POTENTIAL FOR SMALL-SCALE IRRIGATION IN SUB-SAHARAN AFRICA UNDER CLIMATE CHANGE

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ABSTRACT

Irrigation has been proposed as a key solution to address adverse impacts of rainfall shortfalls and variability on Sub-Saharan Africa. However, the potential for irrigation investments in Sub-Saharan 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 the application potential for motor pumps, one of the most promising smallholder irrigation technologies, in Sub-Saharan Africa based on various biophysical and socioeconomic factors under climate change. The analysis involved the integrative use of a suite of state-of-the-art data analysis and modeling tools and allowed for integrating a wide variety of data sets on both the biophysical and the socioeconomic side to identify the geographic domains with smallholder irrigation application potential, perform cost-benefit analysis, and assess the long-term environmental impacts of the adoption of the technology. This type of analysis can guide country- and local-level assessment of irrigation potential under climate change, which will be important to agricultural and economic development in Africa.

KEY WORDS

Smallholder irrigation, climate change, Sub-Saharan Africa

1. Introduction

Sub-Saharan Africa contains many least developed countries in the world and is faced with great challenges for improving food security and poverty reduction. Water is an important input factor in agricultural production. Given that only 6 percent of crop area in the region receives irrigation, and that more than three quarters of the population in the region is dependent on agriculture for their livelihood and incomes, agricultural GDP and total GDP in the region are closely linked to seasonal and annual rainfall availability. Sub-Saharan Africa has been plagued by frequent droughts and erratic rainfall, both of which are expected to increase with climate change. How to effectively manage the water resources is thus an issue of major concern and a key strategy for improving agricultural productivity in Sub-Saharan Africa.

Irrigation has been proposed as a key solution to address adverse impacts of rainfall shortfalls and variability. Moreover over the last several years, interest in promoting smallholder irrigation over large-scale irrigation has been steadily growing. Small-holder irrigation is described as a “bottom-up” approach for development (Kay, 2001) and may have some advantages over large-scale irrigation in terms of feasibility and reaching the rural poor. However, the potential for irrigation investments is dependent upon various 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 implements a regional-scale assessment to analyze the application potential for motor pumps, one of the most promising smallholder irrigation technologies, in Sub-Saharan Africa, taking the impacts of climate change on water resources into account. Climate is one of the most influential factors in irrigation decisions, and climate change has created concerns with agricultural resources in Sub-Saharan Africa.

The rest of the paper is organized as follows: a brief description of the current climate conditions in Sub-Saharan Africa is followed by a description of the methodology we developed for assessing smallholder irrigation technologies, which involves the integrative use of a suite of state-of-the-art data analysis and modeling tools and allows for integrating a wide variety of data sets on both the biophysical and the socioeconomic side to identify the geographic domains with smallholder irrigation application potential, perform cost-benefit analysis, and assess the long-term environmental impacts of the adoption of the technology. The preparation of the meteorological data that represent the possible future climate under the selected climate change scenario used in our study is explained in section 4. Section 5 contains the main results of the assessment. The paper concludes with a summary of the major findings from our study and a few remarks on the uncertainties in the assessment and suggestions for future work.

2. Study area

The study covers 42 Sub-Saharan African countries. Sub-Saharan Africa straddles the Equator. Temperature is high in most areas and throughout year, but precipitation varies significantly both temporally and spatially (Fig. 1). Tropical rainforest and tropical savanna are two dominant climate zones in Sub-Saharan Africa. The tropical rainforests are primarily located in the Congo River Basin and on the southern coast of West Africa and eastern coast of Madagascar. The climate in tropical rainforests is characterized by year-round heavy rainfall. As the precipitation decreases, the tropical rainforests are supplanted by tropical savanna. The seasonal variability of rainfall under the tropical savanna is strong with wet and dry seasons alternating every year. Other major climate zones in Sub-Saharan include Sahel, and the desert and semi-desert zones.

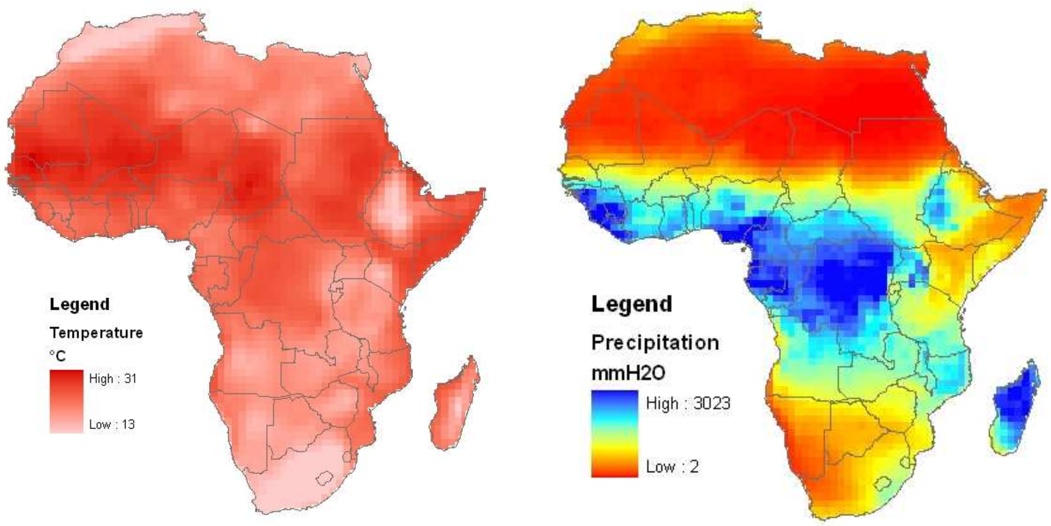


Fig.1 Muti-year averages of total annual rainfall and daily temperature (2002-2009)

3. Methods for assessing smallholder irrigation potential

The following methodology was developed to assess the smallholder irrigation (motor pumps) potential in Sub-Saharan Africa.

3.1 GIS ex-ante analysis

A Geographic Information System (GIS) tool was first applied to carry out a pixel-level suitability analysis to demark the area with motor pump application potential. The criteria and weights we used to calculate the pixel's environmental suitability index are shown in Table 1. Protected areas, urban areas, and areas with mean terrain slopes greater than 30% were excluded. Rural population analysis was also performed to ensure that there would be both sufficient adopting labor and sufficient suitable land for motor pump technology uptake.

Table 1 Criteria and weights for calculating environmental suitability index

Criteria for electric/diesel pumps:	Criteria Weights
Fluvisols(FAO)	False = 0; 1-15 %=11; 16-50%=22; 51-100%=33
Market Access (Nelson Travel Time)	5km=10minutes=33.33; 10km=20minutes=22.22 20km=40minutes=11.11; 30km=60minutes=0 60km = 120 minutes = 0
Distance to Surface Water	< 0.5 km = 33.333; > 0.5 km = 0
Minimum Suitability Threshold	55/100

The pixel's environmental suitability index scored from 0 to 100 with 0 assigned to grid-cells meeting none of the requirements of the technology and 100 assigned to grid-cells meeting all requirements of the technology. A minimum suitability threshold (55) was then applied. Grid-cells with suitability scores below this threshold were then excluded from suitable area calculations.

The ex-ante GIS analysis serves as a major input/constraint into the predictive modeling analysis.

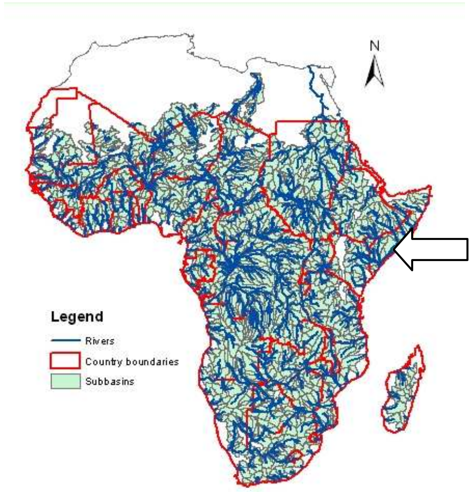
3.2 SWAT and DREAM predictive modeling

The spatially-disaggregated estimates on crop yields, water use intensities, runoff quantities and ground recharge rates, which are required to calculate the indicators for the adoption potential of motor pumps and the environmental impacts, were provided by the Soil and Water Assessment Tool, or the SWAT model (Arnold et al., 1998). SWAT is a comprehensive watershed model with proven capacities for hydrological and crop simulation. The SWAT model we developed in this study for Sub-Saharan Africa (SWAT-SSA) integrated a wide variety of data sets from various sources and contains 1488 basins, which also serve as the spatial units in the crop mix optimization (Fig.2). Notably, the simulation in SWAT is driven by climate data. The meteorological data, including precipitation, temperature, solar radiation and relative humidity, that represent the historical/current climate were obtained from the NASA Langley Research Center POWER Project funded through the NASA Earth Science Directorate Applied Science Program.

The SWAT-SSA model was evaluated and improved using the GRACE (Gravity Recovery and Climate Experiment) global total water storage anomaly data, the river discharge data from the Global Runoff Data Centre (GRDC) and the crop production statistics from FAOSTAT database. Considering the time frame of data sets with actual observations, the SWAT model was run for 2002-2009, and the averages of the estimates for the variables of interest over this eight year period were taken as the estimates for the baseline period under current climate..

In the crop simulation and the simulation of irrigation, two key assumptions were introduced. First, it is assumed that the crop water demands are always fulfilled through irrigation. Moreover, it was observed that simulated crop yields are quite responsive to the input rates of nutrients. We assume, for this study, that nutrient input rates were not a constraint to crop yield attainment.

Another major predictive modeling tool we used in this study is the "Dynamic Research EvaluAtion for Management" (DREAM) model. It is expected that the adoption of motor pump irrigation will enhance agriculture productivity, increase the supply of agricultural products and lower their prices. The lowered price may impose constraints on the adoptions of irrigation technologies in some countries, especially for the cultivation of horticulture crops. The relationship between the improved agricultural productivity and the prices of agricultural products was depicted by the DREAM model in this study. DREAM is an economic model and is capable of simulating the price shifts caused by the changed supply-demand relationship given specified initial market conditions. The initial food demand and price data required for the DREAM application were derived from the FAOSTAT database for 2000-2009.



Category	Source
Elevation	HydroSHEDS (Bernhard Lehner et al., 2006)
Soil	Harmonized world soil database (HWSD) (FAO/IIASA/ISRIC/ISSCAS /JRC)
Land cover	Global land cover (GLC)
Lakes & reservoirs	Global lakes and wetlands database
Climate	NASA Langley Research Center POWER Project

Fig.2 The watershed delineation and data sources for SWAT-SSA model development

3.3 Adoption scenario and crop mix optimization framework

The assessment step of predictive modeling was carried out under the following motor pump adoption scenario and crop mix optimization framework:

In Sub-Saharan Africa (and elsewhere) smallholder irrigation technologies are primarily used to produce high-value crops. In this study, thirteen such crops were included in the analysis for motor pump irrigation: tomatoes, onions, peppers, cabbages, beans, peas, potatoes, sweet potatoes, wheat, maize, rice, sugar cane, and groundnuts.

Secondly, smallholder irrigation may help extend the seasons of agricultural production in Sub-Saharan Africa. Currently, crop production in most countries in Sub-Saharan Africa is concentrated in the rainy season. In this assessment, we assumed that the adoption of motor pumps will allow for the farming in dry seasons, and farmers' welfare improvement as a result of the adoption of motor pumps primarily originates from the revenues received from the cultivation of high-value crops in the added growing season.

Thirdly, under the circumstance that there is a lack of information to determine the crop mix in the dry growing seasons, the cultivation areas of each crop in a country are assumed to be the ones that will maximize farmers net revenue and were computed by solving the following optimization problem,

$$\max_{\mathrm{A_{rc}}} \mathrm{NR} = \sum_r \sum_c \left[Y_{rc} \cdot A_{rc} \cdot P_{rc} - (IC_{rc} + LC_{rc} + PC_{rc}) \cdot A_{rc} \right]$$

Subj. to: $\sum_c \mathrm{A_{rc}} < \mathrm{A_{r,max}}$

$$\mathrm{A_{rc}} \geq 0, \forall \mathrm{r}, \mathrm{c}$$

where NR is the total net revenues farmers in a country may receive ($/yr), and r and c are the indexes for river basin and crop (river basin serves as the basic spatial unit in the optimization). A_{rc}'s are the decision variables of crop's cultivation areas (ha). Y_{rc}'s are crop yield (ton/ha-yr), and P_{rc}'s are crop prices ($/ton). The estimates for these two variables were provided by the predictive modeling tools which will be described below. IC_{rc}'s are the irrigation costs per unit of cultivated area ($/ha-yr), LC_{rc}'s are the labor costs, and PC_{rc}'s are the labor and other production costs per unit of cultivated area ($/ha-yr). Although these cost terms were indexed by river basin and crop, no basin- and crop-specific estimates for them are available. Therefore, constant numbers were taken (IC_{rc} =\$78/ha-yr, LC_{rc} =\$195/ha-yr and PC_{rc} =\$615/ha-yr.). $A_{r,\max}$'s are the maximum areas with irrigation potential in each river basin (ha). The inputs from the GIS ex-ante analysis serve as these land constraint terms.

Motor pumps may take water from either surface water bodies or aquifers, or use water from both. Due to the lack of information to evaluate the absolute storage in groundwater aquifers, no constraints on water availability were imposed in the optimization. However, some restrictions have already been imposed by the ex-ante GIS analysis, including location of this intervention in proximity to surface water sources. Moreover, we calculate two ratios as indicators for the environmental risks that may be caused by the application of motor pump irrigation.

Irrigation water use-runoff ratio:

$$r_1 = \sum_r \sum_c (w_{rc} \cdot A^*_{rc}) \Big/ \sum_r Q_r$$

and irrigation water abstraction-groundwater recharge ratio:

$$r_2 = \sum_r \sum_c (w_{rc} \cdot A^*_{rc}) \Big/ \sum_r \sum_c (GR_r \cdot A^*_{rc})$$

where w_{rc}'s are water use intensities for irrigation (m^3H_2O/ha-yr); A^*_{rc}'s are cultivated areas of crops obtained from optimization (ha); Q_r's are runoff available for irrigation during the dry (growing) season (m^3H_2O/ha-yr); and GR_r's are groundwater recharge rate (m^3H_2O/ha-yr). The values of w_{rc}'s , Q_r's and GR_r's are determined through predictive modeling as well. The larger the values of the first indicator, the more stress is put on the surface water system by the irrigation and the more likely that farmers use groundwater as the source for irrigation. The second indicator indicates the irrigation-related risks of groundwater depletion.

4. Climate data for future scenario preparation

The SWAT-SSA model takes climate data as input. The impacts of climate change on the application potential of motor pumps can be evaluated by incorporating climate data that could represent the possible future climate under the selected climate change scenarios.

For this study, we use the downscaled GCM output of the CSIRO-Mk3.0 scenario for 2030 using the IPCC's A2 scenario (Jones et al., 2009). The data set also contains the climate data for 2030 produced by other GCMs and with other emission scenarios. Among several climate variables, we primarily consider the impacts of precipitation and temperature. A preliminary analysis indicates that the precipitation and temperature changes in all these data sets project overall drier climates for Sub-Saharan Africa in 2030; the CSIRO-A2 data lead to a driest projection. The projected total annual precipitation change and daily temperature change between 2030 and 2002-2009 were plotted in Fig. 3.

The SWAT model requires daily time-series climate data for the simulation. However, the CSIRO-A2 data set provides only the downscaled GCM output on a monthly basis and for a single time slice. The required data series of precipitation and temperature for 2030 were generated based on the daily time-series of precipitation and precipitation data for 2002-2009 and the calculated difference between their multi-year average monthly means and the monthly values provided in CSIRO-A2 data set using the 'delta" method.

Throughout the analysis, it was assumed that the adoption scenario and the socioeconomic factors that are related to the GIS ex-ante analysis and DREAM modeling (e.g., population, price elasticities) are unchanged.

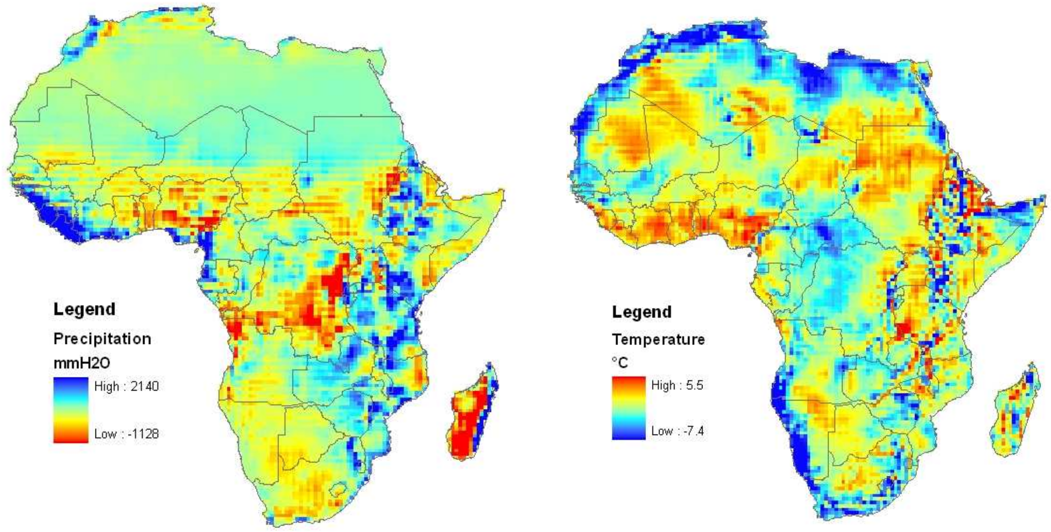


Fig.3 The projected precipitation change and temperature change between 2030 and 2002-2009

5. Results and discussions

The assessed application potential of motor pumps for the baseline period (2002-2009) under current climate and for 2030 with climate change in terms of application areas, farmer net revenues and environmental outcomes were summarized by country and are shown in Table 2.

Table 2 Application potential of motor pumps for the baseline period (2002-2009) and 2030 (assuming climate change)

(a) Application areas (ha)

Country	Baseline	Climate change	Change (%)	Country	Baseline	Climate change	Change (%)
Angola	58,440	58,440	-0.0003	Madagascar	102,873	104,700	1.8
Benin	59,014	53,225	-9.8	Malawi	122,432	120,761	-1.4
Botswana	663	649	-2.2	Mali	23,697	26,596	12
Burkina Faso	27,077	27,346	0.99	Mauritania	4,086	5,648	38
Burundi	30,079	29,790	-0.96	Mozambique	37,100	43,152	16
Cameroon	50,461	53,608	6.2	Namibia	4,005	3,942	-1.6
Central African Republic	12,747	12,563	-1.4	Niger	29,614	30,330	2.4
Chad	23,778	25,932	9.1	Nigeria	1,397,540	1,324,678	-5.2
Congo	8,089	7,913	-2.2	Rwanda	24,822	24,416	-1.6
Congo, DRC	143,384	144,182	0.6	Senegal	50,938	51,349	0.8
Cote d'Ivoire	102,570	89,201	-13	Sierra Leone	42,362	34,695	-18
Equatorial	575	523	-9.1	Somalia	11,272	11,049	-2.0

Guinea							
Eritrea	1,380	1,454	5.4	South Africa	480,327	498,520	3.8
Ethiopia	353,576	366,593	3.7	Sudan	143,852	153,544	6.7
Gabon	3,478	3,482	0.1	Swaziland	7,680	7,680	0.07
Ghana	173,856	151,467	-13	Tanzania	198,697	199,697	0.5
Guinea	29,599	25,239	-15	The Gambia	957	1,014	6.0
Guinea-Bissau	10,004	10,164	1.6	Togo	21,474	19,360	-9.8
Kenya	217,044	216,961	0.0	Uganda	197,560	196,004	-0.8
Lesotho	3,666	3,695	0.8	Zambia	110,144	109,502	-0.6
Liberia	13,645	12,416	-9.0	Zimbabwe	105,408	103,741	-1.6
Total	4,439,964	4,365,221	-1.7				

(b) Net revenues (10^6\$/yr)

Country	Baseline	Climate change	Change (%)	Country	Baseline	Climate change	Change (%)
Angola	106	109	3.2	Madagascar	35.8	37.4	4.2
Benin	43.5	41.6	-4.4	Malawi	387	389	0.3
Botswana	0.3	0.3	-0.5	Mali	48.8	50.1	2.8
Burkina Faso	9.5	9.3	-2.8	Mauritania	0.6	0.9	46
Burundi	38.4	38.9	1.4	Mozambique	73.0	73.4	0.5
Cameroon	109	111	1.2	Namibia	1.3	1.5	13
Central African Republic	3.7	4.5	24	Niger	84.4	84.7	0.4
Chad	17.2	16.8	-2.2	Nigeria	1470	1508	2.6
Congo	25.1	25.5	1.7	Rwanda	31.8	33.5	5.2
Congo, DRC	76.8	79.4	3.4	Senegal	26.7	36.3	36
Cote d'Ivoire	22.7	18	-21	Sierra Leone	8.1	6.0	-25
Equatorial Guinea	0.6	0.7	11	Somalia	9.4	10.1	6.7
Eritrea	2.3	2.4	4.8	South Africa	300	302	0.6
Ethiopia	137	148	8.1	Sudan	286	285	-0.2
Gabon	2.4	2.4	1.9	Swaziland	30.8	32.5	5.8
Ghana	123	114	-7.2	Tanzania	316	325	2.7
Guinea	4.9	6.0	23	The Gambia	0.2	0.4	42
Guinea-Bissau	7.4	8.8	19	Togo	5.7	4.3	-25
Kenya	321	332	3.4	Uganda	250	249	-0.5
Lesotho	12.5	12.8	1.9	Zambia	98	102	4.3
Liberia	4.5	4	-11	Zimbabwe	95	97	2.9
Total	4,626	4712	1.9				

(c) Irrigation water use-runoff ratio

Country	Baseline	Climate change	Change (%)	Country	Baseline	Climate change	Change (%)
Angola	0.11	0.28	151	Madagascar	0.46	0.63	36
Benin	41.3	161	291	Malawi	2.50	4.25	70
Botswana	0.01	0.14	851	Mali	13.8	28.5	110
Burkina Faso	38	117	210	Mauritania	233	537	130
Burundi	2.93	2.56	-13	Mozambique	1.14	1.43	26
Cameroon	0.46	0.58	26	Namibia	0.32	1.93	510
Central African Republic	0.11	0.45	302	Niger	59.2	75.1	27
Chad	5.55	10.91	97	Nigeria	37.2	80	110
Congo	0.02	0.05	123	Rwanda	7.09	3.39	-52
Congo, DRC	0.03	0.09	189	Senegal	387	795	110
Cote d'Ivoire	13.54	16.5	22	Sierra Leone	2.86	1.44	-50
Equatorial Guinea	0.00285	0.00291	2	Somalia	1.84	7.28	300
Eritrea	62.1	115	86	South Africa	4.18	9.08	120
Ethiopia	80.2	138	72	Sudan	1088	1418	30
Gabon	0.01	0.02	88	Swaziland	142	31	-78
Ghana	73.2	119	62	Tanzania	0.53	2.63	390
Guinea	0.91	1.56	72	The Gambia	29.6	858	2800
Guinea-Bissau	9256	12864	39	Togo	8.15	149	1700
Kenya	13.4	22.1	65	Uganda	53.8	103	91
Lesotho	3.24	4.70	45	Zambia	0.47	1.36	190
Liberia	4.69	1.75	-63	Zimbabwe	3.7	7.9	110

(d) Irrigation water abstraction-groundwater recharge ratio

Country	Baseline	Climate change	Change (%)	Country	Baseline	Climate change	Change (%)
Angola	0.9	2.2	141	Madagascar	0.2	0.3	37
Benin	1.3	5.1	296	Malawi	0.8	1.4	71
Botswana	2.7	26.1	867	Mali	6.1	11.3	85
Burkina Faso	1.9	5.8	203	Mauritania	59.2	138.7	134
Burundi	1.1	1.0	-9	Mozambique	0.7	0.8	19
Cameroon	0.4	0.5	32	Namibia	10.8	65.8	509
Central African Republic	0.3	1.1	275	Niger	23.5	29.6	26
Chad	2.7	5.1	88	Nigeria	0.8	1.7	114

Congo	0.1	0.2	116	Rwanda	0.5	0.2	-57
Congo, DRC	0.2	0.6	183	Senegal	6.5	13.1	102
Cote d'Ivoire	1.0	1.2	16	Sierra Leone	0.3	0.2	-45
Equatorial Guinea	0.3	0.3	2	Somalia	4.1	14.2	245
Eritrea	11.7	17.7	51	South Africa	9.9	20.9	111
Ethiopia	1.7	2.7	62	Sudan	3.4	4.5	31
Gabon	0.1	0.2	88	Swaziland	2.7	0.6	-80
Ghana	1.3	2.1	59	Tanzania	1.1	5.1	367
Guinea	0.4	0.7	84	The Gambia	1.8	51.8	2775
Guinea-Bissau	0.8	1.1	39	Togo	1.2	20.8	1632
Kenya	1.9	2.7	41	Uganda	0.5	0.9	88
Lesotho	1.8	2.2	21	Zambia	0.8	2.3	189
Liberia	0.3	0.1	-65	Zimbabwe	3.7	7.3	98

According to Table 2, for the baseline period the estimated areas with application potential of motor pumps across Sub-Saharan Africa is about 4.4 million hectares and total net revenues generated from the adoption can reach $4.6 billion. Nigeria has the largest adoption potential for motor pumps and accounts for about 30% of the total potential in Sub-Saharan Africa by area. Other Sub-Saharan African countries with large motor pump adoption potential include South Africa, Tanzania, Ethiopia, Kenya, Uganda and Ghana. The fact that for most Sub-Saharan countries the estimated irrigation water use-runoff ratios are greater 1 indicates that in these countries, farmers have to resort to groundwater resources to meet the irrigation water demands. Particularly high groundwater depletion risks exist in Mauritania, Niger, Eritrea, Namibia and South Africa.

The numbers in Table 2(a) and Table 2(b) also show that climate change does not influence the estimates for potential application areas and the total net revenues substantially. However, sharp rises in the values of two environmental indicators for most of Sub-Saharan African countries were observed (Table 2(c) and Table 2(d)), which suggests strong adverse environmental impacts of the changed climate on the adoption of motor pump irrigation.

The different responses between the two sets of variables to climate change can be explained considering that no constraints on water availability were imposed in the crop optimization model developed for estimating the potential application area and total net revenues. With the “full” irrigation assumption, the estimated agricultural productivity improvements, which were used for the crop mix optimization, were only affected by the shifted mean temperature, and the crop simulation by the SWAT-SSA model showed that the changed temperature only has limited influence on crop yields. On the other hand, the SWAT-SSA model predicted significant increases in the amount of water used for irrigation as a result of climate change (Fig. 4). This substantial increases, together with predicted change in runoff and groundwater recharge, leads to inflated values of the two environmental indicators.

6. Conclusions and future work

The potential for irrigation investments is highly dependent upon various geographic, hydrologic, agronomic, and economic factors. In this paper, the application potential of a promising smallholder irrigation technology, motor pumps, in Sub-Saharan Africa, and the impacts of climate change on its adoption potential, were analyzed using an integrated data analysis and modeling system. The analysis showed that the areas with motor pump application potential could reach 4.4 million hectares and the estimated application potential were not substantially affected by the climate change if its environmental impacts/requirements were ignored. On the other hand, our analysis also revealed that climate change tends to increase the total irrigation water demand/use and imposes more stress on aquatic environments in most Sub-Saharan African countries, and therefore has adverse impacts on the application potential of motor pumps in Sub-Saharan Africa from an environmental and overall perspective.

As a final remark, it was observed that the estimates of the application potential and the related environmental impact indicators are highly sensitive to the input data used (e.g. irrigation, labor and production costs). In future work, we will refine these estimates when updated input data are available and address the concern of sensitivity of assessment results through sensitivity analyses.

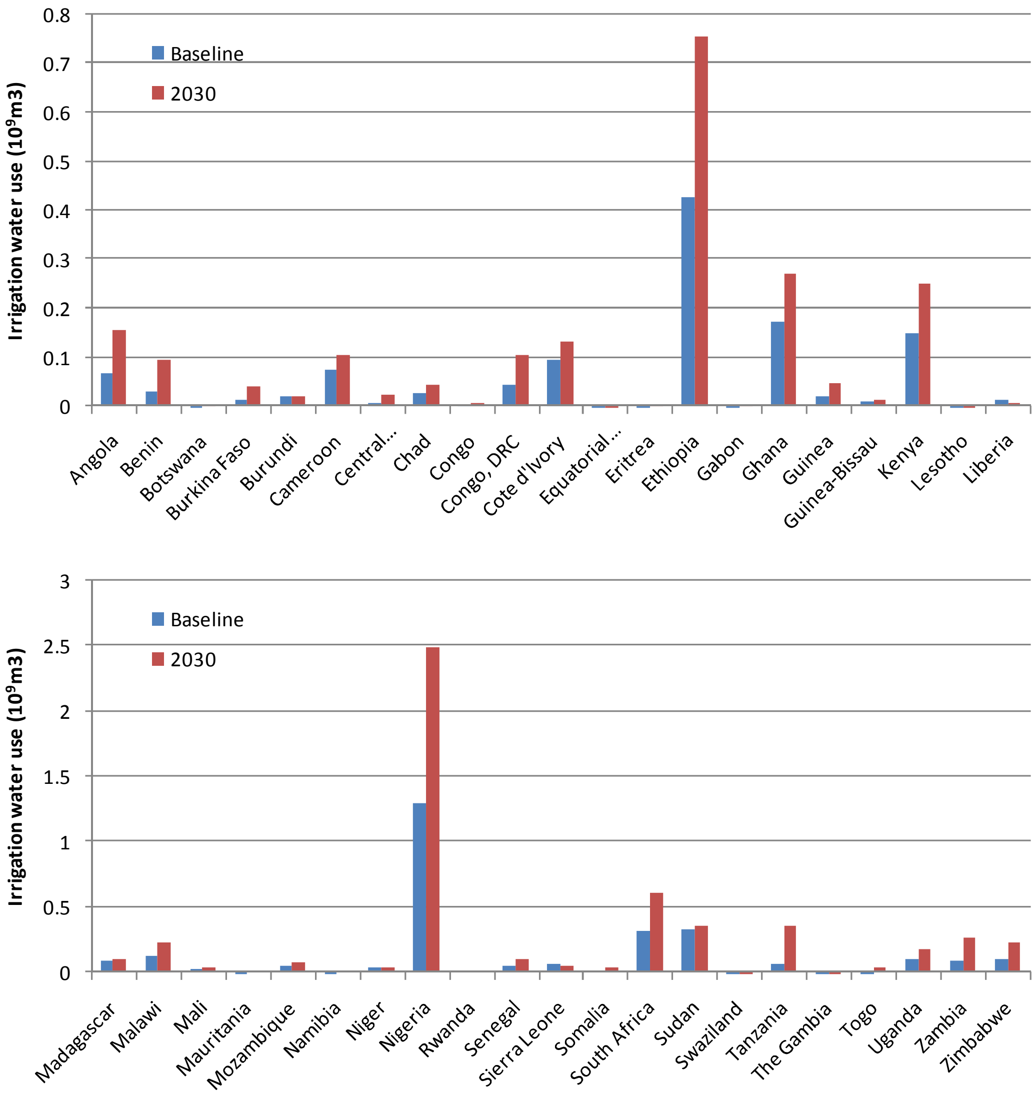


Fig. 4 Estimated motor pump irrigation water uses for baseline years (2002-2009) and 2030

References:

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams (1998), Large area hydrologic modeling and assessment-Part I: model development. Journal of the American Water Resources Association, 34(1): 73-89

FAO/IIASA/ISRIC/ISSCAS/JRC, 2009. Harmonized World Soil Database (version 1.1). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

Kay, M. (2001), Smallholder Irrigation Technology: Prospects for Sub-Saharan Africa, FAO

Lehner, B. and P. Döll (2004): Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology 296/1-4: 1-22

Lehner, B., K. Verdin, and A. Jarvis (2006), HydroSHEDS Technical Documentation Version 1.0

Jones, P.G., P.K. Thornton, and J. Heinke (2009), Characteristically Generated Monthly Climate and Daily Weather Data using Downscaled Climate Model Data from the IPCC's Fourth Assessment

Nelson, A. (2000), Accessibility, transport and travel time information. CIAT Hillsides Project Report, CIAT, Cali, Colombia. pp 16.

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