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What Is the Irrigation Potential for Africa?

A Combined Biophysical and Socioeconomic Approach

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Contents

List of Tables

List of Figures

ABSTRACT

Although irrigation in Africa has the potential to boost agricultural productivities by at least 50 percent, food production on the continent is almost entirely rainfed. The area equipped for irrigation, currently slightly more than 13 million hectares, makes up just 6 percent of the total cultivated area. Eighty-five percent of Africa's poor live in rural areas and mostly depend on agriculture for their livelihoods. As a result, agricultural development is key to ending poverty on the continent. Many development organizations have recently proposed to significantly increase investments in irrigation in the region. However, the potential for irrigation investments in Africa is highly dependent upon geographic, hydrologic, agronomic, and economic factors that need to be taken into account when assessing the long-term viability and sustainability of planned projects. This paper analyzes large, dam-based and small-scale irrigation investment needs in Africa based on agronomic, hydrologic, and economic factors. This type of analysis can guide country- and local-level assessment of irrigation potential, which will be important to agricultural and economic development in Africa.

Keywords: irrigation potential, internal rate of return, large-scale irrigation, small-scale irrigation, investment, Africa

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ABBREVIATIONS AND ACRONYMS

NEPAD	New Partnership for Africa's Development
IRRs	internal rates of return
SPAM	Spatial Production Allocation Model
IGBP	International Geosphere-Biosphere Program
MW	megawatts
SRTM	Shuttle Radar Topographic Mission
DEM	digital elevation data

1. INTRODUCTION

Irrigation does not currently play a significant role in African agriculture. Despite highly variable and—in many cases—insufficient rainfall and a high incidence of droughts, food production in Africa is almost entirely rainfed. Irrigated area as a share of total cultivated area is estimated at only 6 percent for Africa, compared with 37 percent for Asia and 14 percent for Latin America (FAOSTAT, 2009). Moreover, more than two-thirds of existing irrigated area is concentrated in five countries—Egypt, Madagascar, Morocco, South Africa, and Sudan—which each have more than 1 million hectares of irrigated area. For the remaining countries, the irrigated area varies from a few thousand hectares to almost half a million hectares each for Algeria, Libya, and Tunisia (FAOSTAT, 2009). The African continent has ample water resources overall; however, they are spread unevenly over a wide range of agroecologic zones. Efforts to manage water and to make it available where it is most needed are hampered by the undeveloped state of institutions for irrigation (and water-resource management more generally) and by the prevalence of subsistence farming. Ample groundwater resources in much of the continent remain largely untapped, except in southern Africa and parts of northern Africa, where overexploitation of the resource is common. Compared with the global average, Africans withdraw only a quarter as much water for human uses as does the world as a whole and the irrigated share of their cropland is less than one-fourth of the world average (Svendsen, Ewing and Msangi 2009).

Eighty-five percent of Africa's poor live in rural areas and depend largely on agriculture for their livelihoods. Agricultural growth is clearly the key to rural poverty reduction and can make an important contribution to achieving the Millennium Development Goal of halving poverty by 2015 (see also Rosegrant et al. 2005). Given that irrigated crop yields are double or more of comparable rainfed yields on the continent, irrigation development is considered by many as an important cornerstone for agricultural development in Africa. The 2005 Commission for Africa report (2005), for example, called for a doubling of the area of irrigated arable land by 2015. Faures and Santini (2008) report that 58 percent of the rural population in Sub-Saharan Africa could benefit from some type of investment in water. Finally, irrigation development is a key investment priority for NEPAD (New Partnership for Africa's Development). To implement such area expansion, we need to improve our understanding of the locations and technologies with greatest potential for irrigation. In particular, we need information about geographic, agronomic, and economic factors that need to be taken into account when assessing the long-term viability and sustainability of planned projects. This paper identifies opportunities for dam-based, large-scale irrigation investments based on a series of operational, proposed, and to-be-rehabilitated hydropower and other multipurpose projects that are considered profitable based on their planned or existing uses already. In addition, it examines the potential for small-scale, complementary irrigation expansion based on bio-geophysical, market access, and profitability characteristics.

The following sections first present background on the current state of irrigation in Africa, and then describe the methodology and data used for the analysis. Sections 3 and 4 present results for both large-scale and small-scale irrigation for all African countries, as well as sensitivity analyses for key parameters. The paper ends with policy recommendations.

2. THE CURRENT STATE OF IRRIGATION IN AFRICA

Table 1 presents basic descriptive features of agriculture, population, and water resources for Sub-Saharan Africa, all of Africa, and the world. Africa cultivates a slightly lower share of its land area compared with the global average; cultivated area per person engaged in agriculture at 1.1 hectares is also slightly below the global average. As expected, both population density and share of rural population in total population are above the global average. The continent receives, on average, 124 millimeters less precipitation per year than the world average. Internal renewable water resources per capita are above world average in Sub-Saharan Africa but below average for all of Africa. However, total water withdrawals per capita are less than half the global average, and withdrawals in Sub-Saharan Africa are less than a third the global average. This is explained, in large part, by the much lower share of area equipped for irrigation—6 percent versus a global average of 18 percent.

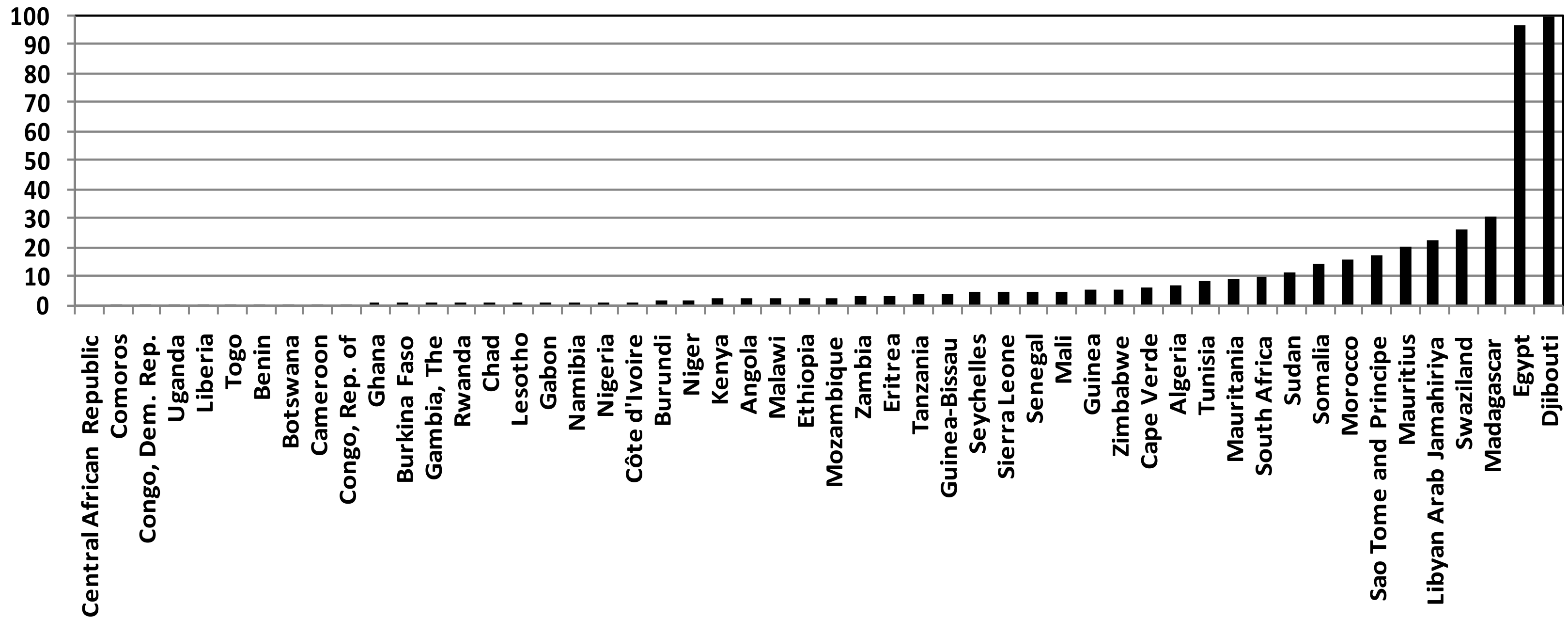
Table 1. Basic descriptive features of Africa and the world

Variable	Unit	World	Africa	Sub-Saharan Africa
Cultivated area (2003)	1,000 ha	1,541,488	225,284	197,189
- Share of total area	%	11	7	8
- Per inhabitant	ha	0.24	0.25	0.27
- Per person engaged in agriculture	ha	1.16	1.07	1.02
Total population (2005)	1,000	6,464,452	887,965	732,836
Population density	inhab/km^2	47	78	81
Rural population as % of total	%	51	60	62
Precipitation	mm/year	1,169	1,045	1,136
Internally renewable water resources	km^3/year	43,744	5,570	5,463
- Per inhabitant	m^3/year	6,859	6,273	7,455
Total water withdrawals	km^3/year	3,818	214	120
Per inhabitant	m^3/year	599	241	163
Irrigation (total area equipped)	1,000 ha	277,285	13,416	7,117
- % of cultivated area	%	18	6	4

Source: Based on Svendsen, Ewing, and Msangi (2009).
Note: Sub-Saharan Africa includes South Africa. Some or all data are missing for British Indian Ocean Territories, Equatorial Guinea, Mayotte, Saint Helena, Seychelles, and Western Sahara. If more than half of the observations were empty, then values were not calculated.

The share of cultivated area equipped for irrigation in Africa varies considerably by country but is generally very low, with the exceptions of Djibouti and Egypt (Figure 1).

Figure 1. Share of cultivated area equipped for irrigation (percent)



Source: Based on Svendsen, Ewing, and Msangi (2009)..

Table 2 presents selected irrigation investment indicators for Africa by agroecologic zone. The values show the large variation across subregions in Africa and the stark contrast in water use between northern Africa and Sub-Saharan Africa. Whereas only 4 percent of area cultivated in Sub-Saharan Africa is equipped for irrigation, 28 percent of northern African agriculture is irrigated. Whereas northern Africa has almost exhausted its irrigation potential, potential for expansion is significant in Sub-Saharan Africa. Much of irrigation development in the north has been implemented through the unsustainable withdrawal of groundwater resources (in Libya, for example) or the use of water resources that were generated elsewhere (e.g., Egypt's use of Nile water for irrigation). Thus, whereas agricultural withdrawals as a share of total renewable water resources reach a high of 219 percent in northern Africa, that share is only 1 percent in Sub-Saharan Africa. Among the regions in Sub-Saharan Africa, only southern Africa, led by South Africa, withdraws 6 percent of total renewable water resources for agriculture. Surface-water storage capacity in Africa relative to the size of its rivers is above the global average. But storage is unevenly distributed, much of it is used solely for hydropower generation, and per capita development is low.

Table 2. Selected irrigation investment indicators for Africa (all in percent)

Region	Share of cultivated area equipped for irrigation	Share of irrigation potential realized	Agricultural water withdrawal as share of total renewable water resources	Dam capacity as share of total available surface water	Ground water pumped as share of total renewable groundwater	Average annual expansion of irrigated area 1973–2003	Value of irrigated output as share of the total value of agricultural output
Northern	28.1	88	218.6	203.8	306.7	2.4	86.2
Sudano-Sahelian	6.9	50	21.8	9.7	38.1	2.7	58.3
Eastern	2.6	11	4.9	5.5	3.1	2.4	5.0
Gulf of Guinea	1.5	7	1.2	47.1	0	2.2	6.3
Central	0.7	1	0.1	1.7	0	0.5	7.3
Southern	4.2	36	6.2	99	17.8	3.2	6.6
Indian Ocean Islands	30.4	71	4.2	0.1	8.7	3.5	0
SSA average	3.5	18	1.3	11.2	17.5	2.3	24.5
Africa average	5.8	29	3.3	14.6	72.9	2.3	37.7
World average	17.7	n/a	5.2	7.6	n/a	n/a	n/a

Source: Svendsen, Ewing, and Msangi (2009).
Note: Agroecologic zones include the following: Northern: Algeria, Egypt, Libya, Morocco, Tunisia; Sudano-Sahelian: Burkina Faso, Cape Verde, Chad, Djibouti, Eritrea, The Gambia, Mali, Mauritania, Niger, Senegal, Somalia, Sudan; Eastern: Burundi, Ethiopia, Kenya, Tanzania, Uganda, Rwanda; Gulf of Guinea: Benin, Côte d'Ivoire, Ghana, Guinea, Guinea-Bissau, Liberia, Nigeria, Sierra Leone, Togo; Central: Angola, Cameroon, Central African Republic, Congo (Rep. of), Dem. Rep. of Congo, Equatorial Guinea, Gabon, Sao Tome and Principe; Southern: Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa, Swaziland, Zambia, Zimbabwe; Indian Ocean Islands: Comoros, Madagascar, Mauritius, Seychelles.
n/a= not available; SSA = Sub-Saharan Africa.

The average rate of expansion of irrigated area over the past 30 years was 2.3 percent in both Sub-Saharan Africa and all of Africa. Expansion slowed to 1.1 percent per year during 2000–2003 but has since picked up as a result of renewed investments by multilateral and bilateral donors and foundations. Nearly three-fourths of African countries showed a zero rate of recent expansion. In Africa, irrigated agriculture accounts for nearly 38 percent of the value of all agricultural output. This is very high given that only 13 million hectares are irrigated.

Thus, the potential of irrigation development for Africa, and in particular for Sub-Saharan Africa, is large, given existing water resources, the high value of irrigated agriculture on the continent, and the large number of rural poor that could benefit from productivity enhancement as a result of irrigation investment.

3. METHODOLOGY AND DATA

3.1. Methodology

Our methodology to assess the potential for irrigation investment in Africa includes five steps. First, we assess the production geography, existing and potential performance of irrigated agriculture. This involves an assessment of the actual area and average farm-level yields of 20 key crops (and crop groups; see Table 3) under irrigated and rainfed conditions on a 5-minute (about 10-kilometer) GIS (geographic information system) grid, supplemented by estimates of the potentially irrigable area and potential irrigated yields of the same 20 crops on the same grid cells. In the second step, we calculate the potential runoff that could be used for small-scale irrigation. Runoff is a measure of sustainable water availability within an area. Small-scale irrigation requires excess rainfall beyond evapotranspiration and groundwater recharge that can be channeled to a storage location for later use by a crop. A semidistributed macro-scale hydrology model is used to calculate runoff potential at half-degree pixels. The runoff potential is the water available for small-scale irrigation (Zhu, Ringler, and Rosegrant 2009). Third, we identify the potentially irrigable area and associated water delivery costs. For dam-based irrigation, we assume that irrigation is gravity-fed until the crop field is reached. This limitation, in connection with local topography, helps us identify the potential command area of each irrigation scheme. After the large-scale potential has been identified, small-scale irrigation converts current rainfed production into irrigated production or could even bring new irrigable area into crop production. In the fourth step, annual net revenue due to irrigation expansion is maximized across potential areas and crops. The increase in annual net revenue with optimum geographic distribution of irrigation water within the potential command area for dam-based irrigation—or within the pixel for small-scale irrigation—is estimated. The most profitable crop mix—given crop prices, yield increases with irrigation, the cost of irrigation water, and a water availability constraint—is also estimated. In the final step, internal rates of return (IRRs) to irrigation are calculated based on various values for water cost (for dam-based irrigation), three alternative levels of irrigation investment costs, and the time trajectory for investment expenditures. For small-scale irrigation, profitable areas are identified by pixel. For large-scale irrigation, IRRs are calculated for each dam.

Table 3. World nominal crop prices (average of 2004–2006)

Crop	Price (US$/metric ton)
Wheat	167
Rice	276
Maize	111
Barley	169
Millet	271
Sorghum	112
Potato	300
Sweet potato	696
Cassava	130
Banana	259
Soybean	283
Bean	336

Table 3. Continued

Crop	Price (US$/metric ton)
Other pulses	263
Sugarcane	33
Sugar beet	38
Coffee	900
Cotton lint	1,420
Other fibers	450
Groundnut	504
High-value crops	800

Source: Most prices are obtained from the World Bank's commodity price data.
Notes: "Other pulses" include peas (187), chick peas (191), cow peas (195), pigeon peas (197), lentils (201), broad beans (dry) (181), bambaba beans (203), vetches (205), lupins (210), other pulses (211). "High-value crops" include fruits, vegetables, and oil crops such as coconuts (249), sunflower seed (267), sesame seed (289), rapeseed (270), linseed (333), oil palm (254), olives (260), safflower seeds (280), mustard seeds (292), poppy seeds (296), oil seed nes (339). "Other fibers" include flax raw or retted (771), kapok fiber (778), flax fiber and tow (773), hemp fiber and tow (777), jute (780), jute-like fibers (782), ramie (788), sisal (789), agave fibers nes (800), abaca manila hemp (809), fiber crops nes (821). Numbers in parentheses are FAOSTAT codes for the commodity.

Each of these steps is described in more detail in the following sections.

3.1.1. Production Geography and Performance

The Spatial Production Allocation Model (SPAM) is used to assess production geography and performance. It is an entropy-based method for making plausible estimates of the area and yield distributions on a 1 to10 km resolution global grid. The method combines a very large collection of subnational production data, satellite imagery of the distribution and intensity of cropland, maps of the share of area currently equipped for irrigation, population density, crop prices, and the biophysical suitability of crop production in each grid cell (You and Wood 2006, You et al. 2009). Crop suitability is estimated based on ambient rainfall, evapotranspiration, length of growing period, temperature regime, elevation, slope, and soil characteristics. Suitability is assessed for each crop for both irrigated and rainfed production. Irrigated suitability is conditioned by slope, soil texture, drainage, and other characteristics of the soil profile (Fischer et al. 2001).

For each grid cell, *i*, SPAM first provides estimates of suitable rainfed and irrigated areas, $PotA_{ijl}$, for each crop, *j* (where water source, l, = 1 [rainfed] or 2 [irrigated]), as well as the corresponding potential biophysically attainable yields, $PotY_{ijl}$. The SPAM approach then uses the various input layers to disaggregate reported subnational (administrative unit) statistical data on actual crop areas and yields to determine a plausible spatial distribution of baseline (e.g., year 2000) production area, A_{ijl}, and yield, Y_{ijl} (by pixel, *i*, crop, *j*, and water source, *l*, as before). In Africa, the baseline production is predominantly rainfed. IFPRI has been working on SPAM model for many years. The SPAM datasets and results are freely available in a dedicated website (www.mapSPAM.info). Model descriptions, model applications, relevant peer-reviewed publications, updates, feedbacks are also accessible through the above website.

3.1.2. Runoff Potential that can be Appropriated for Small-scale Irrigation

Runoff is the flow of water generated from rainfall and snowmelt that flows over land or percolates into aquifers. The amount of runoff and its spatial and temporal variation are influenced by climate, vegetation, soil, and topology. In arid and semiarid areas, runoff generally makes up a small fraction of precipitation. From a resources perspective, runoff offers a measure of sustainable water availability within an area.

Rainfed agriculture relies on rainfall during the growing season. Without sufficient, timely rainfall to satisfy crop-transpiration requirements, yields decrease. Profitable small-scale irrigation requires excess rainfall beyond evapotranspiration and groundwater recharge that can be channeled to a storage location for later use by crops. Without storage facilities, this water would flow into water bodies or evaporate. The interaction between crop water needs, rainfall during the cropping season, and excess rainfall throughout the year determines the potential for yield increases.

A semidistributed, macro-scale hydrology model is used to calculate runoff at 0.5-latitude/longitude-degree pixels. Long-term monthly 0.5-degree climate data from the Climate Research Unit at the University of East Anglia are used to run the model (Zhu, Ringler, and Rosegrant 2009).

Runoff calculations in the hydrology model involve estimation of potential evapotranspiration (ET_p), soil water balance, and runoff generation. The Penman-Monteith method to calculate ET_p is widely used in the hydrology and irrigation profession. Input data for ET_p calculations include—for each grid cell—latitude, elevation, daily maximum and minimum temperature, cloud cover, vapor pressure, and wind speed. Grid-based parameters are estimated from global land cover databases. For each grid cell, albedo and surface resistance parameter values are estimated based on IGBP (International Geosphere-Biosphere Program) land cover classes. Plant root depths are estimated for each grid cell based on vegetation type and are used together with other soil parameters to determine the soil's water-holding capacity. To represent subgrid variability, the model assumes that soil moisture storage capacity varies statistically across the grid cell. Calibration using genetic algorithms determines the parameters of the statistical distribution functions.

Wherever impervious areas or open water exists in a grid cell, direct runoff, which equals rainfall minus evaporation, is generated. Evaporation of these areas is assumed to occur at evaporation potential as long as there is effective precipitation. Effective precipitation, snowmelt, and accumulation are calculated using a simple temperature index method. For bare soil or areas covered by vegetation, a soil water balance algorithm determines actual evapotranspiration (ET_a) and runoff, which are affected by soil moisture content. In the current formulation, ET_a is a linear function of ET_p and the soil water saturation rate. Surface runoff is assumed to occur over the portion of a grid cell where the soil's maximum water-holding capacities are exceeded. Subsurface runoff is a nonlinear function of average soil water content. For each grid cell, total runoff is the sum of direct runoff, surface runoff, and subsurface runoff.

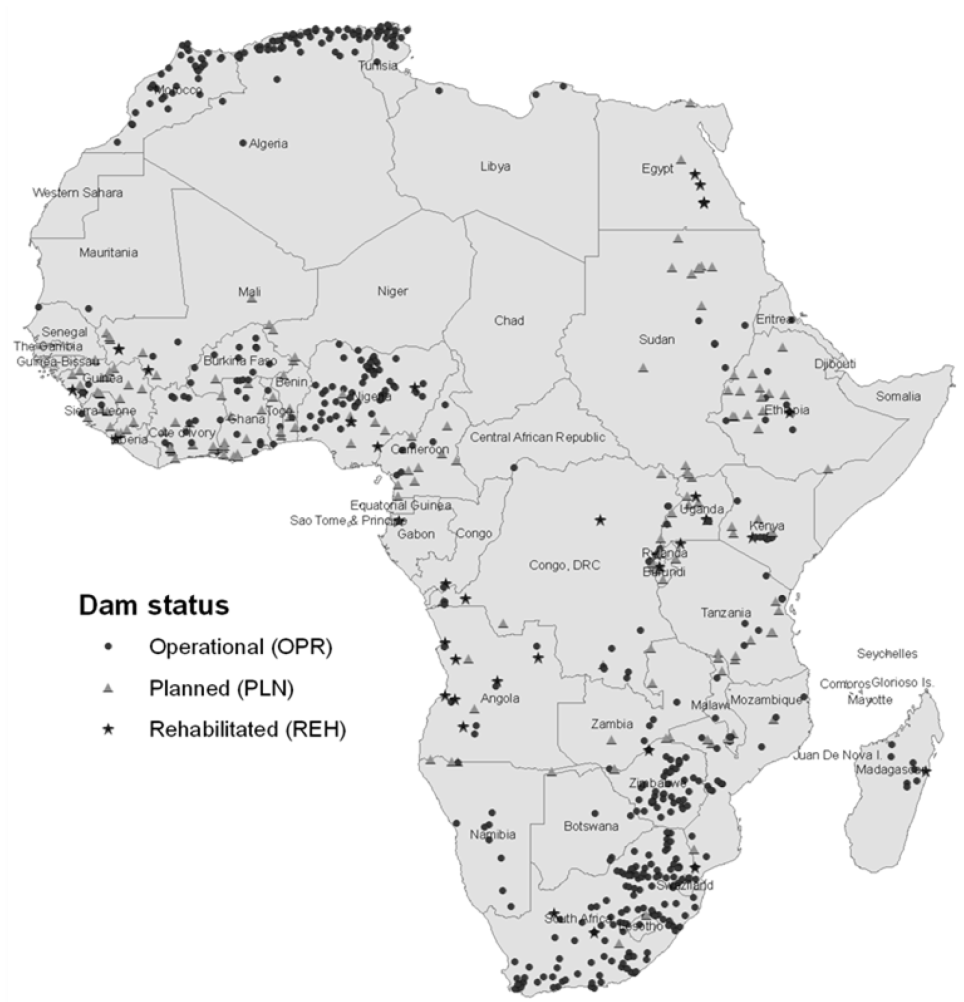
The model produces monthly runoff results for Africa, which were aggregated to obtain annual totals by pixel. These runoff values represent the maximum amount of water available for irrigating crops (You et al. 2009).

3.1.3. Potentially Irrigable Area and Water Delivery Costs

Dam-based irrigation is limited by local topography, because we assume irrigation to the field is gravity-fed. The identification of potentially irrigable locations and the cost of delivering water to them present complex hydrological and engineering tasks; we used several simplifications to address this issue. To obtain parameters for existing and planned dams, including location, we used datasets from the World Bank AICD (Africa Infrastructure Country Diagnostic) study (Eberhard et al. 2008, Rosnes and Vennemo 2008) as well as the FAO African dams database (FAO 2006); we also consulted Google Earth and did our own Internet search. Figure 2 presents graphically the dams used in our analysis, and Table 4 presents selected statistics on those dams.

Included in this analysis are 448 operational dams, 30 rehabilitated dams, and 142 proposed dams. Because most of the dams are designed for power generation, we include a summary of the generation capacity. The total capacity in the dams under consideration is 73,348 megawatts (MW). Three-quarters of the generation capacity, about 54,000 MW, is only in the planning stages, reflecting the considerable underinvestment of hydropower in Africa. Three-quarters of the planned hydropower capacity is in three regions, namely central and eastern Africa and the Gulf of Guinea. For example, of the Democratic Republic of Congo's total capacity, only 1,684 MW are currently operational, whereas 6,000 megawatts are in the planning. For Nigeria, the operational capacity is 1,938 MW, whereas 2,065 MW are slated for rehabilitation and about 7,000 MW are in the planning stage. On the other hand, the majority of the reservoir capacity is in either operational or rehabilitated dams.

Figure 2. Dam status and locations



Whereas Africa has more than 488 billion cubic meters of operational reservoir capacity, its planned reservoirs have only about 157 billion cubic meters of capacity. Almost 250 billion cubic meters of capacity could be rehabilitated. Rehabilitation could play a critical role in irrigation expansion in Africa. Because we assume that 30 percent of the dam storage capacity is available for irrigation, the total irrigation water availability is about 268 billion cubic meters, more than half of which stems from operational dams. Almost a third of this is in Ghana alone. Zambia accounts for about 20 percent and Mozambique for almost 15 percent.

Table 4. Summary information on dams

		Number of dams			Generation capacity (MW)			Reservoir capacity (million m^3)		
Region	Country	Operational	Rehabilitated	Planned	Operational	Rehabilitated	Planned	Operational	Rehabilitated	Planned
Central		25	9	11	2,318	1,106	14,295	17,749	235	13,313
	ANGOLA	6	6	2	4	804	6,760	1,728	221	4,574
	CAMEROON	6	0	7	630	0	1,275	15,640	0	8,637
	DEM. REP OF CONGO	12	2	2	1,684	245	6,260	161	6	102
	GABON	1	1	0	0	58	0	220	8	0
Eastern		23	7	38	2,019	817	11,236	10,830	2,232	51,638
	BURUNDI	0	1	5	0	18	103	0	2	17,065
	ETHIOPIA	5	1	13	410	43	7,369	1,570	1,900	32,990
	KENYA	9	1	5	673	40	560	4,069	20	195
	RWANDA	1	1	1	12	12	19	5	5	5
	TANZANIA	5	1	6	528	54	2,005	5,071	5	1,055
	UGANDA	3	2	8	396	650	1,180	115	300	328
Gulf of Guinea		84	6	49	3,843	2,697	12,102	228,821	71,005	18,392
	BENIN	1	0	5	0	0	214	24	0	4,140
	COTE D'IVOIRE	12	0	9	591	0	1,055	37,120	0	5,600
	GHANA	9	0	9	1,158	0	853	148,234	0	6,240
	GUINEA	3	2	11	75	28	2,126	327	20	1,495
	LIBERIA	0	1	3	0	64	336	0	30	165
	NIGERIA	55	3	5	1,938	2,605	7,010	41,152	70,955	450
	SIERRA LEONE	2	0	5	50	0	479	250	0	290
	TOGO	2	0	2	31	0	29	1,715	0	12
Indian Ocean Islands		7	1	0	58	24	0	489	12	0
	MADAGASCAR	7	1	0	58	24	0	489	12	0
Northern		89	3	2	0	2,254	45	20,421	162,035	15
	ALGERIA	42	0	0	0	0	0	4,265	0	0
	EGYPT	0	3	2	0	2,254	45	0	162,035	15
	LIBYAN ARAB JAMAHIRI	3	0	0	0	0	0	215	0	0
	MOROCCO	31	0	0	0	0	0	14,816	0	0
	TUNISIA	13	0	0	0	0	0	1,125	0	0

Table 4. Continued

Region	Country	Number of dams			Generation capacity (MW)			Reservoir capacity (million m^3)		
		Operational	Rehabilitated	Planned	Operational	Rehabilitated	Planned	Operational	Rehabilitated	Planned
Southern		201	2	19	3,666	600	9,802	198,035	180	57,646
	BOTSWANA	4	0	0	0	0	0	409	0	0
	LESOTHO	2	0	0	110	0	0	867	0	0
	MALAWI	4	0	3	280	0	600	112	0	150
	MOZAMBIQUE	14	0	6	2,182	0	4,737	68,905	0	46,746
	NAMIBIA	9	0	4	0	0	800	667	0	4,465
	SOUTH AFRICA	117	2	1	42	600	1,332	26,701	180	900
	SWAZILAND	4	0	0	0	0	0	559	0	0
	ZAMBIA	6	0	4	1,052	0	2,033	95,067	0	5,345
	ZIMBABWE	41	0	1	0	0	300	4,748	0	40
Sudano-Sahelian		19	2	23	340	46	6,080	11,494	13,440	15,620
	BURKINA FASO	10	0	2	30	0	66	1,812	0	25
	ERITREA	1	0	0	0	0	0	22	0	0
	MALI	2	1	6	0	46	458	180	2,170	235
	MAURITANIA	1	0	0	0	0	0	500	0	0
	NIGER	0	0	3	0	0	201	0	0	1,656
	SENEGAL	1	1	0	0	0	0	250	11,270	0
	SUDAN	4	0	12	310	0	5,355	8,730	0	13,704
Total Sub-Saharan Africa		359	27	140	12,244	5,290	53,515	467,418	87,104	156,609
Total Africa		448	30	142	12,244	7,544	53,560	487,839	249,139	156,624

Sources: Adapted from Eberhard et al. (2008), Rosnes and Vennemo (2008) ; the Food and Agriculture Organization African dams database (FAO 2006); and various Internet sources.
Note: Only dams that are part of the analysis are included; smaller dams and dams with potentially overlapping irrigated areas were excluded from the analysis. “Rehabilitated” refers to slated for rehabilitation.

The potential command area was defined initially as any grid cell downstream and below the impoundment point and in the same country as the impoundment. In addition, command areas are arbitrarily limited to a distance of 150 kilometers from the dam location. In a few cases where dam locations were near national borders, the command area was extended into the neighboring country. For each dam, we thus draw the potential command area using NASA Shuttle Radar Topographic Mission (SRTM) 90-meter digital elevation data. SRTM has provided digital elevation data (digital elevation models [DEMs]) for more than 80 percent of the globe, and the CGIAR Consortium for Spatial Information further processed the original DEMs to fill in these no-data voids in the remaining 20% of the globe (http://srtm.csi.cgiar.org/Index.asp). To be consistent with the SPAM resolution, the command areas are resampled into 5-minute resolution.

For small-scale irrigation, we assume that the entire pixel could potentially be irrigated. Thus, the command area is the area of the pixel. Unlike the dam-based irrigation investment calculations, where gravity limits the potential locations for irrigation, we have no simple physical constraints on where small-scale irrigation might take place. Instead, rainfed croplands are used as a proxy for areas exhibiting potential for small-scale irrigation, and appropriable runoff[1] from those croplands determines the extent to which water resources might be sustainably exploited for irrigation purposes. Since market accessibility is an important factor in determining small-scale irrigation, we set five hours' travel time to the nearest market as the cutoff value for market access. That is, we exclude those pixels in which travel time to the nearest market is more than five hours for this type of irrigation. In addition, we exclude those areas where irrigation already takes place, where dam-based irrigation could profitably occur, and where development should not take place, such as national parks and biosphere reserves.

Irrigation water delivery has a cost. Small-scale irrigation is assumed to be built within the pixel, and we assume no water delivery cost. For dam-based, large-scale irrigation, the estimate of the operating cost of water delivery makes two assumptions: a unit cost of water at the dam (CW_u) and a conveyance cost. This is because water may have to travel a long distance to the dam-based irrigation scheme. Water costs at the dam and conveyance costs arise because of seepage, evaporation, and annual operations and maintenance (O&M) expenditures. We base the conveyance cost on two distances: from the impoundment to the nearest point on the river (D_i) and from the nearest point on the river to the grid cell (di). Cost of water at any pixel is then calculated as $CW_i = CW_u \left(1 + b(d_i + D_i)^2\right)$, $b = 0.0005$. The squared term is included to capture diseconomies of distance. The rising cost with distance makes irrigating far-away pixels not viable. For small-scale irrigation, we assume no water delivery cost, and $CW_i = 0$.

3.1.4. Maximizing additions to annual net revenue

Once the potential command area of a given scheme has been delineated, we use the information derived from Sections 3.1.2 and 3.1.3 to set up an optimization model to maximize the potential addition to annual net revenue for the command area, *NetRevenue*, given a water availability constraint. In addition to the data required for Sections 3.1.1 and 3.1.2, this step requires information on crop prices, P_j; costs of production; crop water requirements, WP_j (kilogram [kg] output of crop *j* per cubic meter of water); and the amount of water (either from runoff or stored behind the dam) available for irrigation net of other, prior claims such as hydropower, industrial, and household water uses for consumptive water use in the basin, *AvailWater*. We assume that 30 percent of the reservoir's designed storage capacity is available for irrigation. For small-scale irrigation, local runoff sets the limit to the *AvailWater*. We assume 100 percent of local runoff is available for crops.[2]

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[1] Our hydrological analysis generated a 50-year time series of annual runoffs and growing-season water stresses. For this analysis, we used mean runoffs and stresses over this period.

[2] Runoff calculation is for the whole pixel while crop production mostly occupies a small portion of the pixel. Considering this, this assumption is not too optimistic.

As defined in Section 3.1.1 above, let A_{ijl} be the existing area at pixel i for crop j at water source l (l = 1 [rainfed], 2 [irrigated]) within the command area. Y_{ijl} is the corresponding yield and P_j the price for crop j. With provision of irrigation infrastructure and irrigation water, large-scale irrigated area can expand, and the existing crop mix can change. Irrigation expansion comes from either converting rainfed production to irrigated production or irrigating previously nonproductive (likely too dry but otherwise irrigable) lands. Farmers may change their allocation of crop areas or even plant new crops if irrigation is available.

Let A^*_{ijl} be the harvested area in pixel i for crop j at water source l (here l = 1 [rainfed], 2 [irrigated]) after the irrigation infrastructure is built. The corresponding yield is Y^*_{ijl} . The crop water productivity is WP_j (kg/m3) for crop j, and the cost of irrigation water is CW_i (US$/m^3; all dollars are U.S. dollars). ER_i is the effective rainfall at pixel i. IE is the irrigation efficiency for the irrigation system. We estimate the irrigation water needed per unit area in pixel i for crop j, IW_{ij} (m^3/ha, or 0.1 mm), as

$$IW_{ij} = \begin{cases} 0 & If \quad \left(Y^*_{ij2}/WP_j\right) - ER_i \le 0 \\ \dfrac{\left(Y^*_{ij2}/WP_j\right) - ER_i}{IE} & If \quad \left(Y^*_{ij2}/WP_j\right) - ER_i > 0 \end{cases} \tag{2.1}$$

The potential additional net revenue from dam-based, large-scale irrigation investment is from three sources: (a) increased productivity due to the conversion of rain-fed into irrigated production; (b) new land brought into agriculture; and (c) gains from a new crop mix. The additional net revenue produced by irrigation investment is estimated as

$$\begin{aligned} \text{NetRevenue} = & \sum_i \sum_j (A^*_{ij2} Y^*_{ij2} + A^*_{ij1} Y_{ij1}) P_j * \text{ProfitRatio}_j \\ & - \sum_i \sum_j (A_{ij2} Y_{ij2} + A_{ij1} Y_{ij1}) P_j * \text{ProfitRatio}_j \\ & - \sum_i \sum_j (A^*_{ij2} - A_{ij2}) * IW_{ij} * CW_i \end{aligned} \tag{2.2}$$

The first part of equation (2.2) is the annual revenue from both irrigated and rainfed production after irrigation capacity is increased, the second part is the annual revenue from current crop production, and the third part is the O&M cost of irrigation water delivery (for small scale, it is zero, because CW_i = 0). $ProfitRatio_j$ is the ratio of net profit to the gross revenue for crop j, reflecting labor and input costs. We use the same crop prices and profit ratios before and after the irrigation investment, although equation (2.2) could easily be modified to handle the different prices and profit ratios, if necessary. As we could see, NetRevenue represents the annual revenue increase after the irrigation investment, as compared with no such irrigation investment.

There are three unknowns in equation (2.2):

Y^*_{ij2}, yield from irrigated crops (j);

A^*_{ij1}, rainfed area after irrigation investment; and

A^*_{ij2}, irrigated area after irrigation investment.

We assume that irrigation expansion would first convert existing rainfed areas (A_{ij1}) into irrigated areas before bringing new land into agriculture. With this assumption, A^*_{ij1} would be either zero (if we convert all rainfed area into irrigated area for pixel *i* and crop *j*) or the remaining rainfed area (if only a part is converted).

$$A_{ij1}^{*} = \begin{cases} 0 & If \quad (A_{ij2}^{*} - A_{ij2}) \geq A_{ij1} \\ A_{ij1} - (A_{ij2}^{*} - A_{ij2}) & If \quad (A_{ij2}^{*} - A_{ij2}) < A_{ij1} \end{cases} \tag{2.3}$$

Our goal is to maximize net revenue, *NetRevenue*, subject to certain constraints. To simplify the optimization, we focus on optimizing the irrigated crop areas (A_{ij2}^{*}), given the actual irrigated yields (Y_{ij2}^{*}). It is difficult, if not impossible, for irrigated crops to reach the potential yield. Therefore, we assume a yield reduction factor to estimate the actual irrigated crop yield (Y_{ij2}^{*}):

$$Y_{ij2}^{*} = Yieldfactor_{j} * PotY_{ij2} . \tag{2.4}$$

Equations (2.3) and (2.4) would provide A_{ij1}^{*} and Y_{ij2}^{*}. Therefore, we would have only one set of unknowns: We then formulate our problem as follows:

$$MAX \left\{ Net\,\mathrm{Re}\,vnue(A_{ij2}^{*}) \right\} , \tag{2.5}$$

subject to

$$A_{ij2}^{*} \leq PotA_{ij2} \quad \forall i \forall j , \tag{2.6}$$

$$\sum_{j} A_{ij2}^{*} \leq Max(PotA_{ij2}) \quad \forall i , \tag{2.7}$$

$$A_{ij2}^{*} \geq A_{ij2} \quad \forall i \forall j \text{, and} \tag{2.8}$$

$$\sum_{i} \sum_{i} \left(A_{ij2}^{*} - A_{ij2} \right) * IW_{ij} \leq AvailWater . \tag{2.9}$$

where $PotA_{ij2}$ is the area suitable for irrigation production of crop *j* in grid cell *i*. *AvailWater* is stored water available for irrigation. For dam-based irrigation, we assume *AvailWater* is 30 percent of reservoir capacity. For small-scale irrigation, *AvailWater* is equal to the local runoff potential.

Constraint (2.6) sets the upper limit for the irrigated area in a cell: the suitable irrigable area for crop j after taking account of slope, soil, and other factors. Because the areas suitable for different crops in a cell can be greater than the area of the cell, constraint (2.7) limits the total area of irrigation across all crops to less than or equal to the potentially suitable irrigable area. Constraint (2.8) ensures that there is irrigation expansion (that is, the new irrigated area is not below the original one). Constraint (2.9) limits the expansion of irrigation to the available amount of irrigation water.

The preceding model applies to both small-scale and large-scale irrigation. For small-scale irrigation, we run the model for each grid cell (assuming a small reservoir in each cell), and so all the *i* subscripts disappear.

The preceding is a simplistic view of the feasibility and potential payoff from irrigation investment. We believe it represents a balance between oversimplification and analytical tractability. Additional constraints can be added to this specification to reflect more-specific goals (for example, meeting a specific crop mix or focusing on staples).

3.1.5. Returns on Investment Alternatives

The calculations have thus far ignored the investment costs needed to create the irrigation infrastructure; convert fallow, existing agriculture in rainfed and dry lands to irrigated croplands; and maintain the irrigation infrastructure. Data on such costs are limited. The costs depend on irrigation technology, irrigation scheme (large scale versus small scale), and local conditions. The investment return calculations differ between small- and large-scale irrigations.

For large-scale irrigation, the model provides us the net annual revenue (*NetRevenue*) and total irrigation area increase for each dam (*IrrigA*). We use a variety of assumptions about the irrigation investment cost per hectare and the discount rate (r) to calculate the internal rate of return.

The stream of per-hectare benefits and a discount factor ($\delta = \frac{1}{1+r}$, r – discount rate) is used to determine the net present value for each irrigation scheme. IRR is then defined as the breakeven discount rate where the net present value of investment is zero.

$$\sum_{t=1}^{T} \delta^{t-1}[Net\,\mathrm{Re}venue * B_t - (InvestCost * IrrigA * C1_t + OperCost * IrrigA * C2_t)] = 0 \tag{2.11}$$

Where *NetRevenue* is the annual net benefit for a certain dam, *IrrigA* is the irrigation area increase, both calculated from the above optimization model. We consider two costs: one is the fixed investment cost for irrigation infrastructure (*InvestCost*); the other, the O&M cost (*OperCost*). Three fixed costs and their associated O&M costs[3] per hectare (ha) are considered here: \$3,000/ha, \$30/ha; \$6,000/ha, \$60/ha; and \$8,000/ha, \$80/ha, respectively. B_t, $C1_t$, and $C2_t$ are the time profiles used for fixed investment and O&M (Table 5).

Table 5. Investments and benefits: Time path assumptions for dam-based irrigation

	Fixed investment ($C1_t$)	O&M cost ($C2_t$)	Net revenue (B_t)
Year 1	0.05	0	0
Year 2	0.05	0	0
Year 3	0.10	0	0
Year 4	0.15	0	0
Year 5	0.15	0	0.1
Year 6	0.2	0	0.3
Year 7	0.2	0.5	0.6
Year 8	0.1	0.5	1
Year 9	0	1	1
Year 10	0	1	1
Year 11	0	1	1
Year 12	0	1	1
Year 13	0	1	1

Note: Years 14–50, same as year 13.

Similarly, for small-scale irrigation, the pixel-level optimization model provides us with the net increase in revenue (*NetRevenue*) and the irrigated area increase for a certain pixel. We use the same equation (2.11) to calculate IRR for each pixel. However, the cost and investment cycles are more

[3] Because we already included O&M costs for water delivery in the calculations for large-scale irrigation, the O&M costs here refer only to on-farm maintenance.

complex for small-scale irrigation. The cost of investing in small-scale irrigation depends very much on the choice of technology. Current spatial technologies cannot provide information on specific local conditions that would enable the proper choice of technology. In general, however, a range of unit costs can be assumed based on data found in the literature. Table 6 presents a series of small-scale irrigation technologies and a reasonable range of unit costs per hectare.

Table 6. Typology and unit costs of small-scale irrigation

	Examples	Average cost per hectare
Traditional community based	Water harvesting; flood recession; swamp irrigation	US$600 to $1,000
Individual	Pumps and other small lift systems (e.g., treadle, motorized, with and without sprinklers)	US$1,500 to $3,000
Intercommunity	River diversions; small dams; deep tubewells	US$3,000 to $8,000

Source: IFAD (2000) internal analysis of irrigation projects, presented in Kay (2001).

As in large-scale irrigation, we consider two types of costs: fixed investment cost (*InvestCost*) and variable O&M costs (*OperCost*). Based on Table 6, we use three levels of fixed investment costs and associated O&M costs: $600/ha, $25/ha; $2,000/ha, $80/ha; and $5,000/ha, $200/ha. Small-scale irrigation requires reinvestment every few years to replace or repair old irrigation facilities. The reinvestment cycle for small-scale irrigation depends on the type of technology. Soil moisture management interventions tend to require annual reinvestment, and microdrips and treadle pumps might require renewal every two to five years, whereas small reservoirs can last for up to 10 to 20 years. A second factor important for identifying reinvestment cycles is the relative knowledge level and experience of users of small-scale irrigation technologies. With increased experience, reinvestment cycles and maintenance costs will likely decline. For this paper, we use a five-year reinvestment cycle time profile for costs over a 50-year time horizon. Table 7 shows the benefit and cost time path of this five-year cycle.

Table 7. Investments and benefits time path for five-year reinvestment cycle

	Fixed investment (*InvestCost*)	O&M cost (*OperCost*)	Net revenue (*NetRevenue*)
Year 1	1	0	0.5
Year 2	0	1	1
Year 3	0	1	1
Year 4	0	1	1
Year 5	0	1	1
Year 6	1	0	0.5

Note: From year 6, another five-year cycle starts again until year 50.

We then estimate the breakeven IRR for each pixel using the breakeven calculation as in Equation (2.11). Thus, we obtain the increased irrigated area and a corresponding IRR for each pixel. We could use a prespecified IRR ($\overline{r}$) to determine if the possibility of investment in small-scale technology is rejected. This pixel-level criterion evaluation can be summarized as:

$$\left.\begin{array}{lll} if & r \geq \overline{r} & y_{irrigate} = 1 \\ else & r < \overline{r} & y_{irrigate} = 0 \end{array}\right\} per \quad pixel \qquad (2.12)$$

After carrying out the preceding calculation over each pixel to determine which are economically feasible for small-scale irrigation at a particular cost and rate of return, we aggregate the results to the country level to determine the total small-scale irrigation investment, based on the following calculation:

$$TotalArea = \sum_{p=1}^{P} y_{irrigate}^{p} \cdot IrrigA \tag{2.13}$$

where *IrrigA* represents the potential irrigable area in each of the *P* pixels in a region (indexed by *p*). By determining various IRRs, we developed a relationship between IRRs and total profitable irrigated areas for each region (e.g., country).

3.2. Data Sources and Assumptions about Costs, Prices, Margins, and Efficiency

The main datasets used in this study are the three major spatial datasets: (a) current crop distribution (area, A_{ijl}, and yield Y_{ijl}); (b) crop-specific biophysical potential (A_{ijl}^{*} —area suitable for irrigated and rain-fed crop production by pixel, Y_{ijl}^{*} —potentially attainable yields by pixel); and (c) the potential runoff and effective rainfall from the hydrologic model (ER_i—effective rainfall, $Runoff_i$—local runoff). The first dataset is from IFPRI's spatial allocation model (You and Wood 2006; You, Wood, and Wood-Sichra 2007); the second dataset is from the FAO/International Institute for Applied Systems Analysis (IIASA) global agroecological zone (GAEZ) project (Fischer et al. 2001); the third dataset stems from a global hydrological model (Zhu, Ringler, and Rosegrant 2009). These three datasets have been described in the methodology section.

Crop prices are based on commodity-specific world prices for the period 2004–2006 (Table 3). The 2004–2006 average reflects the price increase since 2004 as a result of biofuel policies shifting large volumes of food crops into bioethanol and biodiesel; bad weather in key production areas, such as droughts in wheat-producing Australia and Ukraine; and higher oil prices contributing to increased costs of production inputs and transportation, among others. Although prices have increased by 40 to 80 percent from 2004 to 2008, and declined thereafter, it is unlikely that the very high levels achieved during 2007 and 2008 will be maintained over the longer term. Similarly, given the long-term underlying factors affecting food prices and continued high energy prices, price levels are also not expected to drop to pre-2000 levels during the next 10 to 20 years.

In addition, several coefficients were specified for the models. The determination of these coefficients is based on literature reviews, consultations with the World Bank AICD team, and expert opinion. They include the following:

Irrigation water delivery cost ($\$/m^3$)—$CW_u$: 0.0025, 0.01, 0.05

Overall irrigation efficiency for large-scale irrigation systems (*IE*): 0.4

Total water availability for large-scale irrigation: 30 percent of reservoir storage capacity

Discount factor to adjust potential yield to actually achievable yields in Africa ($Yieldfactor_j$): varies from 0.3 to 0.8 based on expert estimates

Ratio of net profit to gross revenue for crop *j* ($ProfitRatio_j$): 0.3

We could not factor reduced water availability in downstream reservoirs of hydropower cascades into this analysis.

4. RESULTS

Combined results of the dam-based and small-scale analyses are shown in Table 8. For the dam-based investment analysis, the baseline assumptions—low conveyance O&M/water delivery costs ($0.01/m3), on-farm irrigation investment costs of $3,000/hectare and on-farm O&M costs of $30/hectare,—result in an irrigated area expansion of 16.3 million hectares with an average IRR of 6.61 percent and investment expenditures of $32 billion; most of this area is in Sub-Saharan Africa. Of the 620 dams identified, irrigation development surrounding 352 (out of 448) existing dams, 20 (out of 30) dams slated for rehabilitation, and 103 (out of 142) planned dams would be profitable. Of the newly irrigated land, 8.4 million hectares would surround existing dams, 1.0 million hectares would be associated with dams slated for rehabilitation, and 6.9 million hectares would receive water from proposed reservoirs. The countries with the greatest potential for large-scale irrigation based on IRR are Egypt (IRR of 62 percent), but the additional area is very small (260 hectares), followed by Botswana, Eritrea, Morocco, Tunisia, Sudan, and Mali, all with an IRR above 10 percent. On the other hand, the largest potential for irrigation expansion is in Nigeria, at 3 million hectares, followed by Benin, Guinea, Mozambique, Sudan, Ethiopia, and Tanzania, all with 0.7 million hectares potential or more.

The average IRR of irrigation schemes linked to dams slated for rehabilitation, at 11.3 percent, is substantially higher than the corresponding IRR for both existing and planned dams, at 7.2 and 5.3 percent, respectively. Furthermore, the availability of water for irrigation (assumed to be 30 percent of dam capacity) is generally not a constraint for planned dams.

Under our set of baseline assumptions, the potential to develop small-scale irrigation in Africa is 7.3 million hectares (Table 8), with the potential for investment ranging from 0 hectares to 2.5 million hectares, depending on the individual African country. We assume medium investment costs ($2,000 per hectare), a five-year reinvestment cycle, and a travel-to-market time of five hours. The potential for expansion excludes protected areas (such as parks) and those already identified for dam-based irrigation. Whereas the large-scale analysis was sensitive to spatial proximity to the dam and the costs that are involved in conveying the impounded water, the potential for small-scale irrigation depends on the availability of surface-water runoff, on-farm investment costs, crop mix, and market accessibility.

Just over one-third of the small-scale potential lies in Nigeria, with 2.5 million hectares. This is followed by Uganda, Morocco, Mali, Tanzania, Cameroon, Chad, and Sudan. Investment costs are estimated at $38 billion, with an average IRR of 28 percent. Uganda, Kenya, Niger, Mali, Somalia, and Mauritania have IRRs in excess of 30 percent. On the other hand, IRRs are close to zero for Burundi, Sierra Leone, Gabon, and Swaziland, but irrigated area expansion potential is also very small in those countries.

Overall, IRRs for small-scale irrigation are much larger than those for large-scale, dam-based irrigation. The African average IRR for large-scale, dam-based irrigation is 7 percent compared with 28 percent for small-scale irrigation. Higher IRRs for small-scale irrigation are due to the generally much larger and higher-potential rainfed areas located away from large-scale projects that could be profitably converted to small-scale irrigation, even with the requirement of a maximum of five hours of travel time to an urban center.

Nigeria has the largest potential for both small- and large-scale irrigation investments, at 5.7 million hectares, accounting for almost a quarter of total area potential. Given the large size of its economy, the combined total investment in small- and large-scale irrigation represents only 17 percent of the country's national gross domestic product (GDP) if implemented in one year, or 0.3 percent if implemented over 50 years (compared with 2006 GDP) and 1.7 percent of GDP when spread over 10 years.

Table 8. Total investment needs for both small- and large-scale irrigation, positive IRR

	Large scale			Small scale			Total investment	Total irrigated area	Annualized share of GDP spread over 10 years/a	Annualized share of GDP spread over 50 years/a	Annualized increase in irrigated area spread over 10 years/b	Annualized increase in irrigated area spread over 50 years/b
	Investment cost	Increase in irrigated area	IRR	Investment cost	Increase in irrigated area	Average IRR						
	US$mil	1,000ha	%	US$mil	1,000ha	%	US$mil	1,000ha	%	%	%	%
Angola	442	226	4.02	4	1	9	446	227	0.10	0.02	28.4	5.7
Cameroon	986	505	5.32	1,538	298	29	2,524	803	1.38	0.28	312.9	62.6
CAR		-		68	13	5	68	13	0.45	0.09	967.8	193.6
Congo		-		10	2	5	10	2	0.01	0.00	9.9	2.0
Congo, DRC	861	441	3.03	715	138	12	1,576	579	1.85	0.37	79.7	15.9
Equatorial Guinea		-		-	0	0	n/a	n/a	na	na	na	na
Gabon	1	1	4.99	1.35	0.261	3	2	1	0.00	0.00	2.8	0.6
Central	**2,290**	**1,173**	**4.24**	**2,337**	**452**	**26**	4,627	1,625	**0.51**	**0.10**	**87.9**	**17.6**
Burundi	31	16	2.39	135	26	2	166	42	1.83	0.37	19.6	3.9
Ethiopia	1,467	751	7.05	808	156	12	2,275	907	1.71	0.34	31.3	6.3
Kenya	562	288	7.04	257	50	40	819	338	0.36	0.07	32.7	6.5
Rwanda		-	-		-		n/a	n/a	na	na	na	na
Tanzania	1,392	713	2.81	1,546	299	28	2,938	1,012	2.30	0.46	54.9	11.0
Uganda	1,035	531	2.36	3,203	620	32	4,238	1,151	4.50	0.90	1,257.8	251.6
Eastern	**4,488**	**2,299**	**4.81**	**5,948**	**1,151**	**29**	10,436	3,450	**1.69**	**0.34**	**56.0**	**11.2**
Benin	3,091	1,584	6.45	586	113	8	3,677	1,697	7.70	1.54	1,384.7	276.9
Ghana	473	242	5.75	377	73	14	850	315	0.66	0.13	101.9	20.4
Guinea	2,355	1,207	3.97	603	117	7	2,958	1,324	8.92	1.78	139.5	27.9
Guinea-Bissau		-		165	32	6	165	32	5.41	1.08	14.1	2.8
Ivory Coast	887	455	8.24	955	185	8	1,842	640	1.05	0.21	609.3	121.9
Liberia		-		13	3	4	13	3	0.21	0.04	12.1	2.4
Nigeria	6,185	3,169	6.14	12,942	2,505	22	19,127	5,674	1.66	0.33	193.6	38.7
Sierra Leone	14	7	4.61	48	9	2	62	16	0.43	0.09	5.5	1.1
Togo	381	195	3.73	568	110	18	949	305	4.30	0.86	417.7	83.5

Table 8. Continued

	Large scale			Small scale								
	Investment cost	Increase in irrigated area	IRR	Investment cost	Increase in irrigated area	Average IRR	Total investment	Total irrigated area	Annualized share of GDP spread over 10 years/a	Annualized share of GDP spread over 50 years/a	Annualized increase in irrigated area spread over 10 years/b	Annualized increase in irrigated area spread over 50 years/b
	US$mil	1,000ha	%	US$mil	1,000ha	%	US$mil	1,000ha	%	%	%	%
Gulf of Guinea	**13,386**	**6,859**	**6.02**	**16,257**	**3,146**	**21**	29,643	10,005	**1.87**	**0.37**	**198.9**	**39.8**
Comoros		-			-		n/a	n/a	na	na	na	na
Madagascar	254	130	1.17	381	74	11	635	204	1.16	0.23	1.9	0.4
Mauritius		-			-		n/a	n/a	na	na	na	na
Seychelles		-			-		n/a	n/a	na	na	na	na
Indian Ocean Islands	254	130	1.17	381	74	11	635	204	1.16	0.23	1.9	0.4
Algeria	913	468	7.83	630	122	18	1,543	590	0.13	0.03	10.4	2.1
Egypt	1	0.26	63.51		-		1	0.2600	0.00009	0.00002	0.0008	0.0002
Libya	96	49	8.83	294	57	23	390	106	0.08	0.02	2.3	0.5
Morocco	690	354	17.82	1,596	309	11	2,286	663	0.35	0.07	4.5	0.9
Tunisia	420	215	15.01	1,006	195	21	1,426	410	0.47	0.09	10.4	2.1
Northern	**2,120**	**1,086**	**12.82**	**3,527**	**683**	**32**	5,647	1,769	**0.15**	**0.03**	**2.8**	**0.6**
Botswana	49	25	19.96	3	1	17	52	26	0.05	0.01	177.6	35.5
Lesotho	16	8	1.16	3	1	15	19	9	0.13	0.03	32.5	6.5
Malawi	249	128	1.86	836	162	10	1,085	290	3.43	0.69	51.4	10.3
Mozambique	2,016	1,033	5.35	983	190	12	2,999	1,223	4.39	0.88	103.6	20.7
Namibia	415	213	5.62	0	0	0	415	213	0.63	0.13	281.3	56.3
South Africa	736	377	8.43	975	189	14	1,711	566	0.07	0.01	3.8	0.8
Swaziland	119	61	7.41	0.73	0.142	3	120	61	0.45	0.09	12.3	2.5
Zambia	1,287	660	4.41	107	21	11	1,394	681	1.30	0.26	43.7	8.7
Zimbabwe	1,132	580	8.17	40	8	8	1,172	588	3.43	0.69	33.9	6.8

Table 8. Continued

	Large scale			Small scale			Total investment	Total irrigated area	Annualized share of GDP spread over 10 years/a	Annualized share of GDP spread over 50 years/a	Annualized increase in irrigated area spread over 10 years/b	Annualized increase in irrigated area spread over 50 years/b
	Investment cost	Increase in irrigated area	IRR	Investment cost	Increase in irrigated area	Average IRR						
	US$mil	1,000ha	%	US$mil	1,000ha	%	US$mil	1,000ha	%	%	%	%
Southern	**6,020**	**3,085**	**6.18**	**2,947**	**570**	**12**	8,967	3,655	**0.30**	**0.06**	**17.7**	**3.5**
Burkina Faso	536	275	4.03	505	98	17	1,041	373	1.69	0.34	149.1	29.8
Cape Verde		-		-	-	-	n/a	n/a	na	na	na	na
Chad		-		1,430	277	27	1,430	277	2.19	0.44	91.4	18.3
Djibouti		-		0.04	0.01	27	0.04	0.01	na	na	0.1	0.01
Eritrea	5	3	19.96	55	11	18	60	14	0.55	0.11	6.3	1.3
Mali	370	189	10.36	1,559	302	60	1,929	491	3.29	0.66	20.8	4.2
Mauritania	367	188	8.65	18	4	90	385	192	1.45	0.29	42.5	8.5
Niger	130	67	9.32	658	127	40	788	194	2.15	0.43	26.4	5.3
Senegal	1,066	546	9.64	617	119	19	1,683	665	1.83	0.37	55.6	11.1
Somalia		-		75	14	64	75	14	na	na	0.7	0.1
Sudan	687	352		1,429	276	16	2,116	628	0.57	0.11	3.4	0.7
The Gambia		-		191	37	25	191	37	3.74	0.75	172.0	34.4
Sudano-Sahelian	**3,160**	**1,619**	**8.64**	**6,536**	**1,265**	**43**	**9,696**	**2,884**	**1.33**	**0.27**	**11.0**	**2.2**
All Sub-Saharan Africa	**29,598**	**15,166**	**5.68**	**34,406**	**6,658**		**64,004**	**21,824**				
All Africa	**31,718**	**16,252**	**6.61**	**37,933**	**7,341**	**28**	**69,651**	**23,593**				

Source: Authors' calculations.
Notes: Baseline assumptions: large-scale assumptions are water cost of US$0.01/m3, discount rate of 12 percent, and investment cost of US$3,000/ha on-farm only and operation and maintenance cost of US$30/ha. Small-scale assumptions are five-year cycle of investment, discount rate of 12 percent, fixed cost of US$2,000/ha and operation and maintenance cost of US$40/ha/yr.
a/ GDP data are for the year 2006 from World Development Indicators (2008); investments discounted over 50 years are divided by either 50 or 10 years and share of GDP is calculated. b/ Irrigated area for latest available data from FAO AQUASTAT; irrigated area expansions, based on 50-year discounted investments, are divided by either 50 or 10 years, respectively, and the annual increase over existing area is calculated as a percentage.
n/a = not available.

The profitability and potential for irrigation expansion of both large- and small-scale irrigation are quite sensitive to underlying assumptions, in particular the investment cost and IRRs. Table 9 presents total investment needs for both small- and large-scale irrigation using 12 percent as a cutoff point for IRR. Under this assumption, combined area expansion declines to 6.1 million hectares and total investments to $26 billion, over an investment horizon of 50 years. This investment volume appears feasible over the next 10 years, given the significant push by major donors and national governments to expand agricultural water management in Africa.

Several countries have both large-scale (dam-based) and small-scale potential with IRRs above 12 percent. They include Algeria, Angola, Botswana, Eritrea, Ethiopia, Kenya, Mali, Morocco, Mozambique, Nigeria, Tunisia, South Africa, Sudan, and Zimbabwe. Figure 3 presents potential irrigated areas with varying IRR levels for all of Africa.

Table 9. Total investment needs for both small- and large-scale irrigation, IRR cutoff at 12%

	Large-scale			Small-scale		
Country	**Investment**	**Increase in area**	**IRR**	**Investment**	**Increase in area**	**IRR**
	$million	**ha**	**%**	**$million**	**ha**	**%**
Angola	4	2,028	12	2	305	23
Cameroon				881	170,463	44
Central African Rep				9	1,824	19
Congo				1	220	21
Congo, DRC				225	43,516	28
Equatorial Guinea						
Gabon						
Central	**4**	**2,028**	**12**	**1,118**	**216,328**	**42**
Burundi						
Ethiopia	373	191,149	18	560	108,371	25
Kenya	109	55,698	16	133	25,720	59
Rwanda						
Tanzania				1,013	196,067	42
Uganda				2,300	445,041	46
Eastern	**482**	**246,847**	**17**	**4,006**	**775,199**	**44**
Benin				76	14,620	25
Cote d'Ivoire				200	38,761	24
Ghana				77	14,859	34
Guinea				143	27,710	22
Guinea-Bissau				8	1,551	25
Liberia				1	221	20
Nigeria	1,188	608,755	18	7,948	1,538,121	36
Sierra Leone						
Sao Tome & Principe					0	0
Togo				285	55,087	32

Table 9. Continued

Country	Large-scale			Small-scale		
	Investment	Increase in area	IRR	Investment	Increase in area	IRR
	$million	ha	%	$million	ha	%
Gulf of Guinea	**1,188**	**608,755**	**18**	**8,738**	**1,690,930**	**36**
Comoros						
Madagascar				138	26,726	26
Mayotte						
Indian Ocean Islands				**138**	**26,726**	**26**
Algeria	167	85,698	18	460	88,942	31
Libya				244	47,278	36
Morocco	639	327,613	18	619	119,772	27
Tunisia	296	151,741	17	975	188,678	33
Egypt	1	260	71			
Northern	**1,103**	**565,312**	**18**	**2,298**	**444,670**	**32**
Botswana	49	25,243	20	3	553	29
Lesotho				3	564	27
Malawi				214	41,427	27
Mozambique	24	12,304	14	435	84,095	26
Namibia	2	1,242	20			0
South Africa	105	53,948	16	413	79,911	30
Swaziland						0
Zambia				53	10,205	25
Zimbabwe	277	141,846	15	9	1,742	24
Southern	**458**	**234,583**	**15**	**1,129**	**218,497**	**28**
Burkina Faso				239	46,213	33
Chad				1,193	230,842	40
Djibouti				0.04	7	39
Eritrea	5	2,769	20	55	10,547	30
Mali	38	19,396	17	1,132	219,129	73
Mauritania				18	3,518	102
Niger				607	117,553	52
Senegal				293	56,681	35
Somalia				75	14,433	76
Sudan	464	237,899	14	726	140,404	31
The Gambia				73	14,036	40
Sudano-Sahelian	**508**	**260,064**	**14**	**4,410**	**853,363**	**57**
Total	**3,743**	**1,917,590**	**17**	**21,835**	**4,225,713**	**43**

Source: Authors' own calculation. Notes: Large-scale assumptions are water cost of US$0.01/m3, investment cost of US$3,000/ha on-farm only, and operation and maintenance cost of US$30/ha. Small-scale assumptions are five-year cycle of investment, US$2,000/ha, operational cost US$40/ha. Potentials for rehabilitation, reflected as irrigated command areas currently not irrigated, have to be treated with great caution; neither the location of these areas within countries nor IRRs are known.

How will irrigation investments be financed? The assumption here is that large-scale irrigation will be chiefly sourced from national government budgets, with most funds originating from multilateral donor organizations; schemes are considered an add-on to existing or planned hydropower development. Small-scale irrigation development incorporates on-farm soil moisture management measures. Whereas farmers are expected to be responsible for most on-farm-level irrigation developments, small reservoirs would still require support from the local or central government.

Given the limited experience of many governments in Africa with irrigation investments, it will be important to ensure that planned investments do not surpass a country's financial capacity and that investments are proportional to other agricultural expenditures and value generated in the agriculture sector. Table 8 presents the discounted investment needs divided over 10 and 50 years, respectively, as shares of total (2006) GDP of African countries as well as shares over existing irrigated area. These numbers provide an idea about the absorption capacity of these countries.

Among the countries with data, the investment potential identified across Africa would burden Egypt the least (but area expansion is also tiny), followed by Gabon, Congo, and Botswana. On the other end of the spectrum, several small countries with considerable irrigation potential would be unlikely to implement much of their potential given limited financial resources. These include Guinea, Benin, Uganda, and Mozambique. Results are presented graphically in Figure 4. Given that the investment expenditures would surpass the annual agricultural expenditures for many African countries, and given that current irrigated areas are estimated at 13 million hectares, it is unlikely that more than 1 to 10 percent of the irrigation potential identified can be implemented over the next 20 years, depending on the country in question.

Figure 3. Potential large-scale and small-based irrigated areas, alternative IRR levels

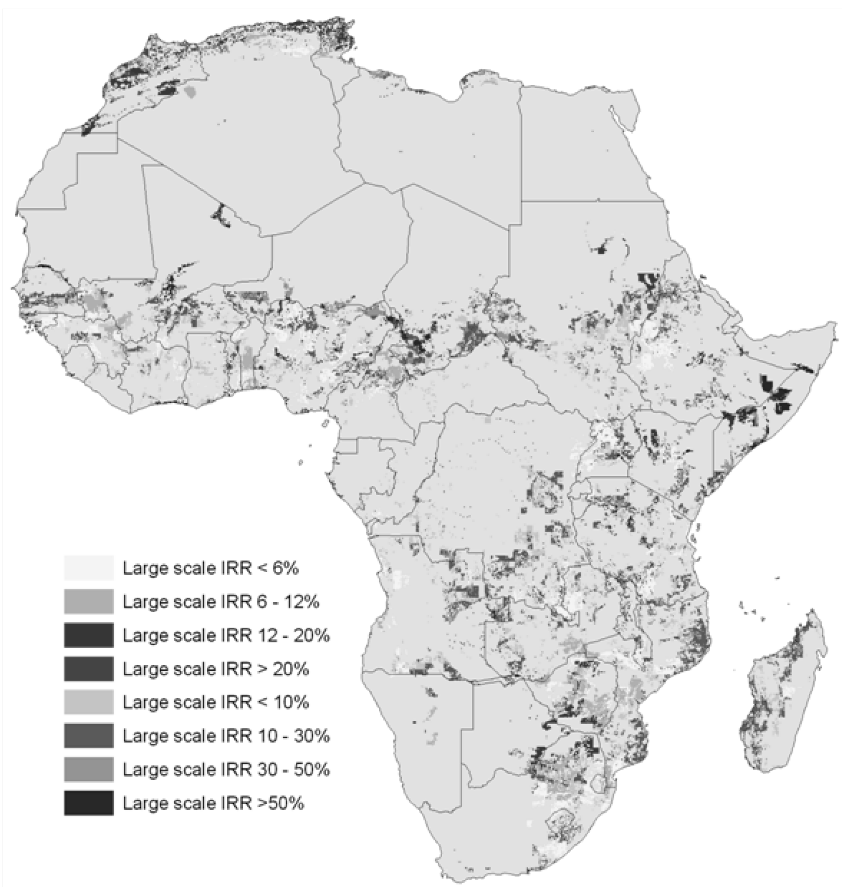
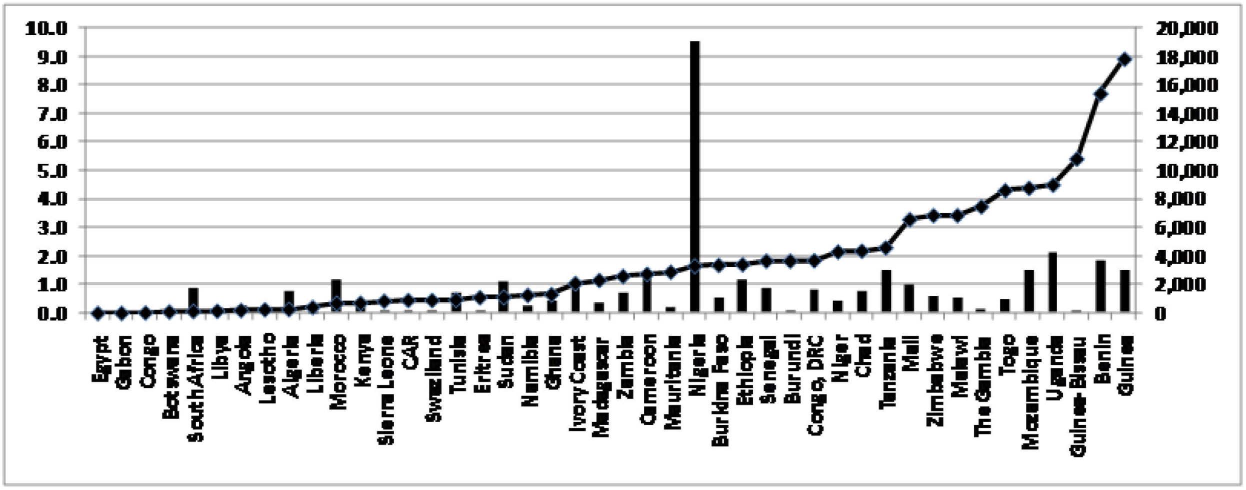


Figure 4. Large-scale, dam-based and small-scale irrigation investment needs and share of GDP if implemented over 10 years



Source: Authors' calculations.
Note: Line indicates discounted investment needs divided over 10 years, respectively, as share of total (2006) GDP of African countries ; columns reflect investment for small-scale and large-scale area expansion (US$ million.

In terms of irrigated area expansion, the area expansion could be carried best by countries that already have significant experience with irrigation or where area expansion would constitute a relatively minor share of existing area, or both. Such is the case for Egypt, Djibouti, Somalia, Madagascar, Libya, Gabon, Sudan, and South Africa. On the other hand, baseline irrigation expansion (even if implemented incrementally over 50 years) is 80 percent or more of current equipped area for countries such as Togo, Ivory Coast, Central African Republic, Uganda, and Benin. Given the limited experience with irrigation in these countries, it is unlikely that such large irrigation could be implemented rapidly.

5. SENSITIVITY ANALYSIS

A comparison between tables 7 and 8 has shown how sensitive area expansion is to the cutoff point of IRR. We have also implemented sensitivity analyses for changing investment costs, changes in irrigated water delivery cost, and changes in water availability. Results are presented in the following paragraphs.

Table 10 presents results under changing investment costs. Potential irrigated area expansion could range from 6.7 million hectares to 32 million hectares, depending on the initial investment cost assumed for small-scale and large-scale irrigation. When small-scale irrigation costs decline from $2,000 per hectare to $600 per hectare, irrigated area expansion potential increases most in the Gulf of Guinea and Indian Ocean Island zones. When large-scale irrigation costs are halved, from $6,000 per hectare to $3,000 per hectare, the potential for irrigated area expansion increases sharply in the Indian Ocean Islands, eastern Africa, and southern Africa. When small-scale irrigation costs are raised from $2,000 per hectare to $5,000 per hectare, the potential for area increase declines relatively uniformly across regions. For large-scale irrigation, on the other hand, an increase of initial investment costs from $6,000 per hectare to $8,000 per hectare leads to large declines in potential area expansion in central and eastern Africa, and only very small declines in northern Africa.

Table 10. Total investment needs for both small- and large-scale irrigation, alternative investment costs (hectares)

		Large scale	Small scale
	INVESTMENT COST	*US$3,000/ha*	*US$600/ha*
	Central	1,173,352	1,725,775
LOW	Eastern	2,299,310	1,987,354
COST	Gulf of Guinea	6,858,817	8,266,261
	Indian Ocean Islands	130,389	177,385
	Northern	1,086,128	871,387
	Southern	3,084,693	1,046,362
	Sudano-Sahelian	1,619,054	1,711,093
	TOTAL	16,251,744	15,785,617
	INVESTMENT COST	*US$6,000/ha*	*US$2,000/ha*
	Central	644,193	452,224
	Eastern	614,733	1,151,170
MEDIUM	Gulf of Guinea	3,576,309	3,146,105
COST	Indian Ocean Islands	-	73,803
	Northern	805,176	682,503
	Southern	1,515,716	570,356
	Sudano-Sahelian	1,619,054	1,264,803
	TOTAL	8,775,181	7,340,964
	INVESTMENT COST	*US$8,000/ha*	*US$5,000/ha*
	Central	302,137	19,326
	Eastern	359,502	47,150
HIGH	Gulf of Guinea	2,402,230	83,022
COST	Indian Ocean Islands	-	70
	Northern	797,023	5,209
	Southern	1,322,623	3,559
	Sudano-Sahelian	1,196,091	163,391
	TOTAL	6,379,606	321,727

Source: Authors' calculations.

Note: Investment costs also include annual maintenance costs and for dam-based irrigation water delivery costs that are not shown here. The base cases are highlighted in grey.

The assumption about the cost of water delivery for dam-based irrigation can have a significant effect on profitable irrigation expansion. At 0.25¢ per cubic meter, 17.3 million hectares could be irrigated with an IRR of 7.03 percent. If instead, the water cost is 5¢ per cubic meter, area expansion drops to 11.9 million hectares with an IRR of 5.78 percent, compared with 16.3 million hectares with an IRR of 6.45 percent for our baseline (Table 11).

Table 11. Water cost effect on large-scale irrigated area and investment return

Water cost assumption (US$ per m^3)	Increase in irrigated area (million ha)	Investment expenditure (US$ million)	Internal rate of return (%)
0.0025	17.3	37,950	7.03
0.0100	**16.25**	**31,718**	**6.45**
0.0500	11.9	21,500	5.78

Source: Authors' calculations.
Note: Values in bold indicate base case. Investment rate of $3,000/ha and discount rate of 12%.

Climate change will certainly have a large impact on the potential for irrigation expansion. It will alter rainfall patterns and therefore reservoir storage, which in turn affects the availability of water for power production and irrigation. In addition, a changing climate will affect both crop yields and patterns (for example, some current crop areas may not be suitable for growing certain crops or might completely go out of production). Explicitly modeling climate change under our current models is highly complex. Even though there is a wide range of studies on the potential impact of climate change on agriculture in Sub-Saharan Africa, most have been carried out at highly aggregated levels (country or beyond), whereas this study is implemented at the level of 9-kilometer pixels. As we cannot now fully evaluate the impact of climate change, we instead use a rudimentary approach through sensitivity analysis for reduced water availability in reservoirs, without accounting for changes in cropping patterns and yields as a result of climate change. We implement this by assuming that the reservoir water storage levels would be reduced by 5, 10, and 25 percent under different climate change assumptions. Table 12 presents the results for this sensitivity analysis.

A small decline in the volume of water (for example, 5 percent) has limited impact on irrigated area and returns to investment. That is because water is not a constraint for many of the large-scale irrigation systems examined here. A 25 percent reduction of water availability, on the other hand, does have a considerable impact on the potential for expansion of irrigated area and the number of dams that can be associated with irrigation expansion. The return to investment, expressed in IRR, is only marginally affected by water availability through climate change.

Table 12. The impact of climate change on irrigated area and investment return

Change in reservoir water (%)	Increase in irrigated area (million ha)	Investment expenditure ($ millions)	Internal rate of return (%)
Baseline	**16.25**	**31,718**	**6.45**
–5%	15.92	30,200	6.70
–10%	13.21	24,602	7.00
–25%	10.91	22,127	5.99

Source: Authors' calculations.
Note: Values in bold indicate base case. The baseline assumes an investment rate of $3,000/ha, discount rate of 12%, and water cost of $0.01/m3.

6. POLICY RECOMMENDATIONS

Africa's agricultural productivity is the lowest in the world, in part because of the underuse of irrigation in Sub-Saharan Africa. Past low food prices, limited government commitment, poor rural infrastructure, diets tied to crops with low water requirements, and low population densities have all contributed to high costs and low levels of irrigation in (Sub-Saharan) Africa. As these trends have been changing and donor commitment for irrigation has increased significantly, irrigation development is set to gradually increase.

Irrigation is an important vehicle for promoting increased productivity, provided investments in irrigation are properly targeted and accompanied by complementary improvements in other agricultural inputs. By taking a closer look at the agronomic, geographic, and economic characteristics of potential project sites with a high level of spatial disaggregation, we can gain a better understanding of the conditions under which irrigation investments will yield their full potential. The analysis presented here provides, in that sense, a first filter that helps to identify the areas of greatest potential. More detailed study of these areas is warranted to evaluate all the other factors—institutional, agronomic, human, and environmental—that ultimately determines the success of irrigation projects at the country level.

The results for large- and small-scale irrigation present a striking contrast. Although the total area expansion potential is small for small-scale irrigation, IRRs are considerably higher for this type of expansion. The average IRR for large-scale irrigation is 6.6 percent, versus an average IRR of 28 percent for small-scale irrigation in our baseline.

In terms of country potential, Nigeria stands out as having particularly great potential for both large- and small-scale schemes. Mali stands out as a particularly lucrative site for small-scale irrigation investments. More than half of the large, dam-based potential for irrigation expansion is with operational dams. This shows the large potential for adding irrigation facilities at existing dam sites. In general, adding large-scale irrigation to dams in need of rehabilitation appears more profitable than either operational or planned reservoirs. This is largely due to the high returns in Egypt and Nigeria. For small-scale irrigation, rates of return are highest in the Sudano-Sahelian zone, followed by the eastern Africa zone.

In geographical terms, clear patterns emerge. The Gulf of Guinea area has the largest potential for area expansion for both operational and planned dams within Africa, reflecting the rich water resources in this region. For small-scale irrigation, almost half of total suitable area is located in the Gulf of Guinea, followed by 1.3 million hectares in the Sudano-Sahelian zone and 1.2 million hectares in the eastern Africa zone.

The results presented, for large and small schemes alike, are sensitive to assumptions about the unit costs of their components, and we conducted tests to determine the extent of that sensitivity. The unit investment cost is a particularly sensitive parameter. The lower values, up to and including the baseline assumption of $3,000, correspond to the incremental investment costs of developing a large-scale scheme when all or most of the costs of the dam are paid from some other source (typically hydropower revenues). The higher values, on the other hand, correspond to situations where some portion of the water-storage costs must be borne by the agricultural sector. When storage costs are excluded, the area in which dam-based irrigation would be profitable encompasses from 16 to 18 million hectares. However, if they are included, the viable area shrinks to just 3 to 6 million hectares. Similarly, for small-scale irrigation, traditional forms of small-scale irrigation, as well as some low-cost higher-end systems—up to investment costs of $600 per hectare—result in a viable area of 16 million hectares; this area shrinks to 0.3 million hectares at high-end small-scale irrigation, valued at $5,000 per hectare. Thus, Africa has significant potential to develop both large- and small-scale irrigation, but economic viability depends on keeping costs down. Only lower-cost technologies and approaches are viable on any significant scale in Africa. Although not a focus of this analysis, there is also significant potential for rehabilitating existing irrigated area in the region, estimated at 2 million hectares. According to both Inocencio et al. (2005) and Riddell (2005), rehabilitation costs are lower than new construction costs in Sub-Saharan Africa. Moreover, Riddell finds that rehabilitation costs do not vary widely between regions within Sub-Saharan Africa.

It was not possible to perform a detailed climate change analysis for this study, but we did test large-scale schemes for reductions in reservoir levels. According to our analysis, a small decrease in storage would have a modest effect on the potential for expansion of irrigated area associated with large dams. On the other hand, a 25 percent reduction in water availability would reduce the size of the potential irrigable area for large-scale schemes by 5 million hectares. Although we did not study this issue in detail, an aggressive campaign of agricultural water development could help reduce adverse effects of global warming on food security in the region.

Given Sub-Saharan Africa's limited experience with irrigation investments, it is important to ensure that planned investments do not surpass a country's financial capacity and that investments are proportional to other agricultural expenditures and value added. One way of keeping the investments affordable would be for the donor community to provide sequenced financing reflecting certain priorities. This could be done in several ways. A purely economic approach would set priorities based on the highest benefit–cost ratios identified previously, with the effort focusing on a handful of countries where the impact would be greatest. An approach driven by food security, by contrast, would target those countries that are both extremely poor and that import more than half of their total cereal demand and would lead to a focus on the Sudano-Sahelian region.

Market access conditions have been shown to be critical for irrigation development to succeed. Whereas they are explicit in the case of small-scale irrigation, they will also play an important role for large-scale irrigation. Here, it is assumed that the size of the irrigation system development would attract additional resources for postharvest processing and marketing. The overall potential assessed here could be reduced by limiting expansion to the poorer regions within countries. The potential could be yet further limited by introducing a food demand component into the analysis—for example, introducing a country- or regional-level limit to irrigated shares for staple crops or high-value commodities. Additional criteria, such as poverty targeting—or the readiness of countries to expand irrigation as described in the World Bank Africa Region Irrigation Business Plan of 2007 (World Bank 2007a)—could also be used to take this analysis further to identify the highest-priority areas. In future research, we plan to incorporate basin-level hydrology modeling into assessing the investment potential to account for upstream and downstream tradeoffs as well as environmental impacts of large-scale irrigation development.

Moreover, although there is considerable scope for the expansion of both dam-based and small-scale irrigation in Africa, investment decisions seldom depend on biophysical and economic criteria alone. Government policy objectives, donor suggestions, and other factors not related to irrigation and agriculture—ranging from plans for energy security and urban water supply to rural development and income generation, and national food security goals—all play a role in the final policy decision to expand irrigation.

(Sub-Saharan) Africa faces large challenges to implementing irrigation. Those challenges are related to low levels of expertise, knowledge, and capacity to develop and manage irrigation; the absence of an adequate policy and strategic framework; the often disappointing results of previous irrigation development and the need for continued support for recurrent costs from the public sector; relatively high costs of conventional irrigation development (but see also Inocencio et al. 2005); and increasing competition over water.

In addition, irrigation is only one of several deficient productivity-improving capital investments and technological inputs in the region. Others include fertilizer, advanced seed-delivery systems, postharvest processing facilities, and access to markets. Thus, even when supported by national agencies and farmers, irrigation thrives only when complementary inputs and rural services are available. Thus, significant efforts are required not only to develop irrigation but also to ensure that irrigation develops its full potential for poverty reduction, food security, and economic growth. Thus, institutional settings, extension and management systems, availability of complementary inputs, and the involvement of farmers in the design and management of irrigation systems will determine final system performance. Thus, strengthening African countries' capacity to address institutional and strategic challenges for irrigation will be just as important as accelerated investments in irrigation infrastructure.

REFERENCES

Commission for Africa. 2005. Our common interest: Report of the Commission for Africa. London: Commission for Africa.

Eberhard, A., V. Foster, C. Briceño-Garmendia, F. Ouedraogo, D. Camos, and M. Shkaratan. 2008. *Underpowered: The State of the Power Sector in Sub-Saharan Africa*. Background Paper 6, Africa Infrastructure Sector Diagnostic. Washington, D.C.: World Bank.

FAO (Food and Agriculture Organization). 2006. African dams database. Note and references. www.fao.org/nr/water/aquastat/damsafrica/NotesRef060405.pdf. Accessed July 2009. .

FAOSTAT. 2009. FAO AQUASTAT: http://www.fao.org/nr/water/aquastat/dbase/index.stm>. Accessed May 2009.

Faures, J. M., and G. Santini, ed. 2008. *Water and the rural poor: Interventions for improving livelihoods in Sub-Saharan Africa*. Rome: Food and Agriculture Organization.

Fischer, G., M. Shah, H. Velthuizen, and F. Nachtergaele. 2001. Global *agro-ecological assessment for agriculture in the 21st century*. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Inocencio, A., M. Kikuchi, M. Tonosaki, A. Maruyama, and H. Sally. 2005. *Costs of irrigation projects: A comparison of Sub-Saharan Africa and other developing regions and finding options to reduce costs.* Report of Component Study for Collaborative Programme. Pretoria: International Water Management Institute.

Kay, M. 2001. *Smallholder irrigation technology: Prospects for Sub-Saharan Africa*. Rome: International Program for Technology and Research in Irrigation and Drainage.

Riddell, P. J. 2005. Investment trends in irrigation, 1980–2003: A brief statistical analysis of a 256-project database. Assembled by the Food and Agriculture Organization of the United Nations, Rome, Italy. . Unpublished.

Rosegrant, M. W., C. Ringler, T. Benson, X. Diao, D. Resnick, J. Thurlow, M. Torero, and D. Orden. 2006. *Agriculture and achieving the Millennium Development Goals.* Report 32729-GLB. Washington, D.C.: World Bank.

Rosnes, Orvika, and Haakon Vennemo. 2008. *Powering up: Costing power infrastructure investment needs in Southern and Eastern Africa*. Background Paper 5, Africa Infrastructure Sector Diagnostic. Washington, D.C.: World Bank.

Svendsen, S., M. Ewing, and S. Msangi. 2009. *Measuring irrigation performance in Africa*. IFPRI Discussion Paper 894. Washington, D.C.: International Food Policy Research Institute.

World Bank. 2007a. Africa region: Irrigation business plan. Revised draft. Washington, D.C.

World Development Indicators (WDI). 2008. The World Bank. Washington, D.C.

You, L., and S. Wood. 2006. An entropy approach to spatial disaggregation of agricultural production. *Agricultural Systems* 90 (1–3): 329–347.

You, L., C. Ringler, G. Nelson, U. Wood-Sichra, R. Robertson. S. Wood, G. Zhe, T. Zhu, and Y. Sun. 2009. *Torrents and trickles: Irrigation spending needs in Africa*. Background Paper 9, African Infrastructure Country Diagnostic. Washington, D.C.: World Bank Group.

You, L., S. Wood, and U. Wood-Sichra. 2007. Generating plausible crop distribution and performance maps for Sub-Saharan Africa using a spatially disaggregated data fusion and optimization approach. *Agricultural System* 99 (2–3): 126–140.

Zhu, T., C. Ringler, and M. W. Rosegrant. 2009. IMPACT global hydrological module: Technical description. International Food Policy Research Institute. Mimeo.

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