5

Availability of water for agriculture in the Nile Basin

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Key messages

- Rain-fed agriculture dominates water use in the Nile Basin outside Egypt, with more than 70 per cent of the total basin rainfall depleted as evapotranspiration from natural systems partially utilized for pastoral activities, and 10 per cent from rain-fed cropping, compared with less than 1 per cent depleted through irrigation. There is a potential to considerably expand and intensify rain-fed production in upstream areas of the basin without significantly reducing downstream water availability.
- Proposals for up to 4 million ha of additional irrigation upstream of the Aswan Dam are technically feasible if adequate storage is constructed. However, if implemented, they would result in significant reduction of flows to Egypt, offset, to some extent, by reduction in evaporative losses from Aswan. Increasing irrigation area in Sudan will have a much greater impact on flows at Aswan than comparable increases in Ethiopia, due to more favourable storage options in Ethiopia. Expansion of irrigation in the Equatorial Lakes Region by up to 700,000 ha would not significantly reduce flows to Aswan, due to the moderating effects of Lake Victoria and the Sudd wetlands.
- Uncertainties in estimates of both irrigation demand and available flows within the basin are so high that it is not possible to determine from existing information the stage at which demand will outstrip supply in Egypt. Higher estimates suggest that Egypt is already using 120 per cent of its nominal allocation and is dependent on 'excess' flows to Aswan which may not be guaranteed in the longer term; and thus it is vulnerable to any increase in upstream withdrawals.
- Managing non-beneficial evaporative losses through a coordinated approach to construction and operation of reservoirs is an urgent priority. Total evaporative losses from constructed storage in the basin are more than 20 per cent of flows arriving at Aswan. By moving storage higher in the basin, security of supply in the upper basin would be improved, and evaporative losses reduced to provide an overall increase in available water. This can only be achieved through transboundary cooperation to manage water resources at the basin scale.
- Conversely, proposals to reduce evaporation by draining wetlands should be approached with caution, since the gains are relatively small and the Nile's large wetland systems provide important benefits in terms of both pastoral production and biodiversity.

- Projected changes in rainfall due to climate change are mostly within the envelope of existing rainfall variability, which is already very high. However, temperature increases may reduce the viability of rain-fed agriculture in marginal areas, and increase water demand for irrigation.

Introduction

Rapid population growth and high levels of food insecurity in the Nile Basin mean that increasing agricultural production is an urgent imperative for the region. In much of the basin, agriculture is dominated by subsistence rain-fed systems with low productivity and high levels of risk due to variable climate. Egypt's highly productive, large-scale irrigation is seen as a model for agricultural development in other Nile Basin countries, but there are concerns that irrigation development in upstream countries could jeopardize existing production in Egypt. The Nile Basin Initiative (NBI) was launched in 1999 as a mechanism to share the benefits of the Nile waters more equitably. A critical question for the NBI is the extent to which upstream agricultural development will impact on water availability in the lower basin. This chapter synthesizes evidence from several of the studies presented in this book to examine current and future water availability for agriculture in the Nile Basin.

A distinction must be made between water availability (the total amount of water present in the system) and water access (ease of obtaining and using it). Availability is generally fixed by climate and hydrology, while access can be improved through infrastructure and/or enabling institutional mechanisms. In much of Africa, access to water is a more pressing constraint on livelihoods, and a contributor to high levels of poverty. In the Nile Basin, there is the apparently contradictory situation that access to water is often poor in the highland areas where water is abundant; but in arid Egypt, access has been significantly enhanced due to well-developed infrastructure. The chapter will examine only water availability (the nexus between water, poverty and vulnerability is discussed in Chapter 3).

Nile Basin overview

The Nile basin covers 3.25 million km^2 in nine countries, and is home to a population of around 200 million. The Nile comprises five main subsystems. There have been a number of different delineations of the extent of the Nile Basin and its component sub-basins. This study adopts the delineation currently used by NBI, amalgamating some sub-basins to eight larger units. Reference is also made to results of Kirby *et al.* (2010), who used a set of 25 sub-basins, which nest within the NBI units. Figure 5.1 illustrates the major tributaries and sub-basins of the Nile basin, which are:

- The White Nile sub-basin, divided into three sections:
  - headwaters in the highlands of the Equatorial Lakes Region (ELR), including Lake Victoria;
  - middle reaches in western and southern Sudan, where the river flows through the lowland swamps of the Sudd (Bahr el Jebel) and Bahr el Ghazal; and
  - Lower White Nile (LWN) sub-basin in central Sudan south of Khartoum.
- The Sobat-Baro-Akobo sub-basin, including highlands of southern Ethiopia and Machar Marshes and lowlands of southeast Sudan.
- The Blue Nile (Abay) sub-basin, comprising the central Ethiopian plateau and Lake Tana, and the arid lowlands of western Ethiopia and eastern Sudan, including the major irrigation area at Gezira where the Blue Nile joins the White Nile near Khartoum.

- The Atbara–Tekeze sub-basin, comprising highlands of northern Ethiopia and southern Eritrea and arid lowlands of northeast Sudan.
- The Main Nile system, divided into two distinct sections:
  - Main Nile in Sudan above the Aswan Dam; and
  - Egyptian Nile below Aswan, including the Nile Valley and Delta.

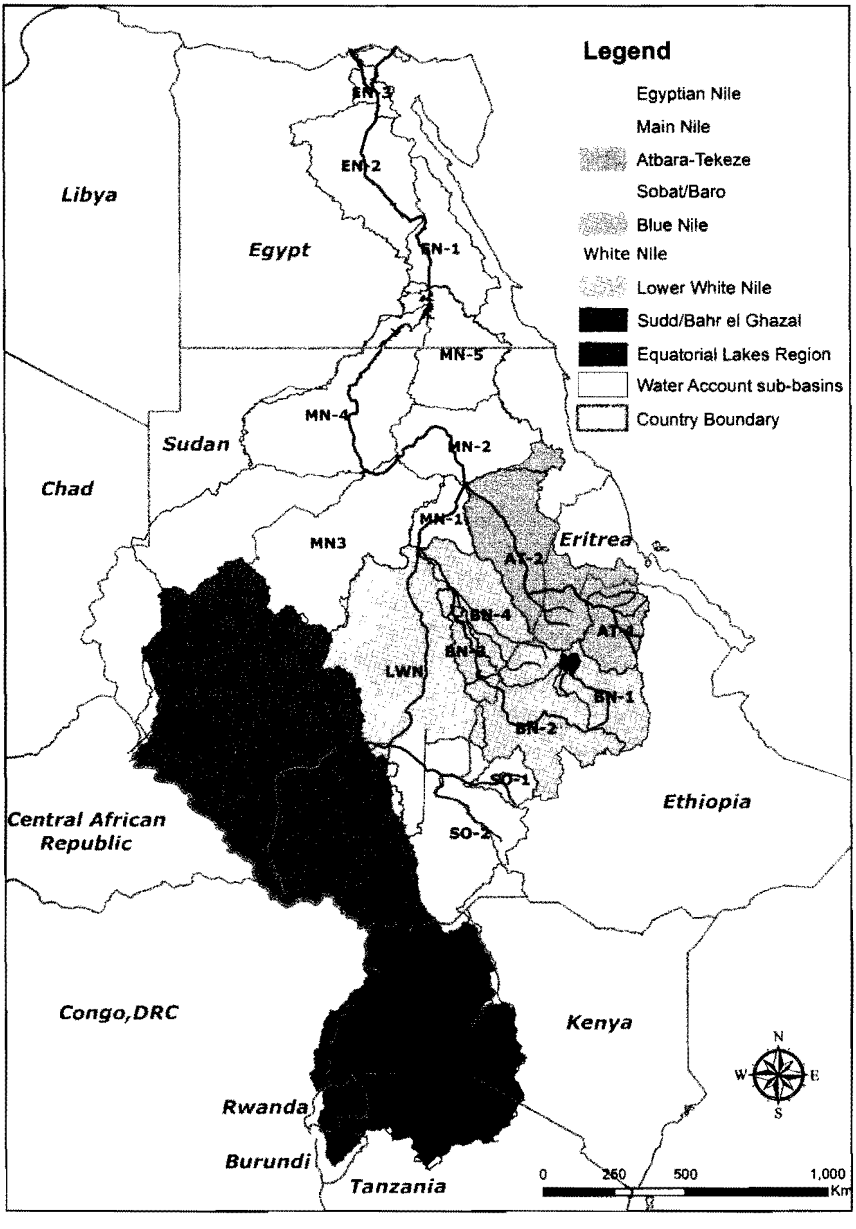

Figure 5.1 The Nile Basin, showing major tributaries and sub-basins. Smaller sub-catchments used in the water accounting framework of Kirby *et al.* (2010) are also shown

Climate

The climate of the Nile Basin has strong latitudinal and topographic gradients. Mean annual precipitation (MAP) decreases from the highlands of the south and east to the lowland deserts in the north, and ranges from more than 2000 mm around Lake Victoria and in the Ethiopian highlands to less than 10 mm in most of Egypt. Rainfall in the basin is strongly seasonal, although the timing and duration of the wet season vary. In the Equatorial Lakes Region there is a dual wet season with peaks in April and November; parts of the Ethiopian Highlands also experience a weak second wet season. In most of the basin, the wet season peaks around July–August, becoming shorter and later in the eastern and northern parts of the basin. Evaporation exceeds rainfall over most of the basin, with the exception of small areas in the equatorial and Ethiopian Highlands. Temperatures and potential evapotranspiration (PET) are highest in central and northern Sudan, where maximum summer temperatures rise above 45°C and annual PET exceeds 2 m. The northern third of the basin is classified as hyper-arid (MAP/PET <0.05); but the southern half of the basin is semi-arid to humid with MAP above 600 mm. In the equatorial regions in the south, temperatures and PET vary only slightly through the year; in the north of the basin, seasonal changes in temperature are reflected in PET, which almost doubles in mid-summer (see Figure 5.2).

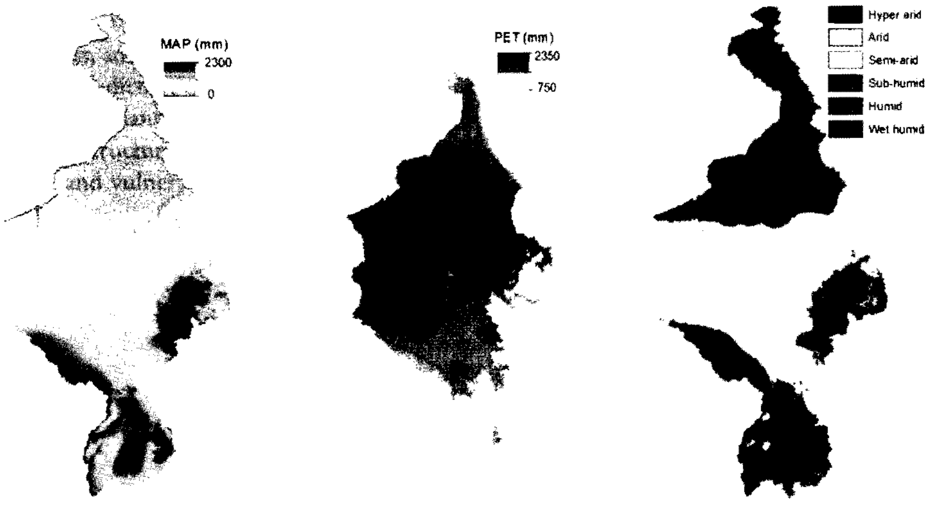

Figure 5.2 Mean annual precipitation (MAP), mean annual potential evapotranspiration (PET) and humidity index for the Nile Basin

Source: World Climate Atlas (http://waterdata.iwmi.org)

Inter-annual rainfall variability is very high, related to the movements of the Inter-tropical Convergence Zone and to the Southern Oscillation Index, with low rainfall in El Niño years. Camberlin (2009) describes long-term rainfall variability on the scale of decades, with different patterns in different regions. Over the period 1951–2000, the northern belt (15–16° N) experienced high rainfall in the 1950s and 1960s, with dryer conditions from 1970 to 2000; the African Sahel (7–14° N) saw a severe downward trend in rainfall through the 1970s and 1980s,

with partial recovery in the 1990s; and equatorial regions experienced a wet period in the 1960s, but rainfall was otherwise stable. Seasonal and inter-annual climate variability has a more significant impact on river flows than long-term climatic trends (Awulachew *et al.*, 2008; Di Baldassarre *et al.*, 2011). For temperature over the same period, a majority of warming trends are observed, with a rise of 0.4° C reported for 1960–2000 across East Africa (Hulme *et al.*, 2001).

Hydrology

The hydrology of the Nile Basin is reviewed in detail by Sutcliffe and Parks (1999) and Sutcliffe (2009). A schematic of flow distribution in the Nile system based on average flows is shown in Figure 5.3. The total annual flow arriving at the Aswan High Dam varies between 40 and 150 km^3, averaging around 85 km^3; of this total, the White Nile, Sobat and Atbara systems each contributes about one-seventh, with the Blue Nile contributing four-sevenths (Blackmore and Whittington, 2008). The Main Nile is a losing system, with high transmission losses due to evaporation and channel infiltration (NWRC, 2007). The volume and distribution of flows in the various Nile sub-basins vary markedly from year to year and over decades, reflecting variability in rainfall. Table 5.1 compares discharge from the main sub-basins for periods in the first and second half of the twentieth century. In the south of the basin, there was a marked increase in flows but in the north, flows decreased by around 20 per cent. These differences reflect a complex interplay of climate variability and human modification of the river system, and do not necessarily represent continuing trends.

Table 5.1 Variability of Nile flows; comparison of long-term average flows over different time periods

Sub-basin	*Station*	*Annual discharge (km^3)*				*Change*	*Data source*
		Pre-1960		*Post-1960*			
White Nile/ Equatorial Lakes Region	Lake Victoria	1901–1960	20.6	1961–1990	37.5	1.8	Sutcliffe and Parks, 1999
White Nile above Sudd	Mongalla	1905–1960	26.8	1961–1983	49.2	1.8	
White Nile below Sudd	Sudd outflow	1905–1960	14.2	1961–1983	20.8	1.5	
Sobat	Doleib Hill	1905–1960	13.5	1961–1983	13.7	1.0	
LWN above Jebel Aulia	Malakal	1905–1960	27.6	1961–1995	32.8	1.2	
LWN below Jebel Aulia	Mogren	1936–1960	23.1	1961–1995	28.1	1.2	
Blue Nile	Khartoum	1900–1960	52.8	1961–1995	48.3	0.9	
Atbara	Atbara at mouth	1911–1960	12.3	1961–1994	8.6	0.7	
Main Nile above Aswan	Dongola	1911–1960	86.1	1961–1995	73.1	0.8	
Egyptian Nile below Aswan	Aswan	1952–1960	89.7	1970–1984	56.9	0.6	Dai and Trenberth, 2003
Egyptian Nile Delta	–	before 1970	32.4	after 1970	4.5	0.1	El-Shabraway, 2009

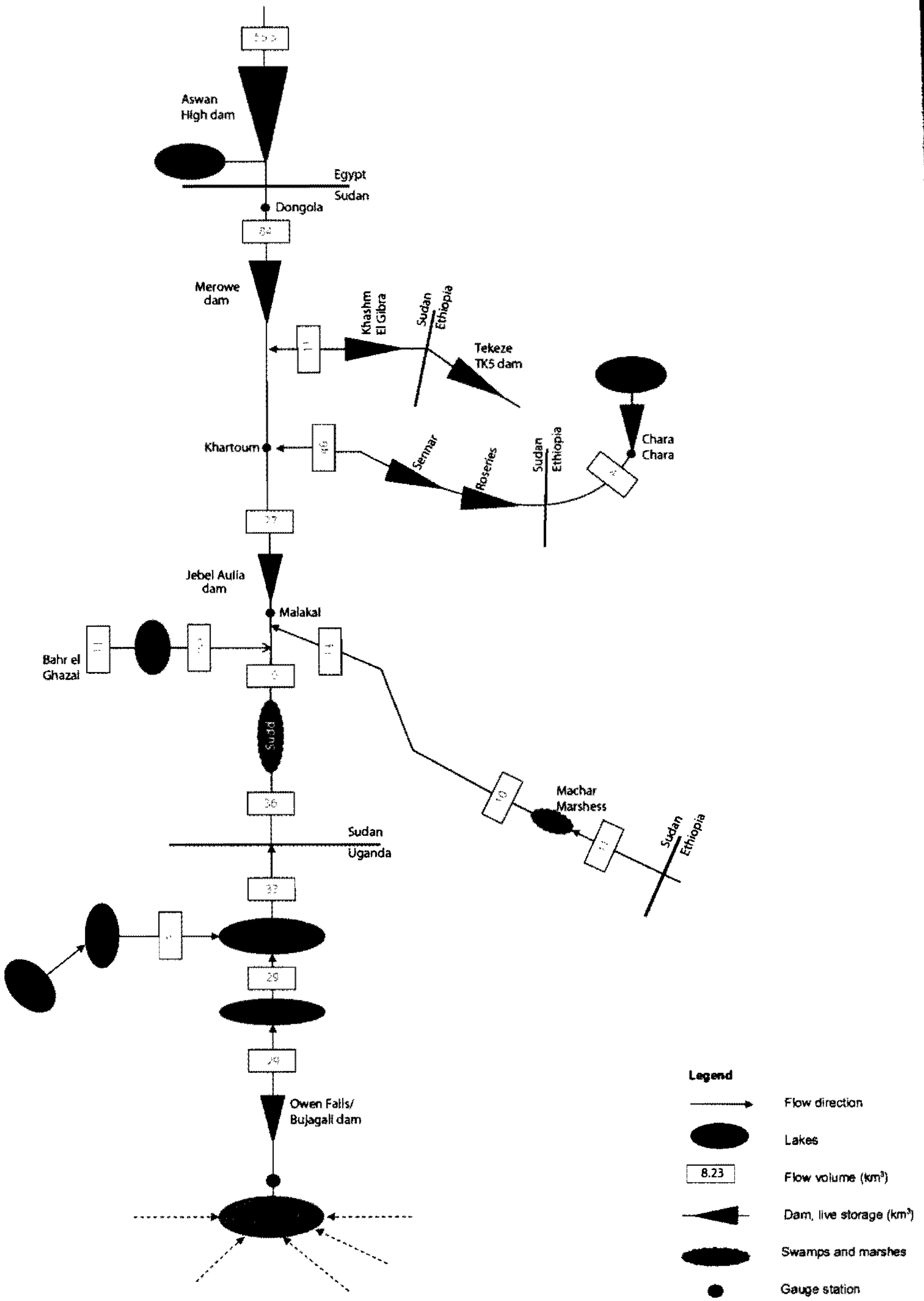

Figure 5.3 Schematic of Nile flows

Source: modified from Awulachew *et al.*, 2010

Flows in the Nile are highly seasonal, with different patterns in different parts of the basin, in response to rainfall distribution. The White Nile, fed mainly from Lake Victoria and moderated by the vast wetlands of the Sudd, has a relatively constant flow throughout the year. In contrast, the tributaries rising in the Ethiopian Highlands have pronounced peak flows during the wet season with little base flow. As a result, the Main Nile below Khartoum has peak flows (from the Blue Nile, Sobat and Atbara) superimposed on modest base flows (from the White Nile). Peak flows are substantially reduced below the Aswan High Dam (AHD) as releases are timed to meet agricultural demand. Figure 5.4 illustrates the spatial distribution of seasonal variability in flows, based on calculated discharge from 25 sub-basins for the period 1952–2000 (Kirby *et al.*, 2010).

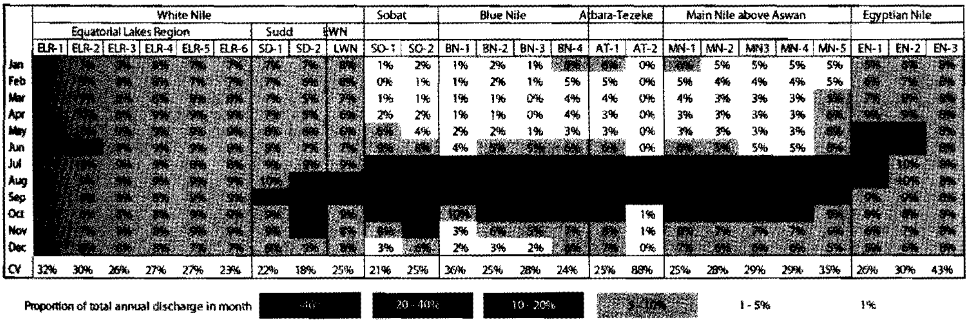

Figure 5.4 Spatial patterns of seasonal flow in the Nile sub-basins, displayed as proportion of annual flow in each calendar month

Note: Averages are for 1952–2000, except for the Egyptian Nile, which are 1970–2000 (i.e. after construction of Aswan High Dam). Coefficient of variation (CV) is for annual flows, 1952–2000

Source: Based on CRU data compiled by Kirby *et al.*, 2010

In response to this variability, dams were constructed prior to 1970 on the White Nile (Jebel Aulia), Blue Nile (Roseries and Sennar) and Atbara (Khasm el Girba) with total storage of 7.7 km^3, to retain peak flows for irrigation in Egypt and Sudan. In 1970, AHD was constructed to provide over-year storage to safeguard flows to Egypt. The reservoir was designed for 'century storage', to guarantee a supply equal to the mean inflow over a period of 100 years. Total storage is 162 km^3, almost twice the mean annual flow. Prior to its construction, Egypt and Sudan signed an agreement which divided the expected yield of the project between the two countries. Based on the long-term annual flow of 84 km^3 and estimated evaporative losses of 10 km^3, the remaining amount of 74 km^3 was apportioned as 55.5 km^3 to Egypt and 18.5 km^3 to Sudan. The upstream Nile Basin countries were not party to the agreement, and do not recognize it.

Agriculture in the Nile Basin

Farming systems in the Nile Basin are diverse, including a range of pastoral, agro-pastoral and cropping system (for more detail, see Chapter 8). Livestock are an important component of agricultural systems throughout the basin. Irrigation from the Nile and its tributaries has allowed development of agriculture in otherwise arid regions of Egypt and Sudan. Otherwise,

land use reflects climatic gradients, with a transition from rain-fed mixed agriculture in the humid south and east, through agro-pastoral systems in the semi-arid central regions, to low-intensity rangelands and desert in the arid north. The length and timing of the growing season (defined as months where precipitation/PET >0.5, depicted in Figure 5.5) exercise a primary control on land use.

	White Nile									Sobat		Blue Nile				Atbara-Tezeke		Main Nile above Aswan					Egyptian Nile		
	Equatorial Lakes Region						Sudd		LWN																
	ELR-1	ELR-2	ELR-3	ELR-4	ELR-5	ELR-6	SD-1	SD-2	LWN	SO-1	SO-2	BN-1	BN-2	BN-3	BN-4	AT-1	AT-2	MN-1	MN-2	MN3	MN-4	MN-5	EN-1	EN-2	EN-3
Jan				0.2	0.3	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Feb				0.3	0.4	0.1	0.0	0.0	0.0	0.2	0.1	0.2	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Mar						0.4	0.2	0.0	0.0	0.4	0.2	0.3	0.2	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Apr							0.4	0.1	0.1		0.4	0.5	0.4	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
May								0.2	0.2					0.2	0.1	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jun	0.2	0.2						0.4	0.4						0.4		0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jul	0 1	0.1	0.4															0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0
Aug	0.2	0.3	0.4															0.3	0.1	0.3	0.0	0.0	0.0	0.0	0.0
Sep	0.5		0.5														0.3	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Oct								0.2	0.3			0.5		0.2	0.2	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nov						0.5	0.1	0.0	0.0		0.3	0.2	0.2	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Dec				0.3	0.5	0.1	0.0	0.0	0.0	0.2	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
CV	10%	11%	14%	14%	10%	13%	9%	16%	15%	11%	20%	13%	9%	17%	16%	25%	25%	55%	68%	44%	76%	66%	54%	38%	33%

Rainfall/PET: >1 | 0.7-1.0 | 0.5-0.7 | 0.2-0.5 | <0.2

Figure 5.5 Monthly variation in humidity index (rainfall/PET) for Nile sub-basins 1951–2000, illustrating spatial variability of timing and duration of growing season

Note: CV is for annual rainfall 1951–2000

Source: Based on CRU data compiled by Kirby *et al.*, 2010

Dominant land use in the basin in terms of area is low-intensity agro-pastoralism, with grasslands and shrublands interspersed with small-scale cropping, covering more than a third of the basin (see Figure 5.6). Extensive seasonally flooded wetlands in South Sudan (Machar Marshes, Sudd and Bahr el Ghazal) support large livestock herds: it is estimated that there are over one million head of cattle in the Sudd (Peden *et al.*, 2009). In the semi-arid to arid zones of central Sudan, sparse grasslands are utilized for low-intensity agro-pastoral production and extensive grazing. In the northern parts of the basin, low and variable rainfall jeopardizes availability of feed in the rangelands, and demand for drinking water for stock exceeds supply in most areas (Awulachew *et al.*, 2010). Water productivity in these areas is generally very low; in most areas, rainfall cannot meet crop water demands resulting in low yields. At Gezira and New Halfa, development of irrigation has significantly improved productivity (Karimi *et al.*, 2012) and further large expansion of irrigation is proposed in these areas.

The total area of rain-fed cropping in the basin is estimated at over 33 million ha (FAO, 2010; Table 5.2). Almost half of this area is in the ELR, where major crops are bananas, maize and wheat, with some commercial cultivation of coffee, sugar cane and cotton. Natural swamps and marshes are used extensively for agriculture, with over 230,000 ha of cultivation in wetlands and valley bottoms in Burundi, Rwanda and Uganda (FAO, 2005). Despite mostly adequate rainfall, yields and productivity in this region are low to moderate (Karimi *et al.*, 2012).

Sudan has almost 15 million ha of rain-fed cropping, mainly subsistence cultivation of cereals, groundnut and soybean. During the 1960–1980s, the Sudan government promoted

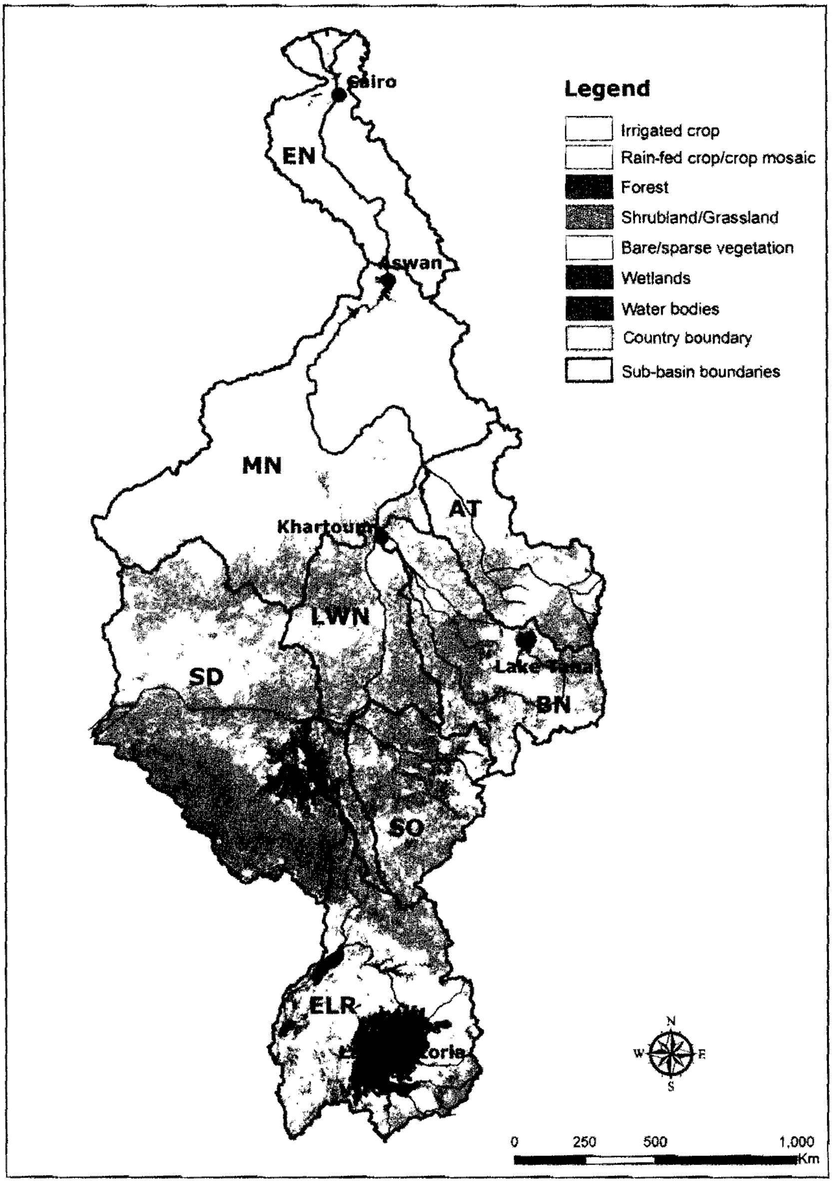

Figure 5.6 Land cover in the Nile Basin

Source: Globcover 2009, © ESA 2010 & UCLouvain, http://ionia1.esrin.esa.int

mechanized rain-fed agriculture, designed to utilize the fertile cracking clay soils that were not suited to traditional cultivation practices. Over 0.75 million ha were cultivated under official schemes or informally, with sorghum, groundnut and sugar cane. Initial yields were high, but unsustainable farming practices, drought and civil war meant that, by the mid-1990s, much of the land had been abandoned (Mongabay, 1991; UNEP/GRID, 2002).

Table 5.2 Areas of irrigated and rain-fed cropping in the Nile Basin reported by different studies

Country	*FAO (2010)*			*Chapter 15, this volume*	*Bastiaanssen and Perry, 2009*
	Rain-fed (thousand ha)	*Irrigated* (thousand ha)*	*Percentage irrigated*	*Irrigated (thousand ha)*	*Irrigated (thousand ha)*
Egypt	0	5117	100	3324	2963
Sudan	14,785	1207	8	2176	1749
Eritrea	64	5	7	–	–
Ethiopia	3328	15	0	16	91
Uganda	8123	33	0	9	25
Kenya	2153	42	2	6	34
Tanzania	2593	0	0	0	7
Rwanda	1375	21	1	5	18
Burundi	808	0	0	–	14
Total	33,229	6440	16	5536	4901

Note: *Includes multiple cropping

In the Ethiopian Highlands, a variety of crops are grown, including cereals (wheat, barley, maize), enset root crops, coffee, teff and sorghum; livestock are an important component of farming systems. Double-cropping is possible in some areas. Erosion from steep cultivated lands is a major problem, reducing agricultural productivity and causing rapid sedimentation in downstream reservoirs (Awulachew *et al.*, 2008).

Estimates of total irrigated area in the basin range from 4.9 million to 6.4 million ha (Table 5.2). Large areas of formal irrigation are developed only in Egypt and Sudan. In Sudan, irrigation schemes totaling around 1.5 million ha have been developed at Assalaya and Kenana on the Lower White Nile (0.08 million ha), New Halfa (0.16 million ha) on the Atbara downstream of Khasm el Gibra Dam, and Gezira on the Blue Nile (1.25 million ha). The Gezira scheme, one of the largest in Africa, draws water from reservoirs at Roseires and Sennar. The major irrigated crops are sorghum, cotton, wheat and sugar. In addition, small-scale pump irrigation occurs along the main Nile channel. Most irrigation in Sudan overlaps at least a part of the wet season, with little irrigation in the winter dry period. Generally, low productivity in Sudan's irrigation areas is attributed to a range of factors including poor farming practices, problems with water delivery resulting from siltation of reservoirs and lack of flexibility due to the requirements of releases for hydropower, poor condition of canals, drainage problem, salinization and an unfavourably hot climate (Bastiaanssen and Perry, 2009).

In Egypt, total agricultural area in the Nile Valley and Delta exceeds 3 million ha; double-cropping means that over 5 million ha are planted annually (Bastiaanssen and Perry, 2009; FAO, 2010; Chapter 15, this volume). Water is provided by the AHD and seven barrages diverting water into an extensive network of canals (32,000 km of canals) with complementary drainage systems. There are three agricultural seasons: winter (October to February), when main crops are wheat, fodder and berseem; summer (March–June), when the main crops are maize, rice and cotton; and *nili* (July–September), when the main crops are rice, maize, pulses, groundnut and vegetables. Sugar cane, citrus, fruits and oil crops are grown all year. Because rainfall is so low, virtually all agriculture is irrigated, although there may be opportunistic rain-fed cropping in some years. In the last 10 years, new irrigation areas have been developed at the 'New Valley'

irrigation project near the Toshka lakes, drawing water from Lake Nasser via a pumping station to irrigate around 0.25 million ha, with total water requirements of 5.5 km^3 when fully operational (NWRC, 2007; Blackmore and Whittington, 2008). Withdrawals from the Nile are also used outside the basin in the Sinai irrigation development, where 0.168 million ha are to be irrigated using 3 km^3 of water derived from 50 per cent Nile water mixed with 50 per cent recycled water (NWRC, 2007).

Karimi *et al.* (2012) assessed water productivity in the Nile Basin, and found that overall productivity in irrigated systems in Egypt is high, with intensive irrigation, high yields and high-value crops. Bastiaanssen and Perry (2009) point out that there is great variability in productivity between different irrigation districts, with some functioning very poorly, but some of the systems in the Delta ranking among the best in the world.

Water balance/water account

The Nile River flows constitute only a very small proportion of total water resources in the basin. On average, a total of around 2000 km^3 of rain falls over the basin annually, but annual flow in the Nile at Aswan is <5 per cent (around 85 km^3). In order to assess availability of water for agriculture, water accounts have been constructed for the basin at different spatial and temporal scales to illustrate the way rainfall is distributed, stored and depleted in the basin.

Kirby *et al.* (2010) developed a dynamic water use account for the Nile Basin, based on 25 sub-catchments at monthly time steps, with hydrological and evapotranspiration (ET) components. The sub-catchments used in the analysis are shown in Figure 5.1. A hydrological account of inflows, storages, depletion by ET and outflows is based on lumped partitioning of rainfall into run-off and infiltration; downstream flows are calculated using a simple water balance. ET is estimated from PET and the surface water store, and partitioned between land uses based on the ratio of their areas, using crop coefficients to scale ET relative to other land uses. The account uses a 50-year run of climate data (1951–2000; Climate Research Unit, University of East Anglia; CRU_TS_2.10), and provides information on both seasonal and inter-annual variability in rainfall, flows and ET. It does not account for changes in land use over the period, but assumes static land cover, derived from 1992–1993 Advanced Very High Resolution Radiometer (AVHRR) data. The results were validated against available flow data from 20 gauging stations in the basin from the ds552.1 data set (Dai and Trenberth, 2003). For this study, some corrections and adjustments were made to the Kirby *et al.* model and the results were recalculated.

The results (summarized in Figure 5.7) indicate that, at the basin scale, only a small fraction of total rainfall is depleted as ET from managed agricultural systems (10% from rain-fed cropping and 3% from irrigation). A large proportion of rainfall (70%) is used by grasslands, shrubland and forest that are not actively managed, although a large proportion of this area is used for pastoral activities at different intensities. Significant run-off volumes are generated only from a few catchments, mainly in the highlands of the ELR and Ethiopia. Calculated values for local run-off, totaling 7 per cent of basin rainfall (163 km^3), are higher than net discharge through the river system, since flows are depleted by channel losses and evaporation.

Over 8 per cent of total basin water resources are depleted through evaporation from water bodies (lakes, dams and open water swamps). Of this, around half is from Lake Victoria (ELR-3 in Figure 5.7), and another third from the major wetland systems of the Sudd and Bahr el Ghazal (SD-1 and SD-2). Excluding these, the water account indicates that total annual evaporative losses from man-made reservoirs exceed 15 km^3.

Karimi *et al.* (2012) constructed a water account for the Nile at basin scale using remotely

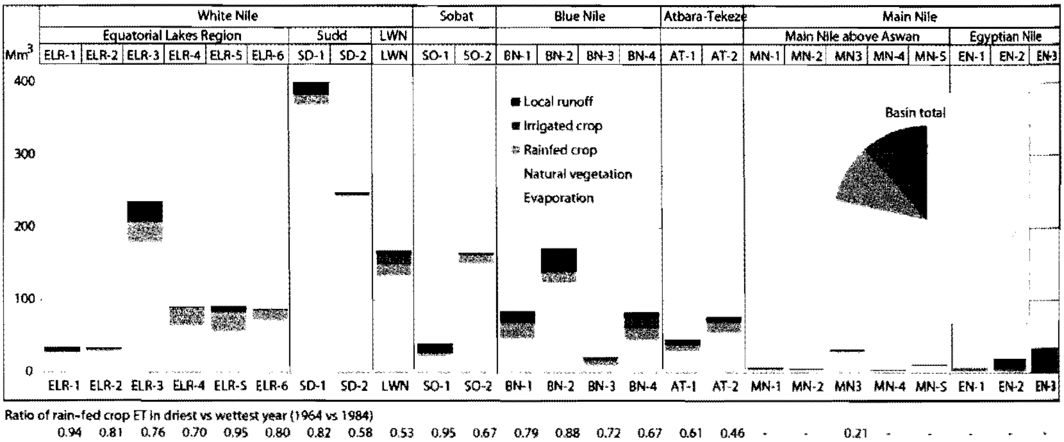

Figure 5.7 Water account for the Nile, showing partitioning of rainfall into ET (by land use category) and locally generated run-off for each sub-catchment and the basin as a whole

sensed data on rainfall, land use and evapotranspiration (ET) for a single year (2007). They estimate that of the 2045 km^3 of rainfall delivered to the basin, only 13 per cent was depleted from crops (10% rain-fed cropping and 3% irrigation). Surface run-off represented only 4.5 per cent of rainfall, with outflows to the seas less than 2 per cent of total inputs. These results correspond well with those from the modelled water account above.

Availability of water for rain-fed agriculture

Four important points about availability of water for rain-fed agriculture in the Nile Basin emerge from the water accounts. First, the proportion of rainfall in the basin that is currently depleted from cropping is very small – around 13 per cent in total, 10 per cent in rain-fed cropping and only around 3 per cent in irrigated production. Most of the rainfall is depleted from natural grasslands and woodlands used for extensive pastoralism, often with very low productivity (Karimi *et al.*, 2012). This is despite the fact that in the subhumid regions in the southern basin (particularly in South Sudan and central Sudan), average rainfall is more than sufficient to support rain-fed cropping. There is significant opportunity to extend more intensive and productive cropping and agro-pastoral land uses into areas currently dominated by low productivity grazing through improved water management, including rainwater harvesting and storage for small-scale irrigation.

While the proportion of ET from rain-fed crops remains relatively stable between years, the absolute amount varies very significantly, from 180 to 256 km^3, representing a large difference in potential crop production between years and illustrating the risks associated with rain-fed agriculture in the region. The variability is higher in low rainfall areas: the ratio of rain-fed crop ET between the driest and the wettest years is around 0.7–0.9 in the humid uplands, but falls to around 0.5 in the semi-arid catchments of central Sudan and the Atbara basin. In terms of food security, this annual variability is exacerbated by the occurrence of multi-year droughts. Under these conditions, opportunistic cropping in wet years (routinely practised in dryland production in semi-arid regions in Australia) may be a viable strategy commercially, although it is difficult to reconcile it with the need for smallholders to produce a crop every year to

ensure food security. Small-scale agricultural water management techniques, such as rainwater harvesting, small-scale storages and groundwater have a potentially important role in securing rain-fed crops in these regions. Araya and Stroosnijder (2011) found that in northern Ethiopia, where crops failed in more than a third of years in the period 1978–2008, one month of supplementary irrigation at the end of the wet season could avoid 80 per cent of crop yield losses and 50 per cent of crop failures. Other strategies used in the area to manage erratic rainfall include supplementary irrigation to establish crops (to avoid false starts to the wet season), postponement of sowing until adequate soil moisture is available, and growing quickly maturing cash crops such as chickpea at the end of the growing period, to utilize unused soil water reserves.

Estimates of net discharge indicate that the majority of flow is generated from only a small number of sub-catchments in the ELR and Ethiopian Highlands, which constitute water source zones (see Chapter 4). Land use in areas outside of these zones will have little impact on downstream flows. Thus, there are significant areas where rainwater harvesting, intensification of cropping and conversion of natural vegetation to agriculture are unlikely to significantly reduce downstream water availability.

In the ELR below Lake Victoria, the Sudd, Bahr el Ghazal and lower Sobat sub-basins, locally generated run-off is high, but net discharge from the sub-basin constitutes only a small fraction of total run-off (<20%). These areas retain water in natural sinks (wetlands, shallow groundwater) that are used to secure rain-fed production. There is cultivation of over 230,000ha in wetlands and valley bottoms in the Nile Basin in Burundi, Rwanda and Uganda (FAO, 2005). The wetlands of South Sudan are very important for livestock grazing: over one million head of cattle are estimated to be in the Sudd (Awulachew *et al.*, 2010). Better understanding of the hydrology of these regions, and particularly the connections between surface water and groundwater, could open up new opportunities for agriculture, capitalizing on annually recharged wetlands and shallow aquifers.

There is at this stage no compelling evidence that climate change will significantly alter total rainfall across the Nile Basin in the next 50 years. Different studies project both increased and decreased rainfall (Di Baldassarre *et al.*, 2011; Kim *et al.*, 2008). Most projected changes are within the envelope of existing rainfall variability. However, projected temperature increases of 2–4° C by 2090–2099 (IPCC, 2007) will increase ET and water stress, and may reduce the viability of rain-fed agriculture in marginal areas. Shifts in seasonality or variability of rainfall may also increase risks to rain-fed production, even if total rainfall remains constant. Climate adaptation efforts that focus on local agricultural water management interventions to reduce risks to agriculture from rainfall variability constitute 'no-regrets' options that can help in addressing current as well as future vulnerability.

Availability of water for irrigated agriculture

Current demands for water for irrigation in the upstream Nile countries (excluding Egypt and Sudan) are very low compared with available resources. In the White Nile sub-system, total estimated annual demand in the ELR is less than 1 km^3 in total (see Table 15.4, page 306), representing only a small fraction of the average flow of around 32 km^3 leaving Uganda. Available resources are more than adequate to supply current demand, and constraints on irrigation development are about infrastructure and access, rather than about water availability. Similarly, in Ethiopia current demand is minimal compared with available resources.

In Sudan, however, current irrigation demand is much higher, though difficult to estimate precisely. Reported irrigated area ranges from 1.2 million to 2.2 million ha (see Table 5.2);

depending on assumptions made about per hectare application rates, channel losses and return flows, total demand exceeds 12.5 km^3 and could be as high as 22.4 km^3 annually. The higher figure is considerably in excess of the 18.5 km^3 allocated to Sudan under the 1959 agreement, but represents only a quarter of total annual flows in northern Sudan. Water shortages do occur in both Gezira and New Halfa, but these are due to inadequate seasonal storage and siltation of reservoirs (Bastiaanssen and Perry, 2009). At this stage, there is no indication that Sudan's withdrawals have resulted in flows to Egypt becoming less than the 55.5 km^3 annual allocation; in fact, during the early 2000s, arrivals at Aswan were beyond the capacity of the reservoir, and releases were made through the Toshka Escape (see below). It seems likely that actual withdrawals in Sudan have been at the lower end of this range, although that may now be changing. Since 2009, there have been additional evaporative losses from Merowe Dam, estimated at 2.1 km^3 annually (Blackmore and Whittington, 2008); and the current expansion of Roseires Dam will also result in increased evaporative losses (DIU, 2011).

Availability of water for agriculture in Egypt is determined predominantly by the volumes arriving at, and released from, the AHD, but it is surprisingly difficult to get a clear idea of the exact volumes. Since these numbers are critical for determining how much is available for downstream use and how much additional withdrawal can be made upstream without jeopardizing downstream commitments, it is worthwhile examining the problem in some detail.

The first problem is which measurement best represents water available to Egypt. Long-term records are available from stations at Dongola in Sudan and at Aswan. The Dongola station is a composite record, which has been moved upstream twice since the 1920s to accommodate changes in lake level with construction of dams at Aswan and is now at Dongola, 430 km south of the border. At Aswan itself, flows are computed from reservoir levels and sluice discharges, not measured directly. Flows are reported as 'water arriving at Aswan' (derived by adding change in reservoir contents to downstream discharge), 'natural river at Aswan' (corrected for water abstracted upstream and for some evaporative losses) and 'flows below Aswan' (outflows from Aswan reservoir). Sutcliffe and Parks (1999) conclude that 'water arriving at Aswan' is the more reliable of the upstream records, since the basis for calculating 'natural river at Aswan' has changed over time. However, comparison of records for 'water arriving at Aswan' with flows at Dongola shows marked inconsistencies, with apparent high losses in most years. Long-term average for 'water arriving at Aswan' is 85.4 km^3 (1869–1992), while flows in the main Nile at Dongola averaged 88.1 km^3 over the same period. Suttcliffe and Parks (1999) attribute these differences to channel losses, measurement errors, the shift in the Dongola station and, since 1970, to evaporative losses from Aswan. To compound the uncertainty, records of Nile flows below Khartoum have not been released publicly beyond 1990, although flow measurements have been collected within government agencies; and (as discussed above) the volume of extractions within Sudan is not well constrained.

Under the Nile Agreement, the average annual flow in the Nile was agreed to be 84.5 km^3, based on the long-term average flows at Aswan and it is on this basis that 55.5 km^3 yr^{-1} were allocated to Egypt. However, reported annual flows are very variable, ranging from 150 to 40 km^3 (Blackmore and Whittington, 2008). A decline in flows is observed after the mid-1960s (despite higher flows in the White Nile in this period; see Table 5.1), attributed partly to increased abstraction and evaporative losses from reservoirs, and partly to the decline in rainfall in the Blue Nile and Atbara catchments. In the period 1970–1984, reported flows at Dongola averaged only 69 km^3. Though considerably below the notional long-term average on which the Agreement was predicated, this volume exceeds the average of 65.5 km^3 expected at Aswan if Sudan used its entire entitlement.

During the 1990s, flows to Aswan were much higher. Figures for 'water arriving at Aswan'

have not been published, but around 1998 Egypt began diverting water through the Toshka Flood Escape, a canal leading to a depression in the western desert about 250 km above Aswan. By 2002 an area of more than 1500 km^2 had been flooded with a calculated stored volume in 2002 of 23 km^3 to form the Toshka Lakes (El-Shabrawy and Dumont, 2009). Since annual PET in the region is about 2 m, over 3 km^3 must have been pumped from Lake Nasser each year in order to maintain the lakes. Imagery from May 2011 shows the lakes still very much in evidence (Earth Snapshot, 2011). In addition, releases below Aswan were considerably above the nominated 55.5 km^3 – between 1998 and 2001, they averaged around 65 km^3 (Blackmore and Whittington, 2008). AHD operated at close to maximum level through 1995–2005. What is not clear in this equation is the extent to which the surplus can be attributed to low withdrawals by Sudan (below their allocation of 18.5 km^3).

Even during the extreme drought of 1984–85, releases from Aswan were maintained at above 53 km^3 yr^{-1}, confirming the success of the 'century storage' concept. Thus, since the construction of the AHD, availability of water for Egypt has not only not fallen below the nominated 55.5 km^3 yr^{-1}, but has, in many years, considerably exceeded it. The extent of the 'surplus' is not clear, but is probably about 5–10 km^3.

Demand within Egypt is similarly poorly quantified. The volume of irrigation withdrawals and return flows in the Nile Valley and Delta are complex and difficult to account, particularly given widespread use of recycled water and shallow pumped groundwater mixed with river water. FAO (2005) estimated total withdrawals in Egypt as 68.3 km^3 yr^{-1}, with 59 km^3 diverted to agriculture. A later study by FAO (2010) estimated annual water use for irrigation in the Nile Basin in Egypt at 65.6 km^3. Blackmore and Whittington (2008) report Egypt's current total water use as 55.5 km^3 based on government estimates. A much lower agricultural demand of around 43.2 km^3 is estimated in Chapter 15 of this volume.

In addition, at least 6–8 km^3 of flow from the delta to the Mediterranean are needed to mitigate saline intrusion and preserve the salt balance of the Nile Delta (El-Arabawy, 2002). The actual extent of discharge from the Nile to the Mediterranean is highly debated. Because of the complexity of the delta, direct measurement of outflows is not possible, and calculation on the basis of upstream flows is hampered by incomplete data. Various modelling studies (Bonsor *et al.*, 2010; Karimi *et al.*, 2012; Chapter 15, this volume) estimate outflows of about 28 km^3. However, Hamza (2009) estimated that total annual releases are as low as 2–4 km^3; similarly, El-Shabraway (2009) reports that annual outflows decreased from about 32 km^3 before construction of AHD to 4.5 km^3 after.

The uncertainty surrounding estimates of total water use within Egypt thus remains very high. In planning terms, the difference between estimates is highly significant. Given that Egypt's nominal total allocation (for all uses including irrigation) under the Nile Agreement is 55.5 km^3, the lower estimate indicates that Egypt has room for substantial proposed increases from current levels of irrigation, within the supply limit guaranteed by the agreement. In contrast, the higher estimates suggest that Egypt is already overusing its allocation by 10 km^3 (20%) and is dependent on 'excess' flows to Aswan which may not be guaranteed in the longer term; and is thus potentially vulnerable to any increase in upstream withdrawals.

Future development

All Nile countries have ambitious proposals to expand irrigated agriculture to meet growing food demands and boost economic development. Based on national planning documents (Chapter 15), the overall increase will be more than 10 million ha in the Nile Basin, doubling from current levels of around 5 million ha. The question is whether such plans are feasible,

where the limits to development lie in terms of the balance between demand and availability of water for irrigation in the basin, and at what stage withdrawals by upstream countries will impact upon Egypt.

Modelling studies (Blackmore and Whittington, 2008; McCartney *et al.*, 2010; Chapters 14–15) have examined the potential impact on flows of large-scale developments in the basin, for a range of scenarios with different levels of irrigation development. In the upper basin, much of the proposed irrigation development is part of multi-purpose schemes with an emphasis on hydropower generation, particularly in Ethiopia where dams with a total storage of over 167 km^3 have been proposed (McCartney *et al.*, 2010). These large-scale developments, which include water transfer schemes as well as storage, would profoundly change patterns of water availability.

Results from all studies indicate that absolute shortage of water is not limiting for proposed development in the upper basin countries. Proposed expansion of irrigation in the ELR will have no significant impact on downstream flows – increasing irrigated area in the ELR by 0.7 million ha would decrease average outflows from the Sudd by less than 1.5 km^3. In contrast, proposed development in Ethiopia and Sudan will cause large net reductions in flow in the Main Nile above Aswan, estimated at between 15 and 27 km^3 for expansion of total irrigation above Aswan by 2.2 million and 4.1 million ha, respectively (Chapter 15). If adequate storage is constructed, extractions of this magnitude are physically feasible (setting aside downstream impacts for the moment). Blackmore and Whittington (2008) also concluded that deficits in Ethiopia and Sudan would be negligible or small under even the most extreme of the scenarios they modelled. In reality, of course, the need to ensure downstream flows cannot be neglected, but these results reinforce that, to a large extent, limits to water availability for irrigation in the upstream Nile Basin countries are likely to be political rather than physical.

Uncertainties in estimates of total demand and supply within the basin are so high that it is difficult to draw firm conclusions about the stage at which irrigation demand in Egypt will outstrip supply – or whether this has already happened. The model results presented in Chapter 15 illustrate the trends resulting from increased withdrawals, but until current flows to Aswan and usage within Egypt are better constrained, it is not clear where along these trends Egypt sits. However, the results confirm three important points. First, withdrawals in the White Nile system upstream of the Sudd only have limited impact on water availability for Egypt. Second, irrigation development in Sudan will have a larger impact on water availability for Egypt than comparable increases in irrigation areas in Ethiopia. For example, under the 'long-term' scenario, expanding irrigation by 0.47 million ha in the Blue Nile Basin in Ethiopia resulted in an annual decrease compared with current conditions of only 2 km^3 at the Sudan Border; while an increase of 0.89 million ha in Sudan resulted in a decrease in projected flows in the Blue Nile at Khartoum of almost 10 km^3. This is due in large part to favourable options for storage in Ethiopia that can reduce evaporative losses, which are very high in Sudan. Third, model results illustrate the potential gains from managing evaporative losses from Aswan. Under the current and medium-term scenarios, where Aswan operates at relatively high levels, projected losses at Aswan are 11 km^3 while under the long-term scenario, Aswan operates at close to minimum levels, with evaporative losses reduced to 2 km^3, providing a significant offset to the increased withdrawals upstream of the dam.

Transboundary and environmental flow requirements

In estimating availability of water for irrigation, consideration must be given to requirements for environmental flows to maintain the ecosystems of the river, and to the obligations to

maintain flow levels under international treaties and agreements. Since the late 1800s, international treaties and agreements have been in place to prevent upstream developments or withdrawals that would reduce Nile flows. These agreements were negotiated by Britain as a colonial power, and their validity is now contested. In the early 1950s, on construction of the Ripon Falls Dam on the outflow of the White Nile from Lake Victoria, an agreement was signed between Egypt and Uganda to ensure that releases from the lake retained their natural pattern (the 'Agreed Curve'). In 1959, prior to the construction of Aswan Dam, the Nile Agreement was signed which allocated the water of the Nile between Egypt (55.5 km^3) and Sudan (18.5 km^3). Ethiopia and the upstream countries were not signatories to the treaty, and do not recognize its validity. In 1999, the NBI was inaugurated to develop the river in a cooperative manner, without binding rules on flow management. In 2010–2011, six of the nine Nile Basin countries (Burundi, Ethiopia, Kenya, Rwanda, Tanzania, Uganda) signed the Entebbe Agreement on Nile River, which calls for Nile Basin countries to modify the existing agreement and reallocate water shares. The Entebbe Agreement has been strongly opposed by Egypt and Sudan (Swain, 2011; Ibrahim, 2011).

No comprehensive assessment of environmental flow requirements for the Nile has been conducted, but the various transboundary agreements have, to some extent, acted to secure environmental flows. The Agreed Curve governing releases from Lake Victoria based on lake levels formed the basis for releases from the 1950s to 2001 (except for a period in the 1960s when lake levels rose above the limit of gauging). When the Kiira Power Station (an extension of the Owen Falls hydro scheme) began operation in 2002, water levels fell. To meet demand for hydropower, Uganda has released 55 per cent more than the Agreed Curve (Kull, 2006); combined with several years of low rainfall this reduced lake levels to an 80-year low (Awange *et al.*, 2008). Lake levels have recovered since 2007, but manipulation of the lake level for hydropower generation remains controversial. Adverse impacts are felt primarily around the lake itself, since the additional flows were released from Kiiraare, moderated by the Sudd.

Studies in the Sudd on the feasibility of the proposed Jonglei Canal examined potential impacts of diversions on the extent of flooding in the wetlands. Sutcliffe and Parks (1999) estimated that diversion of 20–25m^3 day^{-1} (about 20–25% of flows on an annualized basis) would reduce the area of permanent swamp by more than a third, and of seasonal swamp by around 25 per cent; the decrease in seasonally flooded area could be mitigated to some extent by varying withdrawals according to season. Related proposals to regulate the inflows to the Sudd through storage in Lake Albert or Lake Victoria would also reduce the seasonal flooding. Seasonally flooded grasslands are a vital component of the grazing cycle for the herds of the Nuer and Dinka, while the permanent swamps are an important dry-season refuge for wildlife, including large populations of elephants. South Sudan has recently declared the Sudd a national reserve, with plans to develop eco-tourism in the area.

McCartney *et al.* (2009) conducted a study to determine environmental flow requirements (both high and low flows) for the Blue Nile downstream of CharaChara weir on Lake Tana. They estimate that an average annual allocation of 22 per cent of the mean annual flow (862Mm^3) is needed to maintain the basic ecological functioning in this reach, with an absolute minimum mean monthly allocation not less than approximately 10 million m^3.

Construction of the AHD and large withdrawals for irrigation have modified the ecosystem of the Delta through reductions in both flow and sediment, and exacerbated the decline in water quality from agricultural, urban and industrial uses (Hamza, 2009). A minimum level of flow (around 6–8 km^3) is critical in a number of different contexts: to prevent intrusion of salt water into the agricultural systems of the Delta; to flush other salts and pollutants from the system; and to maintain the coastal ecosystems of the Delta and the fringing lakes (El-Arabawy,

2002). Continued degradation of the water quality and ecosystems of the Delta suggests that these requirements are not being met.

Finding more water

It has long been recognized that there is potential to increase total water availability in the Nile Basin by reducing 'losses' of water through evaporation and infiltration to groundwater from both natural and man-made water bodies and irrigation schemes. There are three mechanisms proposed to achieve this: diversion of flows from natural wetlands; management of man-made storage to minimize evaporation; and improving the efficiency of irrigation. In addition, there is potential to expand the role of groundwater resources in supplementing surface supplies.

Since the 1930s, there have been proposals to divert flows from the floodplains of southern Sudan through canals to reduce evaporative losses. The best known and most ambitious is the Jonglei Canal project, diverting water for 360 km around the Sudd to gain around 4 $km^3 yr^{-1}$ in flows (Sutcliffe and Parks, 1999). Construction began in 1978, but was interrupted by civil unrest and suspended from 1982, and has never been completed. A similar proposal for the Bahr el Ghazal would divert flow to the White Nile using collector canals; Hurst *et al.* (1978) suggested that as much as 8 $km^3 yr^{-1}$ could be diverted. Such schemes should be approached with caution, however. The dynamics of the wetland systems are not well understood, and potential impacts on both ecology and livelihoods are very high. Sutcliffe and Parks (1999) concluded that the Jonglei diversion would reduce the area of both permanent swamps and seasonally flooded regions in the Sudd, with potential impacts on livelihoods of the local populations.

There are similar proposals to reduce evaporative losses from the Sobat-Baro either by regulating peak flows with upstream storage to reduce floodplain spillage, or by diverting flows from the Machar Marshes (Hurst, 1950). However, an analysis by WaterWatch (reported in Blackmore and Whittington, 2008) indicates that more than 90 per cent of water in the marshes is derived from local rainfall, with only 1 km^3 from overbank spills. They conclude that gains from diversions would be small, but that potential impacts on local livelihoods and ecology could be severe.

Total evaporative losses from constructed storage in the basin are now estimated at around 15 – 20 $km^3 yr^{-1}$, more than 20 per cent of flows arriving at Aswan (Blackmore and Whittington, 2008; Kirby *et al.*, 2010). Annual evaporative losses from Lake Nasser/Lake Nubia (impounded by AHD) vary with water level, from around 5 km^3 at 160 m to more than 10 km^3 at 180 m (El-Shabrawy, 2009). Blackmore and Whittington (2008) estimate somewhat higher losses of 14.3 $km^3 yr^{-1}$ at maximum levels, compared with 10 km^3 under 'normal' operations. Other areas where significant evaporative losses occur include the recently completed Merowe hydropower dam on the Main Nile in Sudan (more than 1.3 $km^3 yr^{-1}$); Toskha Lakes (2–3 $km^3 yr^{-1}$); and Jebel Aulia Dam, upstream of Khartoum, with losses estimated at 2.1 $km^3 yr^{-1}$ (WaterWatch, 2011) to 3.45 $km^3 yr^{-1}$ (Blackmore and Whittington, 2008). Jebel Aulia was originally constructed in 1937 to prolong the natural recession for irrigation downstream. Since construction of the AHD, its primary function has become redundant, and it has been operated mainly to optimize costs for pumped irrigation from the river downstream of Khartoum. Removal of the dam would provide significant evaporative gains for very little cost compared, for example, to the cost of the Jonglei scheme.

As demonstrated in Chapter 14, by shifting storage from broad shallow reservoirs in arid downstream areas (Aswan, Merowe, Jebel Aulia) to deep reservoirs in upstream areas with lower rates of evaporation, overall losses from reservoir evaporation can be reduced very significantly.

Evaporative losses from reservoirs outweigh putative gains from proposed canal systems at Jonglei and Bahr el Ghazal designed to reduce ET from natural systems. Evaporation from reservoirs is entirely non-beneficial, while ET from natural wetlands provides important benefits in terms of both pastoral production and biodiversity. Managing non-beneficial evaporative losses through a coordinated approach to construction and operation of reservoirs is a much more urgent priority as a water-saving measure than draining wetlands.

Irrigation demand in the basin could be substantially reduced by improving the efficiency of irrigation systems (see Chapter 15). The estimates suggest that if efficiency of water use could be increased from 50 to 80 per cent, total demand in the long-term (high development) scenario would be reduced by 40 km^3. Bastiaanssen and Perry (2009) provide a comprehensive review of the productivity of large-scale irrigation schemes within the Nile Basin, including criteria related to water use efficiency (crop water consumption and beneficial fraction). In Sudan, beneficial fraction emerged as one of the lowest scoring criteria in almost half of the irrigation schemes studied, and crop water consumption scored very poorly in Gezira, the largest irrigation area. In Egypt, beneficial fraction scored well, but crop water consumption was very high in many of the schemes studied. These results confirm that there are significant gains to be made in terms of efficiency of water use in existing schemes; and that measures to ensure efficiency of water use in new schemes are an important priority.

Role of groundwater

Shallow groundwater systems, seasonally recharged from local run-off, exist over large areas of the southern half of the basin where rain-fed cropping dominates. These aquifers generally have low to moderate flow rates, and are not suitable for large-scale irrigation, but could provide an accessible source of supplementary irrigation to reduce risk in rain-fed cropping. Calow and MacDonald (2009) concluded that groundwater has the potential to provide limited irrigation across wide areas of sub-Saharan Africa, and could increase food production, raise farm incomes and reduce vulnerability. Surface seepage from shallow groundwater systems is already utilized in wetland and valley bottom cultivation in ELR and the Ethiopian Highlands. In many cases, shallow groundwater and surface waters are connected, and function as a single system. This is true both in the Ethiopian Highlands, where groundwater supply baseflow for rivers in the dry season and in the alluvial aquifers of the Nile Valley, which are directly linked to the river. In these cases, groundwater must be accounted as part of the surface water system, though there may still be advantages in drawing water from the subsurface in terms of evaporative losses and local access. In southern and eastern Sudan, local to regional aquifer systems recharged from adjacent highlands and swamps are not directly linked to the rivers, and potentially constitute a very significant resource that Sudan could exploit with no impact on downstream flows.

In rangeland pastoral systems in Ethiopia, Sudan and Uganda, access to drinking water for stock can be limiting even when fodder is available. If surface water sources dry up in the dry season, alternatives are to travel long distances to permanent sources, to harvest and store rainwater, or to provide watering points from groundwater. Shallow wells are the mainstay for provision of human and animal drinking water in the arid zone. Provision of local watering points can significantly improve livestock productivity, both by reducing energy requirements for additional travel to water and by reducing grazing pressure around surface water sources (Peden *et al.*, 2009).

Currently, groundwater is used for large-scale irrigation only in Egypt, where it accounts for 11 per cent of irrigated agricultural production (FAO, 2005), though a substantial proportion of this is from shallow aquifer systems linked directly to the Nile. The Nubian Sandstone Aquifer System (NSAS) supplies water for large-scale irrigation in Egypt and Libya, and there

is potential for similar developments in northern Sudan and areas of Egypt within the Nile Basin. The aquifer is an enormous resource of 375,000 km^3, but recharge is very limited, and extraction is essentially mining fossil waters. Given the size of the resource, properly managed extractions could support irrigation for hundreds, or even thousands of years; but experience in Chad, Egypt and Libya has demonstrated that over-extraction can lead to rapid drawdown locally. In addition, irrigation-induced salinization must be carefully managed; and both establishment costs and energy costs for pumping are high (IAEA, 2011).

Evaporative losses from man-made reservoirs account for a large and increasing fraction of Nile flows. Internationally, sub-surface water storage is being explored as one option for managing evaporative losses using managed aquifer recharge (MAR), storage and recovery techniques – for example, in Menindee Lake in Australia (Geoscience Australia, 2008). The Egyptian government has investigated options for injecting excess water from Lake Nasser into the Nubian Sandstone Aquifer for subsequent recovery by pumping to provide water for new irrigation for land development. Preliminary studies indicate feasibility of the approach, but caution that irrigation combined with local groundwater mounds from injection could lead to waterlogging and salinization (Kim and Sultan, 2002). MAR requires a detailed knowledge of aquifer structures and properties, and may not be feasible in the short term; but in the longer term, the potential evaporative savings mean that it deserves serious technical appraisal.

Groundwater use in the Nile Basin is, to a large extent, buffered from the impacts of climate change. NSAS draws on fossil water, and so will not be affected by changes in recharge. In low rainfall areas (<200 mm) recharge is minimal, and groundwater sustainability is determined by the balance between withdrawals and local drawdown, and is unlikely to be affected by climate change. Current levels of use for domestic and livestock supplies require very little recharge to be sustainable: Calow and MacDonald (2009) estimate 3 mm yr^{-1} across much of Africa. In the complex basement hydrogeology of the southern basin, low-yielding aquifers are to some extent self-regulating – excessive withdrawals result in local drawdown and decreased yield. Large regional aquifers are at more risk of depletion. Dependence on groundwater is likely to increase as populations grow, and increases in demand will be more significant than any changes in overall supply due to climate change. Groundwater resources in the Nile Basin are discussed in more detail in Chapter 10.

Conclusions

Although the debates about availability of agricultural water in the Nile Basin are usually framed primarily around irrigation, rain-fed agriculture dominates production in the basin outside of Egypt. The dominant land use in the basin is low productivity agro-pastoralism. More than 70 per cent of rain falling in the basin is depleted as ET from natural systems partially utilized for pastoral activities. Rain-fed cropping, which constitutes around 85 per cent of total cropped area, uses only about 10 per cent of total basin rainfall. In the subhumid to humid regions of the southern Nile Basin, there is significant potential to intensify rain-fed production and to increase the area of rain-fed cropping at the expense of grasslands and savannahs, transferring at least some of this component to more productive, higher-value uses. In the semi-arid zones of the central basin, there is capacity to reduce risks and improve productivity of rain-fed agriculture using supplementary irrigation from small-scale storages and groundwater, and improved soil water management and agronomic practices. Since most of the flow is generated from only a small number of highland sub-catchments in the ELR and Ethiopian Highlands, rainwater harvesting, intensification of cropping and conversion of natural vegetation to agriculture are unlikely to significantly reduce downstream water availability.

Current demand for irrigation water in the upstream Nile countries (excluding Egypt and Sudan) constitutes only a small fraction of available resources, and constraints on irrigation development are about infrastructure and access, rather than about water availability. In Sudan, estimates of current extractions vary, but may be as high as 20 km^3, exceeding Sudan's nominal allocation under the 1959 Agreement. However, at this stage there is no indication that Sudan's withdrawals have resulted in reduced flows to Egypt. In fact, evidence from several sources suggests that for most of the last 15 years, flows to Egypt have considerably exceeded the nominal allocation of 55.5 km^3 yr^{-1}. The extent to which the surplus can be attributed to withdrawals in Sudan below their nominal allocation is not clear.

Demand within Egypt is similarly poorly quantified, with estimates varying from 43 to 65 km^3 yr^{-1}. High releases from Aswan in at least some years, and low outflows to the Mediterranean (~4 km^3) suggest that usage within Egypt is at least in the middle range of estimates. In planning terms, the difference between estimates is highly significant. The lower estimate indicates that Egypt has scope to expand water use for irrigation, within its nominated allocation under the 1959 Agreement. The higher estimates suggest that Egypt is already overusing its nominal allocation by up to 10 km^3 (20%) and is dependent on 'excess' flows to Aswan, which may not be guaranteed in the longer term, and is thus potentially vulnerable to any increase in upstream withdrawals.

All the upstream Nile countries have ambitious plans to expand irrigation to meet growing food demands and boost economic development. Modelling studies indicate that absolute shortage of water is not limiting for proposed development in the upper basin countries. If adequate storage is constructed, proposed expansion of an additional 4 million ha of irrigation upstream of Aswan is technically feasible but would result in significant reduction of flows to Egypt, though this would be offset to some extent by reduction in evaporative losses from Aswan. Due to the moderating effect of the Sudd on peak flows, development of up to 0.7 million ha of irrigation in ELR would not significantly reduce outflows from the White Nile system. Increasing irrigation area in Sudan will have a much greater impact on flows at Aswan than comparable increases in Ethiopia, due to more favourable storage options in Ethiopia.

While it is clear that upstream development will cause a reduction in flows to Egypt, uncertainties in estimates of total irrigation demand and available flows within the basin are so high that it is not possible to determine from existing information the stage at which demand will outstrip supply in Egypt, or even whether this has already happened. Shortages already occur in some years, but high flows in others present opportunities to expand irrigation through increased upstream storage, better management of flow variability and improved efficiency of use. A more flexible approach to management of high flows, including over-year storage in upstream areas, could provide an overall increase in available water, but requires management of water resources at the basin scale. Total evaporative losses from constructed storage in the basin are now estimated at around 15–20 km^3 yr^{-1}, more than 20 per cent of flows arriving at Aswan. By supplementing Aswan with storage higher in the basin, options for managing and storing high flows could be extended, security of supply in the upper basin improved, and evaporative losses reduced to provide an overall increase in available water, but this can only be achieved through transboundary cooperation to manage water resources at the basin scale.

Evaporative losses from reservoirs outweigh putative gains from proposed canal systems at Jonglei and Bahr el Ghazal, designed to reduce ET from wetland systems. Evaporation from reservoirs is entirely non-beneficial, while ET from natural wetlands provides important benefits in terms of both pastoral production and biodiversity. Managing non-beneficial evaporative losses through a coordinated approach to construction and operation of reservoirs is a much more urgent priority as a water-saving measure than draining wetlands.

Groundwater has a potential role in increasing water availability in the Nile Basin in four different contexts: small-scale supplementary irrigation in rain-fed zones; improving productivity of rangeland pastoral systems; large-scale irrigation in arid areas; and a potential role in reducing evaporative losses in storage through the use of managed aquifer recharge.

Climate change projections for the basin are equivocal, with no compelling evidence for large changes in rainfall. Projected changes mostly fall within the envelope of existing rainfall variability, but increases in temperature increases may reduce the viability of rain-fed agriculture in marginal areas and increase water demands for irrigation.

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