount of water that is available for agriculture (Chapter 2).

Renewable freshwater expressed as long-term mean runoff has been estimated at 33,500–47,000 km^3/year (Hassan *et al.*, 2005). Fresh groundwater supply, including renewable and fossil groundwater, has been estimated to range between 7 and 23 million km^3, according to the Millennium Ecosystem Assessment (Hassan *et al.*, 2005); a more recent estimate is between 8 and 10 million km^3 (WWAP, 2012). Other water 'resources' that need to be considered are water storage and the associated infrastructure, such as dams, and natural storage such as soils, lakes, snow and ice (McCartney and Smakhtin, 2010). Water resources are unevenly distributed across the globe, and availability also depends to a large extent on the specific local context, such as physiography, land use, accessibility, infrastructure, governance, institutions and investment.

After glaciers, permanent ice and aquifers, soils are the largest store of freshwater (Hassan *et al.*, 2005) and therefore can substantially contribute to food production. However, the use efficiency of soil water depends heavily on many interacting ecophysiological processes, which ultimately determine plant growth. These processes may also be threatened by land degradation and erosion (Chapter 4).

A recent analysis of selected river basins in developing countries in different regions (those of the Andes and São Francisco in South America; of the Volta, Niger, Limpopo and Nile in Africa; and of the Karkheh, Indus-Ganges, Mekong and Yellow in Asia) showed that among these, the Mekong Basin has the relatively highest and the Limpopo and Yellow basins have the relatively lowest water balance (Mulligan *et al.*, 2011). The Yellow River is among several of the world's largest and most important rivers for socio-economic development that have been so heavily depleted and over-abstracted as to show a total lack of flow at their mouths and damage to their condition;

other examples are the Colorado and Murray–Darling Rivers (WWAP, 2009).

Infrastructure such as dams can make important contributions to development in terms of hydropower, flood control and water supply, particularly for irrigation. Notwithstanding, irrigation development has all too often come at a high environmental price tag (Faures *et al*., 2007) and has caused the degradation of aquatic ecosystems, fragmentation and desiccation of rivers, drying up of wetlands and increased transmission of water-related diseases. Dams in particular may also affect fisheries and ecosystems in downstream areas; worldwide, the Millennium Ecosystem Assessment (Hassan *et al*., 2005) has described around 45,000 dams larger than 15 m in height and with more than 3 million m^3 reservoir volume, and 800,000 smaller dams, with many more planned or under construction. For example, the Indus–Ganges Basin, which has an area of 0.81 Mkm^2, has 785 large dams; the Mekong Basin, which has an area of 0.54 Mkm^2, has 344 large dams; and the Yellow River Basin has 125 dams on an area of 0.86 Mkm^2 (Mulligan *et al*., 2011). The volume of water stored in dams is estimated at 6000–7000 km^3 (Hassan *et al*., 2005). The construction of dams and other structures along rivers has affected flows in 60% of the world's largest river systems.

The alteration of landscapes and waterscapes to increase food production has resulted in adverse, sometimes irreversible, ecological changes (Millennium Ecosystem Assessment, 2005b). For instance, intensive hydraulic infrastructure development, much of it for food production, is one of the reasons for the 35% decline in freshwater biodiversity reported between 1970 and 2005 (Hails *et al*, 2008). Reservoirs and water diversions have resulted in declining water flows and decreased sediment flows, thus preventing about 30% of sediments from reaching the sea and 10% reaching the estuaries; these sediment flows are a source of nutrients that are important for the maintenance of estuaries (Millennium Ecosystem Assessment, 2005a). Another engineering option for securing water supplies includes inter-basin water transfers; these can result in both societal costs and benefits, as well as affecting ecosystem services and biodiversity.

The extent to which water can be used for different purposes is determined by availability and access, as discussed above, but also by its quality. Despite major gaps in data and monitoring, there are indications that worldwide water quality is declining. Even though the pollution of surface waters by pathogens and organic compounds has decreased over the past 20 years in most industrial countries, water availability is threatened by water pollution in many places, for example in urban areas such as Mexico City, Delhi and Jakarta, but also in China (Millennium Ecosystem Assessment, 2005a). Nitrate concentrations have increased rapidly over the past 30 years, making this the most common chemical contaminating groundwater resources worldwide. This pollution mainly originates from pesticides, of which the USA is the largest consumer, followed by (particularly western) European countries, while Japan is the most intensive user. Excessive nitrogen application contributes to the eutrophication of freshwater and the acidification of freshwater and terrestrial ecosystems, and these can have an impact on ecosystem health and biodiversity. The capacity of ecosystems to purify such pollution is limited and the continued loss of wetlands further decreases the ability of ecosystems to filter and decompose waste (Millennium Ecosystem Assessment, 2005a; WWAP, 2012; Chapter 7).

Understanding Water Use in Agriculture

About 80% of agricultural evapotranspiration originates from rain and approximately 20% from irrigation (Molden, 2007). Estimates of total annual global freshwater withdrawals for various uses amount to 3800 km^3, of which 70% goes into food production or irrigation. Globally, water use in agriculture is larger than that for other uses, but is of relatively low value, low efficiency and highly subsidized (GWP, 2012). Furthermore, there are significant variations between countries (Molden, 2007): agricultural water use tends to decrease with increasing levels of development (WWAP, 2012). In OECD (Organisation for Economic Co-operation and Development) countries, agricultural water withdrawal accounts for 44%

of total water withdrawal, but within the eight countries that rely on irrigation it is more than 60%. For the BRIC countries (Brazil, Russian Federation, India and China), agriculture accounts for 74% of water withdrawals and ranges from 20% in the Russian Federation to 87% in India. Some fast-growing economies use up to 90% of their total freshwater withdrawal for agriculture, and least developed countries use more than 90% (WWAP, 2012). In South Asia, total renewable freshwater resources amount to 3655 km^3 and total withdrawal for agriculture is 842 km^3/year, which is by far the highest use of water (Atapattu and Kodituwakku, 2009). The proportion of the total actual evapotranspiration used in agriculture also varies: for example, it is as high as 67% in the Ganges Basin, 50% in the Yellow River Basin and 38% in the Mekong Basin; in contrast, it is only 6–7% in the Andes and Nile basins (Mulligan *et al*., 2011).

Agricultural yields range from 1.5 t/ha, for example in developing countries, to above 5–6 t/ha, as in commercial rainfed agriculture in tropical areas (Wani *et al*., 2009), up to around 10 t/ha. Irrigation is a well-established method of improving yield in many parts of the world and accounts for more than 40% of the increase in global food production over the past 50 years (FAO, 2011). However, in sub-Saharan Africa, for example, the use of irrigation is still low, and rainfed agriculture remains the dominant practice in subsistence agriculture. The majority of agriculture – 95% in sub-Saharan Africa and 60% in South Asia – is rainfed, but yields rarely reach 40% of their potential (Molden, 2007). Productivity from rainfed agriculture remains low as a result of limited soil nutrient availability, the occurrence of pests and diseases, and spells of minimal or no precipitation during critical growing periods. Several of these factors are related to degradation of ecosystems, and it is widely recognized that there is great potential for improvements in rainfed agriculture, which, if managed properly, could increase agricultural yields, thereby contributing to food security without additional water abstraction (see Chapter 8).

Over the past 50 years, groundwater abstraction has at least tripled, and it continues to increase by 1–2%/year, accounting for around 26% of total global water withdrawal (WWAP, 2012). Groundwater use for irrigation, estimated at 670 km^3/year (as of 2010), or around two thirds of the total groundwater abstraction, is increasing, with almost 40% of irrigated areas relying on groundwater. In some countries, e.g. Saudi Arabia, nearly all of irrigation is from groundwater only (Hassan *et al*., 2005; FAO, 2011), and in many areas with high population density, groundwater is crucial to sustaining irrigation (Giordano and Villholth, 2007). Over-abstraction of groundwater can lead to rapid lowering of groundwater tables, such as in Yemen and in important agricultural areas of South Asia and North China, where groundwater tables have been reported to have declined at over 1 m/year (GWP, 2012).

Despite awareness of the increasing demand for food, and hence for water for agriculture, there is substantial loss from the water that is withdrawn for agriculture, via both evaporation and unsustainable use. An estimated 1210 km^3/year of water is lost from groundwater and surface water sources through net evaporation from irrigation, cooling towers or reservoirs. Water loss from irrigation has been reported to account for one third of global water use (Hassan *et al*., 2005). Around 5–25% of global freshwater use exceeds long-term accessible supplies and is currently met either through engineered water transfers or over-abstraction of groundwater supplies; about 15–35% of irrigation withdrawals are considered to exceed supply rates and are thus unsustainable (Millennium Ecosystem Assessment, 2005a).

Livestock production systems are often considered responsible for depleting, degrading and contaminating large amounts of water (Goodland and Pimentel, 2000; Steinfeld *et al*., 2006). Although this view is relevant in the case of intensive and industrialized cattle systems, smallholder livestock systems have different environmental impacts (Herrero *et al*., 2009; Peden *et al*., 2009). Almost a third of global water used in agriculture is used for livestock; less than 10% of this is for drinking water, and more than 90% of it is used for feed production (Peden *et al*. 2007). The water in fodder that is consumed by livestock in arid and semi-arid rangelands is not readily available for other forms of agricultural production. This is especially true for ruminants such as cows and sheep (Bindraban *et al*., 2010). With the projected increase in demand for products from livestock, agricultural water use may need to double to cater for the increased need for feed production (Chapter 2). In developing countries, the relationship between water and energy in meat that is shown in Fig. 2.4 (Chapter 2) may differ because the production of foods from animal sources can relatively easily be doubled without use of additional water by increasing livestock water productivity (Chapter 8).

Global production from inland fisheries has increased over the past 40 years, particularly from production in Asia and Africa, but in other regions – such as Europe and North America – fish production has declined as a result of environmental changes, while at the same time recreational fisheries have become more important. Productivity in aquaculture and inland capture fisheries depends on healthy ecosystems and adequate flow, quantity and quality of water (Chapter 8). Increasing human influence on freshwater bodies, e.g. through water abstraction, the building of dams, catchment management and pollution has severe impacts on the highly vulnerable fish habitat (UNEP, 2010). Freshwater fisheries are particularly threatened by water extraction or increasing water demand for other uses, and by degradation in water quality; in contrast, coastal fisheries and aquaculture are affected by increasingly nutrient-rich terrestrial runoff (Foresight, 2011). Climate change constitutes an additional risk to fish production; other drivers are changed demand, access to resources and risk margins (Bunting, 2013; Chapter 2).

Health Issues in Water and Agroecosystems

Worldwide, diseases associated with agriculture have important health impacts, particularly on poor people and those who are directly exposed to the risks, such as farmers, consumers and households in agricultural areas. Many of these health risks are related to agricultural water use (Kay, 1999; Parent *et al*., 2002). Intensification through irrigation for productivity gains is often accompanied by increased, typically diffused, agrochemical inputs. These chemicals can also pollute waterways and pose a threat to human, livestock and ecosystem health. Further risks can derive from the toxic algal blooms that are associated with agrochemical water pollution (Chorus and Bartram, 1999).

Among the most important diseases related to agriculture are those transmitted by vectors that breed in or are associated with water, and which tend to increase as a result of irrigation and the building of dams for agricultural purposes. The most important vector-borne water-associated disease is malaria, which resulted in an estimated 655,000 deaths in 2010, with about 90% of these in Africa (Keiser *et al*., 2005a; WHO, 2011). Other examples are lymphatic filariasis (also known as elephantiasis; Erlanger *et al*., 2005), schistosomiasis (Steinmann *et al*., 2006) and buruli ulcer (WHO, 2007). Many vector-borne diseases are zoonoses (animal diseases that are transmitted to people, such as sleeping sickness and Rift Valley Fever), whose presence and prevalence are linked to livestock and wildlife. Other zoonoses are transmitted via the faecal–oral route when animal faeces contaminate water that is subsequently consumed without treatment or when contaminated foods are eaten fresh; among the most notable of these are leptospirosis, salmonellosis and cryptosporidiosis, which together make tens of millions of people sick each year. Other important waterborne diseases that are neither vector borne nor zoonotic include typhoid, cholera, giardiasis, hepatitis and enteric viruses.

Waterborne zoonoses are especially likely when poorly regulated intensive livestock keeping results in the discharge of large amounts of waste to water. People who share scarce water sources with livestock and wildlife are at high risk as water storage systems can support biocoenoses in which people, livestock and wildlife are brought into close contact. This results in a greater effective contact among animals and humans, and ultimately facilitates disease transmission between animals and humans (Woodford, 2009). A study that looked into the genetic similarity of *Escherichia coli* strains from primates and humans in Uganda found that the use of water from an open water source was associated with an increased genetic similarity between the strains of these bacteria found in primates and humans (Goldberg *et al.*, 2008).

Many water-associated diseases are fostered by poorly designed or managed irrigation or water storage systems, or by harmful agricultural practices (Boelee and Madsen, 2006; Diuk-Wasser *et al.*, 2007; Boelee *et al.*, 2013). The emergence of malaria in the Thar Desert in India (Vora, 2008) and of Rift Valley fever in West Africa are notable examples (Pepin *et al.*, 2010).

The ongoing pandemic of highly pathogenic avian influenza provides a different example of the role of irrigation and livestock in disease emergence. Numerous strains of avian influenza virus of low pathogenicity circulate into the natural reservoir and in wild birds. These strains evolve towards virulence through adaptation to domestic ducks, which, through close contact, then transmit the infection to chickens. In East Asia, this is linked to rice farming combined with free grazing duck farming in wetland areas (Artois *et al.*, 2009); ducks are not very susceptible to clinical disease but they are infectious to other domestic poultry by direct contact or environmental contamination (Sims *et al.*, 2005).

Particularly in peri-urban areas, irrigation water is often contaminated with pathogens or chemicals that may affect farmers who come into contact with the water, and that may also enter the food chain, especially when crops or livestock products are eaten raw (Drechsel *et al.*, 2010). At the same time, the use of polluted water to irrigate crops supports the livelihoods of 20–50 million farmers and feeds up to a billion consumers. Water pollutants (chemical and biological) can also impair the health of livestock and of the consumers of animal products within a complex system that includes links between waterborne and food-borne vectors.

Although biological hazards are of much greater overall human health impact, agrochemicals and heavy metals can also contaminate water, and then pose a risk to human health from acute or chronic poisoning. Livestock and fish farming also lead to the presence of antibiotic residues or antibiotic-resistant bacteria in water, with potentially large impacts on human health. Many of these health problems arise from the methods by which agricultural production systems are managed and therefore could be positively influenced by an ecologically sound approach.

Improved and innovative agricultural and water management practices can help to reduce water-associated diseases (Boelee *et al.*, 2013). This reduction has to be carefully balanced with the need to support the livelihoods of farmers and provide affordable food to poor consumers. Further along the value chain, consumers can be protected and costs to the public health sector will decrease. In relation to all of the above health issues, there is vast experience of relevant agro-ecological interventions that can help to mitigate negative health impacts if water management practices are put into place (Keiser *et al.*, 2005b; McCartney *et al.*, 2007).

Similarly, a more integrated management of agroecosystems for a wider range of ecosystem services has the potential to generate additional benefits, such as enhanced pest and disease regulation. In turn, this could reduce the need for agrochemicals and limit the exposure of farmers to harmful substances, currently a significant occupational health hazard in agriculture. People in developing countries bear more than 80% of the global burden of occupational disease and injury, and the agricultural sector is one of the most hazardous (ILO, 2000). It is estimated that 2–5 million people suffer acute poisonings related to pesticides annually, 40,000 of whom die every year (Cole, 2006). Excessive use of pesticides can also lead to resistance in medically important insects. Pesticides are used inappropriately as a result of capacity deficits, inadequate regulation and perverse incentives, as well as lack of alternatives. Other agricultural inputs, such as nitrates, disinfectants, acaricides and veterinary drugs can also have negative health impacts if incorrectly used. Increased biodiversity in agroecosystems, especially when these are managed on a landscape scale and are connected by corridors that provide habitat for natural predators (Molden *et al.*, 2007), reduces the need for agrochemicals and their associated health risks.

Environmental Flows

Competition between water users has existed for millennia, especially between water abstracted for direct human well-being and water required to sustain various water-dependent ecosystem services. People with their livestock and crops have settled near water sources or seasonally migrated to access them for thousands of years, and human alteration of the structure or functioning of coastlines, rivers, lakes and other wetlands is pervasive. Water use in agriculture affects ecosystem services, not only by reducing the amounts of water available but also, among other impacts, by polluting water, altering river flow patterns and reducing habitat connectivity (Gordon and Folke, 2000).

With growing populations and increasing water use per capita, there is often not enough water of sufficient quality to meet all needs. The most common result is that non-agricultural ecosystems do not receive adequate attention and the water needs of ecosystems, or environmental flows, are not met. Consequently, important ecosystem services are often disrupted, including those related to food production, but also in the provision of clean water, fish stocks, flood control and many other functions.

Water flows dedicated to the environment, often aquatic ecosystems such as downstream rivers, have been defined as environmental flows. The most recent, widely adopted definition of an environmental flow (also referred to as the environmental or ecological water requirement, EWR) is the 'quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems' (Brisbane Declaration, 2007). This definition highlights the relationship between water for ecosystem health (or 'water for nature' in integrated water resource management – IWRM) and water to sustain the livelihood needs of people, including their water and food security (there is more on the role of environmental flows in IWRM in Chapter 10).

Nowadays, agricultural water requirements can be calculated with a fair degree of accuracy, and considerable advances have similarly been made in the quantification of the water requirements of ecosystems (environmental flows) (Postel and Richter, 2003; Tharme, 2003; Poff *et al*., 2010). This leads to reasonably accurate assessments of discrepancies between requirements and supply. In 37% of 227 large river basins that were assessed globally, environmental flows were strongly – and in 23% of them moderately – affected by fragmentation and altered flows (Cook *et al*., 2011).

Physical water scarcity and the associated proliferation of water infrastructure are the primary causes of decreasing and altered patterns and timing of flows to ecosystems (Rosenberg *et al*., 2000). With such impacts, ecosystems may not be able to deliver the full range of ecosystem services that are beneficial to people. Reduction in provisioning capacities can lead to economic water scarcity, which can further result in physical water scarcity once low-cost water resources are over-exploited (WWAP, 2009). Importantly for the future, a spatial analysis has shown that, at the global level, threats to water security are highly associated with threats to river-based biodiversity (Vörösmarty *et al*., 2010). Various studies confirm that the imbalances between irrigated agriculture and nature conservation have reached a critical point on a global scale (Lemly *et al*., 2000; Baron *et al*., 2002). When water use for increasing agricultural production, be it crops, livestock, fisheries or aquaculture, or some combination of these, is examined in a trade-off with environmental flows, the overall food productivity from a given water resource may decrease (WWAP, 2009).

Tensions between water for ecosystems and water for food do not only have an impact on food production. Balancing the water demand for different uses is critically important for maintaining biodiversity and ecosystem resilience (WWAP, 2009), as well as for other ecosystem services – including the provision of firewood, timber, pollination services and clean water, all of which are essential for human well-being (Carpenter *et al*., 2009). Restoring the productive capacity of highly degraded ecosystems requires revegetation and flow restoration, both of which, in turn, need water; these are needs that will compete directly with water demand for food production, as well as for other uses. In some cases, the values generated by irrigation have proved to be less than the values generated by the ecosystems they replaced (Barbier and Thompson, 1998; Acreman, 2000). In order to avoid further degradation, fundamental efforts are required to promote and establish effective ecosystem-based catchment management approaches (IUCN, 2000; UNEP, 2010; Chapter 10).

Water Availability, Poverty and Development

Water contributes to poverty alleviation in various ways, such as improving water supply and sanitation, enhancing health and resilience to disease, improving productivity and output, and helping to provide more affordable food (WWAP, 2009; Chapter 2). Generally, the poorest populations in the world face the most difficulties in accessing water supplies, and they are also the most dependent on water resources for their daily livelihoods (WWAP, 2009). Poor people also tend to be the ones that are most directly dependent on food delivery from healthy and well-functioning natural ecosystems to support often subsistence-driven livelihoods, e.g. river–floodplain fisheries and flood recession agriculture (Richter *et al*., 2010). This places them as the people most vulnerable to changing conditions such as climate change, environmental degradation and population pressures (Molden, 2007; Sullivan and Huntingford, 2009).

While economic poverty decreased from 28% in 1990 to 19% in 2002 (UNEP, 2007), water poverty increased over that same period (WWAP, 2009). Water poverty refers to a situation where a nation or region cannot afford the cost of providing sustainable clean water to all of its people at all times (Feitelson and Chenoweth, 2002; Molle and Mollinga, 2003). This suggests that unless water poverty can be alleviated, economic poverty reduction programmes will be less effective than they would otherwise be. Increased water provision for agricultural production is thus viewed as an opportunity that allows more people to obtain an income from farming and increases food production – thereby decreasing the overall price of food, and allows the poor to consume a more nutritional diet and spend their income on other necessities (Hussain and Hanjra, 2004; McIntyre *et al*., 2008).

Challenges related to water availability, water use for agriculture, and poverty are diverse and complex and therefore need to be analysed by integrating different perspectives, i.e. hydrological, water and land productivity, livelihood and development, and governance and institutions. This will allow the identification of viable options for improving the situation effectively in an integrated approach across relevant sectors. Cook *et al*. (2011) suggested that water is linked to development through: (i) physical water scarcity; (ii) lack of access to water, or economic water scarcity due to infrastructure or institutional frameworks, which has strong linkages to the level of development; (iii) exposure to water-related hazards such as drought, flood and disease, which are expected to be aggravated by climate change and largely affect the poor; and (iv) water productivity, which, particularly in rainfed agriculture, is low, but through improvement offers opportunities to meet future increase in demand for food without increasing agricultural water use. These relationships were analysed by Cook *et al*. (2011) and Kemp-Benedict *et al*. (2011) in a study of ten selected basins in developing countries, in which they classified the basins based upon the agricultural and water-related parameters that characterized their different levels of development (see Box 5.1).

The Yellow River Basin is a characteristic example of an area that is facing physical water scarcity; pressures on existing water resources are also expected to increase further (Ringler *et al*., 2010). This basin, a key food production centre of global importance, is facing growing water-related challenges, which are exacerbated by increasing demands from industrial and urban sectors, environmental needs, increasing water pollution, and potentially severe future climate change impacts that result in increasing water deficit. The main water user in the basin is agriculture, and this is also a main contributor to water pollution. Institutional and policy frameworks for managing water resources in the basin, however, are not sufficiently harmonized and integrated to ensure a basin-wide

Box 5.1. Agriculture and water in a development context (Cook *et al.*, 2011; Kemp-Benedict *et al.*, 2011).

The basins of the Andes and São Francisco (South America), Volta, Niger, Limpopo and Nile (Africa), Karkheh (Iran), Indus–Ganges (India), Mekong (South-east Asia) and Yellow (China) rivers were classified according to their water availability, water productivity and poverty. Arranged along a 'development trajectory', based on the variables of rural poverty and agriculture as a percentage of gross domestic product (GDP), the basins ranged from strongly agricultural economies, via transitional economies, to industrial economies. In this approach, agriculture is seen as a necessary but insufficient basis for development.

Agricultural economies, e.g. those of the Niger, Volta and Nile River basins are characterized by overall very low agricultural productivity and high rural poverty, limited non-agricultural economic activities and poorly developed water infrastructure; 'non-engineered' agriculture is seen as relatively more important than in the two other economies. To move along the development pathway, agricultural productivity needs to be improved, basic needs provided, markets and necessary infrastructure developed, and food security enhanced, mostly through improving rainfed agriculture rather than through irrigation.

In *transitional economies*, e.g. those of the Indus, Ganges, Mekong and Yellow River basins, non-agricultural and value-adding activities increasingly contribute to GDP and attract people from the agricultural sector. Generally, rapid economic and population growth are experienced, coupled with increasing demand for food; water resources are well developed, non-agricultural activities are expanding, but development is overall uneven and localized. Agriculture remains important at the national level, and agricultural productivity is increasing owing to the market and food demands of an increasingly urban population. As a result, pressure on water resources may increase as a result of increased agricultural activity (which possibly competes with other uses), water quality issues emerge and protection against water-related hazards is insufficient. The main opportunity for these economies is institutional development to enable transparent, informed and broadly-based processes of change for enhancing capacity and benefit sharing.

Industrial economies, e.g. those of the Andes and São Francisco River basins, no longer depend on agriculture for economic development, even if agriculture remains important in localized areas of rural poverty. Markets are well developed and income security gains more importance. In this context, water resources may be intensively managed. However, ecosystem services and benefit sharing are increasingly recognized, protection from water-related hazards is enhanced and food security is assured. There are increasing opportunities for sustaining the ecosystem services that are required to maintain water supplies to urban and industrial sectors, hydropower and agriculture.

approach to the sustainable management of water resources. Although measures have been taken to improve water legislation, the implementation of laws and regulations is still at a low level. Responsibilities for managing water resources in the basins are fragmented among different administrative units and levels, and these lack collaboration. Various options have been identified for addressing water scarcity in the Yellow River Basin. These include: improving water use efficiency and increasing water productivity in agriculture, industry and the domestic sector; implementing institutional solutions such as the reform of irrigation management; and using economic incentives for water management, such as pricing, taxes, subsidies, quotas and use or ownership rights. The potential for expanding irrigation in the basin is so limited that creating off-farm employment opportunities is viewed as a more appropriate strategy for advancing future rural economic development. Overall, a more consistent and harmonized approach to water resources management at the basin level, well supported by relevant institutions and policies, seems necessary to resolve the basic issues and make use of the potential of the different options that have been identified (Ringler *et al.*, 2010).

Future Challenges

The increase in water demand for food production is difficult to predict, as it depends to a large extent on variables such as population size, urbanization, diet composition, the ability to increase water use efficiency, and the effective allocation of production through enhanced trade and other means. It has been estimated that demand for water in agriculture could increase by over 30% by 2030, while total global water demand could increase by 35–60% between 2000 and 2025, and could double by 2050 owing to pressures from industry, domestic use and the need for environmental flows (Foresight, 2011). An optimized scenario accounting for regional opportunities and constraints would require global water consumption of agricultural crops to increase by 20% – or rise up to 8515 km^3 by 2050; the estimates vary depending on trade, water use efficiency, area expansion and productivity in rainfed and irrigated agriculture (de Fraiture and Wichelns, 2010). Other calculations arrive at different numbers. The 2012 World Water Development Report (WWAP, 2012) estimates an increase of around 19% by 2050, or more in the absence of technological progress or policy interventions; whereas Rockström *et al.* (2007) estimate that the achievement of food security in 92 developing countries would require 9660 km^3 water for agriculture by 2050. In many countries, water availability for agriculture is already limited and uncertain, and is expected to decrease further. In some arid regions, for example in the Punjab, Egypt, Libya and Australia, major non-renewable fossil aquifers are increasingly being depleted.

Climate change is expected to increasingly affect water, and hence food, security (Chapter 2), particularly in areas of Africa and Asia where agriculture depends on rainwater for its crops. In rainfed areas in Asia and sub-Saharan Africa water storage infrastructure is least developed and nearly 500 million people are at risk of food shortages (WWAP, 2012). Increased occurrence of climatic extremes such as floods and droughts can also have an impact on agricultural outputs, putting food security and economies at risk.

The expansion of irrigation across much of Asia, North America and North Africa has fuelled productivity gains in the past, but the limits have been reached, as little or no additional water is available for use in these areas (Faures *et al.*, 2007). In these physically water-scarce areas, but also in other regions, there will be increasing demand from other users and sectors, such as cities, industries, energy and environment, which will need to be addressed through adequate governance and institutional mechanisms.

Conclusions

Given the increasing demand and competition for freshwater resources, whose unhalted abstraction often undermines environmental flows and effects, the augmentation of water availability for agriculture can no longer rely on increasing water withdrawals, which are likely to result in further river basin closures (Molle *et al.*, 2010) and aggravated ecosystem degradation. Instead, new approaches to water use in agriculture will need to be explored that minimize water withdrawal and its effects on the environment, such as optimized water storage in rainfed agriculture, overall increased water use efficiency, and the treatment and reuse of wastewater where possible. The greatest hope for meeting the food and water demands of the world 50 years from now probably lies in increasing agricultural water use productivity for many of the least productive areas (Molden, 2007; Chapter 8).

Sustainably meeting the agricultural water needs of a growing population will require rethinking the approach to how water is developed and managed. The challenge of the increasing water scarcity for food production and other uses must be addressed through an integrated cross-sectoral approach to water resources and ecosystems management that is linked to ecoagricultural research, and aimed at maximizing water use efficiency and productivity, and minimizing environmental and climate change impacts. Such an approach helps to sustain critical ecosystems and ecosystem services, thereby supporting agricultural production and offering other multiple benefits for ecosystems, food security and human well-being.

Innovative strategies and practices will, however, need to be identified towards sustainable and integrated water resources management for various uses going beyond agriculture. The increasing imbalance between water availability for use and water withdrawn for agriculture, and also between water used in agriculture and water available for other uses, will need to be addressed through different technological, economic and institutional measures. Water conservation is a key measure that can be achieved through improving water use efficiency and water productivity in agricultural production, as well as by limiting the further expansion of water withdrawal. Sustainable pathways to growing enough food with limited water include: increasing water productivity in agriculture and, particularly, in rainfed areas; reducing loss of water in agricultural production through improved management practices and infrastructure; increasing water storage; expanding reuse of wastewater; influencing food consumption patterns; and enabling trade between water-rich and water-scarce areas. Solutions will need to be location and context specific, and adapted to the physical, economic and sociocultural environment. Countries must consider the full social, economic and environmental costs of not conserving existing water resources, as well as the costs of failure to develop new water sources.

Facilitating sustainable and more effective water resources management depends to a large extent on the governance and institutional frameworks that are in place. To enhance equal development and the sharing of resources and benefits, institutions are required to develop an integrated approach across different relevant sectors; this will enable them to balance the demands of different groups of people, as well as the pressures for development and sustainable use of the natural environment (Cook *et al.*, 2011), and also to put the necessary regulatory and incentive mechanisms in place. In the years to come, improvements in the collection of the data relevant to water availability, and to climate change, population growth and development, will help to provide a better basis for informed decision making.

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