Assessment of the Irrigation Potential in Burundi, Eastern DRC, Kenya, Rwanda, South Sudan, Tanzania and Uganda

Final Report

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Client
Nile Basin Initiative
NELSAP Regional Agricultural Trade and Productivity Project

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(Report consist out of Main Report (this one) and seven appendix reports covering each country)

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PREFACE

The Nile Basin Initiative (NBI), under the Nile Equatorial Lakes Subsidiary Action Program (NELSAP) and the project Regional Agricultural Trade and Productivity Project (RATP) announced a Request for Proposals (RFP) entitled "Assessment of the Irrigation Potential in Burundi, Eastern DRC, Kenya, Rwanda, Southern Sudan, Tanzania and Uganda" in July 2010 (RATP/CONSULTANCY/04/2010). The study was categorized as "preparation for a development program" and has therefore a strategic perspective.

FutureWater, in association with WaterWatch, submitted a proposal in response to this RFP. Based on an independent Technical and Financial evaluation FutureWater, in association with WaterWatch, has been selected to undertake the study.

The consulting services contract was signed between the "Nile Basin Initiative / The Regional Agricultural Trade and Productivity Project" and "FutureWater in association with WaterWatch" entitled "Consulting Services for Assessment of the Irrigation Potential in Burundi, Eastern DRC, Kenya, Rwanda, Southern Sudan, Tanzania and Uganda". This contract was dated 5-Feb-2011 and total project duration is 16 months.

The Contract Reference Number is: NELSAP CU/RATP2/2011/01

This Report consist out of the Main Report (this one) and seven appendix reports covering each country.

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The Consultants wish to acknowledge the support, fruitful discussions and useful comments from all NBI-RATP staff and stakeholders in the countries. In particular Dr. Innocent Ntabana and Dr. Gabriel Ndikumana are acknowledged for starting this initiative and their support and advice on the study.

Executive Summary

Continued concern over food security in Africa and a persistent agricultural productivity lag behind other regions, have refocused attention on the importance of key investments in the African agricultural sector. Irrigation carries significant potential to increase agricultural productivity. Irrigation is an investment that has been promoted persistently by donors, research analysts, and scientists within the international agricultural development community to address that lag.

The Nile Basin Initiative (NBI) is a partnership of the riparian states that seeks to develop the river in a cooperative manner, share substantial socioeconomic benefits, and promote regional peace and security through its shared vision of "sustainable socioeconomic development through the equitable utilization of, and benefit from, the common Nile Basin water resources". NBI's Strategic Action Program is made up of the Shared Vision Program (SVP) and Subsidiary Action Programs (SAPs). The SAPS are mandated to initiate concrete investments and action on the ground in the Eastern Nile (ENSAP) and Nile Equatorial Lakes sub-basins (NELSAP). The Regional Agricultural Trade & Productivity (RATP) Project of NELSAP is a technical assistance project financed by Canadian International Development Agency (CIDA) through a recipient-executed trust fund.

The RATP conducted a study, in collaboration with a consortium of various international and national experts, entitled: "Assessment of the Irrigation Potential in Burundi, Eastern DR Congo, Kenya, Rwanda, South Sudan, Tanzania and Uganda". The study took place from February 2011 to August 2012. Results of the study are presented in this Report (including seven Appendixes and a large database). The study was setup as a "preparation for a development program" and "pre-feasibility", and has therefore a strategic perspective. Results of this study can support more detailed feasibility studies that will subsequently lead to a detailed design phase and implementation if resources can be secured.

The current study has some unique features that can be summarized as: (i) similar methodology applied to all countries, (ii) combining quantitative and qualitative information, (iii) high spatial resolution, (iv) daily-monthly approach, (v) use of innovative and advanced analysis tools, and (vi) downscaling to small scale areas. Rather than presenting results in terms of suitable and non-suitable to develop irrigation, the current study expresses the suitability between 0% and 100%, where 0% reflects locations with major restrictions and 100% indicates no restriction at all. Moreover, the overall strength of the current study in the context of strategic planning is that a uniform methodology has been used over the entire area and that all relevant determining factors for irrigation potential have been integrated, while maintaining the information on the specific limiting factors.

The study was undertaken in three phases. During the Inception Phase agreements on methodologies and data were made. Phase 1 focused on assessing the irrigation potential of the study area (six entire countries and for DR Congo only areas located within the Nile Basin) using a combination of advanced and innovative quantitative techniques (remote sensing, modeling tools, data mining) combined with qualitative information. Results of Phase 1 were used to support the selection of the so-called focal areas. A total of 34 focal-areas were agreed upon with stakeholders and during Phase 2 a more in-depth analysis of these areas was undertaken, given the resource limit of about three days per focal area.

The irrigation potential for the entire study area is about 51 million ha. Suitable areas are quite well distributed over the seven countries. One of the main features of the current study is that the suitability is expressed between 0% and 100%, and that for each location a clear indication is given whether limitations are in terrain, soils, water availability, socio-economics and/or accessibility. Results per country include also semi-quantitative and qualitative aspects such as: Millennium Development Goals, poverty reduction strategies, legal aspects, socio-economic contexts, institutional settings, yield gap analysis and potential cropping patterns, environmental aspects, population displacements, upstream-downstream impacts and water treaty agreements.

Results for the seven individual countries are presented in the Annexes to this report and show that in each country suitable (classes >60%) and very suitable (classes >70%) areas can be found. For the more mountainous countries the total suitable area is somewhat lower and suitability includes also small-scale hill-side irrigation. For other countries options for larger scale irrigation exists, although the size of the selected focal areas was limited to a few thousands hectares according to the objectives of the study.

Obviously, a study encompasses such a large area and topics cannot cover all minor details and aspects. Therefore, based on the country results 34 so-called focal areas were selected where more detailed analyses are undertaken. The overall result is that all focal areas have a clear scope to develop irrigation. Initial investments range from about 5 million US$ up to 60 million US$, while Internal Rate of Returns vary quite substantial with averages between 10% and 25% (although also some negative as well as some very high IRRs can be found) . Important to note is that the IRRs depend very much on the expected crop choice, crop yields and prices which are very local specific and have large uncertainties. Equally important is the relevance for people living in the area if irrigation would be developed. The details for each focal area provide full insight in the physical, economic, and social dimensions of the specific focal area and its potential to develop irrigation. Results should be considered as indicative rather than prescriptive given the nature of the study (pre-feasibility).

A clear set of conclusions and recommendations can be given based on the study:

- Expansion of irrigation should be seriously considered in the seven countries given concerns about food security and poverty alleviation. The study shows that the potential to develop irrigation are plentiful in the region.
- Detailed maps are produced for each country not only showing the potential areas, but also flagging what the limitations are.
- The current study is unique as one uniform methodology is applied and that innovative quantitative methods are combined with qualitative information. Moreover, the study used a very high spatial resolution over vast areas and encompassed as well 34 small so-called focal areas.
- The impact of development of irrigation on downstream areas is relatively low. Even in the unlikely event that all the 34 focal areas would be actually broad under irrigation, annual flows in the Nile will be reduced by about 1%.
- The current study has a strategic perspective and is categorized as “preparation for a development program”. Potential investors might select one or more focal areas for a

feasibility study and, in case of positive outcome, move to a detailed design phase and implementation.

- A concrete way forward using the current study is:
    - (i) distribute study results amongst a wide-range of stakeholders such as governments at national and regional level, NBI, potential investors (either private, governments or donors), agricultural organizations, local decision makers and scientists;
    - (ii) organize per country a workshop with the objective to secure resources for one or more feasibility studies and simultaneously prepare mobilization of funds for implementation;
    - (iii) undertake the feasibility studies using results of the current study and focus on strengths and limitations as flagged in the current study;
    - (iv) if successful, detailed design and implementation can be realized.

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1 Introduction

1.1 Relevance

1.1.1 Irrigation and Food Security

Irrigation carries significant potential to increase agricultural productivity. Continued concern over food security in Africa and a persistent agricultural productivity lag behind other regions have refocused attention on the importance of key investments in the African agricultural sector. Irrigation is an investment that has been promoted persistently by donors, research analysts, and scientists within the international agricultural development community to address that lag. Irrigation plays an important role in stabilizing yields in the face of climatic variability, which has increased notably in recent times and is projected to increase further under almost all future climate change scenarios. In addition, much of Africa is expected to experience reduced annual precipitation, which would, along with higher temperatures, enhance the potential productivity-enhancing effects of irrigation. (Svendsen et al., 2009)

1.1.2 Nile Basin Initiative

The Nile Basin Initiative (NBI) is a partnership of the riparian states that seeks to develop the river in a cooperative manner, share substantial socioeconomic benefits, and promote regional peace and security through its shared vision of “sustainable socioeconomic development through the equitable utilization of, and benefit from, the common Nile Basin water resources”. NBI’s Strategic Action Program is made up of the Shared Vision Program (SVP) and Subsidiary Action Programs (SAPs). The SAPs are mandated to initiate concrete investments and action on the ground in the Eastern Nile (ENSAP) and Nile Equatorial Lakes sub-basins (NELSAP). This study falls under NELSAP.

1.1.3 The Nile Equatorial Lakes Subsidiary Action Program (NELSAP)

The Nile Equatorial Lakes Subsidiary Action Program has its Coordination Unit (CU) based in Kigali, Rwanda and reports to the Nile Equatorial Lakes Technical Advisory Committee (NELTAC) and the NBI Secretariat for strategic guidance. The NELTAC reports to the Nile Equatorial Lakes Council of Ministers (NELCOM). The Nile Basin Initiative (NBI) through the Nile Equatorial Lake Subsidiary Action Program (NELSAP) seeks to promote a productive water use in Nile basin agriculture.

The NELSAP through its sub basin programs implements pre-investment programs in the areas of power trade and development and natural resources management. The NELSAP-CU in partnership with the countries carries out selected preparatory initiatives that have trans-boundary implications and helps the countries to mobilize resources for project development including planning, data collection, surveys and feasibility studies. Pre-investment programs comprise specific studies of the various users of the water resources, formulation of options for water resources development taking in to account various intervening factors and users, identification of specific water resources developments integrating options, preliminary design of each project, cost benefit evaluation, preliminary Environmental Impact Assessment, comparative studies based on technical, socio-economic and environmental criteria, selection of priority projects and comparison with other sectoral possibilities. Within the pre-investment framework, the Regional Agricultural Trade and Productivity (RATP) Project, in concert with the NELSAP, will promote irrigation development as a contribution towards agricultural development in the NEL countries[1].

1.1.4 Regional Agricultural Trade & Productivity (RATP) Project

RATP is a technical assistance project financed by Canadian International Development Agency (CIDA) through a recipient-executed trust fund. The project is managed by a Project Management Unit (PMU) based in Bujumbura-Burundi, and is administratively linked to the NBI's Subsidiary Action Program for the Nile Equatorial Lakes (NELSAP), which has a coordinating unit (NELSAP-CU) based in Kigali. Although the activities of the proposed project focus on the Nile Equatorial Lakes sub-basin area, it supports generation of agricultural knowledge that is basin-wide, in line with the aims of the NBI's Institutional Strengthening Project (ISP) and NELSAP's Subsidiary Action Program.

1.2 Review of previous studies

A substantial amount of studies focusing on the Nile has been undertaken over the last centuries. In the scientific literature alone, over half a million publications can be found related to the Nile (Google Scholar, 14-Mar-2011). Beside these scientific studies hundreds to thousands other non-scientific literature and publications are written related to the River Nile. Using the search term River Nile in Google resulted in over five million pages found (Google, 14-Mar-2011).

This review section of the report is not meant to provide an inclusive summary of all publications related to the Nile. The focus of this section is to give an overview of the most relevant publications and studies in the context of the current project. A distinction is made between irrigated related studies, and other relevant studies. Country specific studies are described in the seven country appendixes.

1.2.1 Irrigation related studies

Döll, P. and S. Siebert. (2002) Global modeling of irrigation water requirements. Water Resources Research, Vol. 38, No. 4:

Worldwide almost 90% of the water consumption is used for irrigation purpose. With a rapidly increasing population it can be questioned whether enough water will be available to increase the food production accordingly. The study aims to give a global view, at a relatively detailed scale (0.5º by 0.5º), of the irrigation water requirements. For this reason the current distribution of irrigated land was modelled first. As there was not sufficient information available on what

[1] NEL countries refers to Nile Equatorial Lake countries: the seven countries included in this study.

crops are grown under irrigated conditions where and when, the cropping patterns and the growing seasons were also simulated by the model, based on soil suitability and climate. Furthermore, a distinction was made between only two crop types, rice and no rice.

FAO 1997 – irrigation potential in Africa, a basin approach:

There is a growing concern about the food security in sub Saharan Africa as the import of cereals is projected to triple from 1990 to 2020. Africa is (apart from Australia) the driest continent in the world, with a highly unstable rainfall regime. Droughts are frequent, which put more people at risk each year. Agricultural productivity has not been able to keep up with the population growth. As the cultivated land can hardly be increased the solution should be to increase the yields. The irrigated area of 8.5% of the cultivated area is far beneath the world average of 17%. In the areas where irrigation is most needed the water is getting scarce due to population growth, urbanization, and industrialization. The study concentrates on the quantitative assessment based on physical criteria.

Definition of irrigation potential

The study referred to irrigation as the process by which water is diverted from a river or pumped from a well and used for the purpose of agricultural production. Areas under irrigation thus include areas equipped for full and partial control irrigation, spate irrigation areas, equipped wetland and inland valley bottoms, irrespective of their size or management type. It does not consider techniques related to on-farm water conservation like water harvesting.

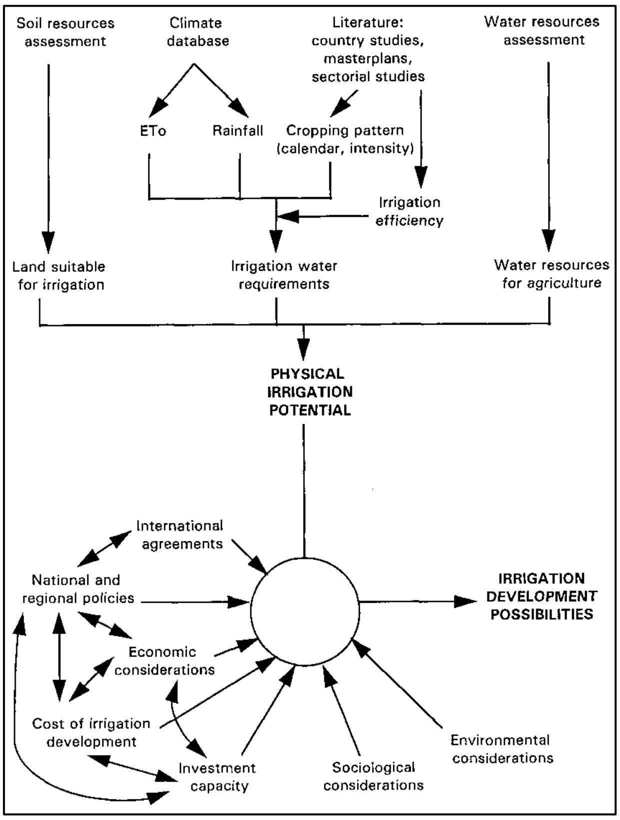


Figure 1: Assessment of irrigation potential.

Methodology

The FAO study was carried out per river basin. Criteria were defined to determine the physical resources (Figure 1). The type of irrigation was set on surface irrigation. Annual renewable water resources were calculated per country mainly based on surface water. Non-renewable water resources were not taken into account. Assessment of the irrigation potential, based on soil and water resources, can only be done by simultaneously assessing the irrigation water requirements, which in turn depend on the cropping pattern and climate. For this reason, irrigation cropping pattern zones were defined for current and potential scenarios and (net and gross) water requirements were computed. Although the physical resources were the main concern of the study, it is acknowledged that economic, political, social and environmental issues were essential for a holistic view. The study highlighted the most important environmental issues related to irrigation.

Soil and terrain suitability for surface irrigation

Two land use types were considered, the upland crops and rice under irrigation. In case the soil was suitable for both; priority was given to rice. The following characteristics were used to assess the soil quality: topography, drainage, texture, surface and subsurface stoniness, depth, calcium carbonate level, gypsum status, salinity and alkalinity conditions (Table 1).

Table 1: Soil and terrain suitability for surface irrigation by country.[2]

Country	Total area of the country (ha)	Soil suitable for irrigation of rice (ha)	Soil suitable for irrigation of upland crops (ha)	Total area of soils suitable for surface irrigation (ha)	As % of total area of country(5/2)* 100
BURUNDI	2 783 400	302 100	286 700	588 800	21
CONGO	34 200 000[3]	9 257 600	45 600	9 303 200	27
KENYA	58 037 000	11 405 600	5 979 100	17 384 700	30
RWANDA	2 634 000	220 600	80 300	300 900	11
SUDAN	250 581 000	66 955 100	1 814 100	68 769 200	27
TANZANIA	94 509 000	23 344 700	908 700	24 253 400	26
UGANDA	23 588 000	7 652 000	23 700	7 675 700	33
Total for Africa	3 029 020 800	511 998 900	84 961 100	596 960 000	20

Water resources

The water resources were only assessed on basin level in the FAO study, although the exchange of water through rivers was very important for some countries. The available information came from a multitude of sources so no reference period has been set. The internal renewable water resources and global renewable water resources were calculated. If no information was available, estimation was made by multiplying the precipitation by the runoff coefficient. Evaporation from open waters did have a significant influence on the water balance. This was considered as much as possible. The distribution of the water resources were not specified further than country level.

[2] Note that figures might vary from source to source and in this report the original numbers as published are presented.
[3] This is obviously wrong in the FAO report. Area of DRC is 234,540,900 ha.

Irrigation water requirements (IWR)

By dividing the available water by the gross irrigation water requirement the maximum irrigated area was calculated. Because of the scale, assumptions had to be made on the definition of areas to be considered homogeneous in terms of rainfall, potential evapotranspiration, cropping pattern, cropping intensity and irrigation efficiency. First the major irrigation cropping patterns were delineated. Second the climatic zones were defined, based on climate stations. The combination of the cropping zones with the climate zones resulted in 1437 areas, homogeneous in irrigation cropping characteristics and climate. The model to calculate the Nett IWR was run for three scenarios and divided by the efficiency to calculate the Gross IWR. The influence of selecting cropping pattern zones and the estimations used for cropping intensity and irrigation efficiencies are of prime importance for the final results. The potential efficiency and the net and gross irrigation water requirement per area have been listed in a table.

Results Nile basin

A review has been given per river basin. This review describes the hydrological situation, the water resources, and the irrigation potential. Table 2 gives a quick insight. The complete review is available at the following link: http://www.fao.org/docrep/w4347e/w4347e0k.htm#the nile basin. It is evident that the figures for some countries of this table are not accurate.

Country area within the Nile basin	Irrigation potential	Gross irrigation water requirement		Actual flows		Flows after deduction for irrigation and losses		Area already under irrigation
		per ha	total	inflow	outflow	inflow	outflow	
	(ha)	(m^3/ha.year)	(km^3/yr)	(km^3/yr)	(km^3/yr)	(km^3/yr)	(km^3/yr)	(ha)
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*	*(8)*
Burundi	80 000	13 000	1.04	0.00	1.50	0.00	0.46	0
Rwanda	150 000	12 500	1.88	1.50	7.00	0.46	4.09	2 000
Tanzania	30 000	11 000	0.33	7.00	10.70	4.09	7.46	10 000
Kenya	180 000	8 500	1.53	0.00	8.40	0.00	6.87	6 000
Zaire	10 000	10 000	0.10	0.00	1.50	0.00	1.40	0
Uganda	202 000	8 000	1.62	28.70	37.00	23.83	30.51	9 120
Ethiopia	2 220 000	9 000	19.98	0.00	80.10	0.00	60.12	23 160
Eritrea	150 000	11 000	1.65	0.00	2.20	0.00	0.55	15 124
Sudan	2 750 000	14 000	38.50	117.10	55.50	90.63	31.13	1 935 200
Egypt	4 420 000	13 000	57.46	55.50	rest to sea	31.13	minus26.33	3 078 000
Sum of countries	10 192 000		124.08					5 078 604
Total for Nile basin	< 8 000 000							

Table 2: Nile basin, irrigation potential, water requirements, water availability and areas under irrigation (source: FAO, 1997).

Environmental and socio economic considerations

The FAO study concluded that irrigation has contributed to poverty alleviation and food security, but the sustainability of irrigated agriculture was questioned, both economically and environmentally. To ensure a sustainable project, funds for maintenance should be available, and the project should be environmental and social embedded. Large scale irrigation project can change the hydrological situation, which may cause groundwater level decline, reduced downstream water supply, pollution, erosion, waterlogging, salinization and increased nutrient levels. Water-related diseases which are commonly associated with the introduction of irrigation should be considered as well. The construction of an irrigation scheme could have numerous of social impacts, which have to be considered in terms of equity, ownership and poverty to develop a sustainable area. Climate fluctuations may influence the possibilities for irrigation development. In the study this is not taken into account. In regions where the irrigation is most important for agriculture, between 60% and 100% of the potential is already irrigated. Most of the potential is located in humid areas. It is estimated that over 50% from the current irrigation schemes need rehabilitation if they are to be managed to the maximum of their potential.

FAO Aquastat survey (2005) Irrigation in Africa in figures:

The comprehensive FAO report presented the most recent information available, up to 2005, on water availability and its use on the African continent, with an emphasis on agricultural water use and management. It analysed the changes that occurred since the first survey in 1995. Many terms related to water and irrigation were defined.

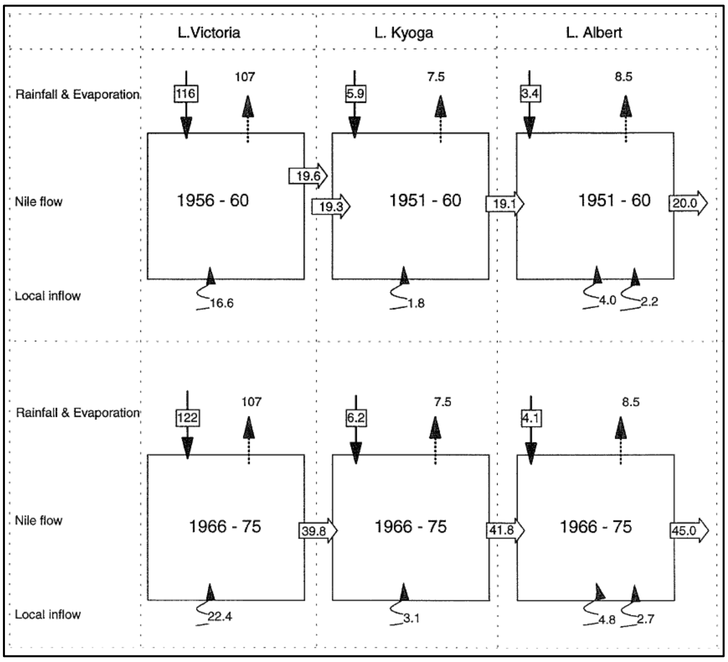


Figure 2: Schematic balance of Lake Victoria, Kyoga, and Albert (km^3/year) (Source: Sutcliffe and Parks, 1999).

Sutcliffe, J. V., Y. P. Parks. (1999) The hydrology of the Nile. IAHS Special Publication 5:

Compared to the size of the Nile basin the total flow is relatively small. Higher precipitation is associated with mountainous areas. The furthest tributary to the Nile is the Kagera, which drains the mountain areas of Burundi and Rwanda, as well as for Uganda and Tanzania, into Lake Victoria. A number of tributaries drain the forested escarpment to the northeast of the lake. Other less productive water courses drain the plains of the Serengeti to the southeast of the lake and the swamps of Uganda to the northwest. From Lake Victoria the flow continues towards the north, and reaches Lake Kyoga. This lake is essentially a grass-filled valley. Trough swamps the Kyoga Nile flows towards the west into Lake Albert. The lake also receives the inflow of the river Semliki, draining Lake Edward, Ruwenzori and other mountains. The Albert Nile leaves the lake at its northern end and flows towards Juba and Mongalla. In the reach between Lake Albert and Mongalla the river receives seasonal runoff from a number of streams known as the torrents; these provide the high flows of the river following the single rainfall season. Within the Sudd the higher flows spill from the main channel into swamps and seasonally flooded areas. Evaporation from the flooded areas greatly exceeds rainfall. The effect of this spilling is that the outflow from the swamp is only about half the inflow and has little seasonal variation. At Lake No[4] the Bahr el Jebel turns east and becomes the White Nile, and the Bahr el Ghazal flows into the lake from the west. The Bahr el Ghazal basin is relatively large and has the highest rainfall of any basin within the Sudan. However, the flows of the various tributaries of the Bahr el Ghazal are spilled into seasonal and permanent swamps, and virtually no flow reaches the White Nile. The research describes the hydrological situation for every river section, lake or contributory. Possibilities to increase river flow are discussed. Examples include the Jonglei canal, and measures to reduce evaporation from the swamps.

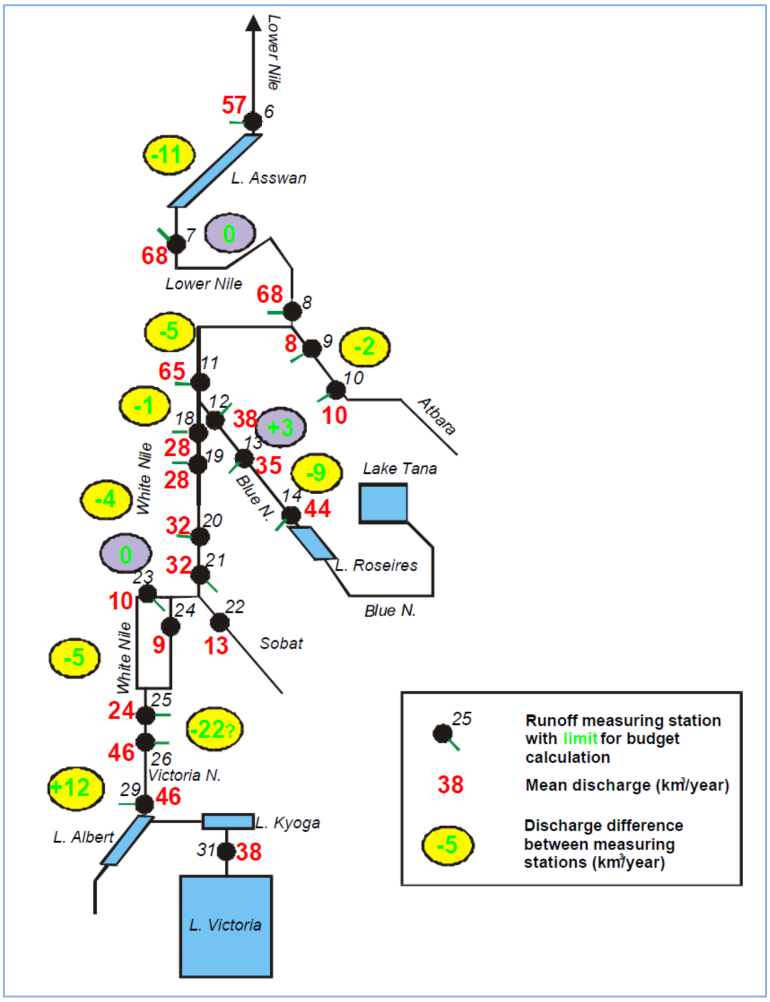


Figure 3: Observed flows in Nile basin (Source: Sutcliffe and Parks, 1999).

You, L. et al (2010) – What is the irrigation potential for Africa? A Combined Biophysical and Socioeconomic Approach. IFPRI discussion paper 00993:

Although irrigation in Africa has the potential to boost agricultural productivities by at least 50%, 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% 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 a key to ending poverty on the continent. Many development organizations have recently proposed to significantly increase investments

[4] This is no spelling error: Lake No is located at the confluence of the Bahr al Jabal and Bahr el Ghazal

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 analyses 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.

Food production in the Nile basin is almost entirely rain fed. Although the water resources are ample the variability is high, and the water is spread over a wide range of agro-ecologic zones. Due to irrigation the yield can easily double compared to rainfed agriculture. For this reason irrigation is considered a main cornerstone for agricultural development and rural poverty reduction. About three percent of the cultivated area is equipped for irrigation, which is about 11% of the irrigation potential for the NEL countries.

The IFPRI study was carried out in five steps:

1. The assessment of the production geography, existing and potential performance of irrigated agriculture is done with the SPAM model.
2. Calculation of the potential runoff that could be used for small-scale irrigation. Attention has been paid to the interaction between crop water needs, rainfall during the cropping season, and excess rainfall throughout the year. These factors determine the potential for yield increases. Calculated with a hydraulic model.
3. Identification of the potentially irrigable areas and associated water delivery costs. All dam and potential dams are mapped, as they assume 30% of dam storage available for large scale irrigation purpose. Rehabilitation of existing dams could play an important role for irrigation. The identification of irrigable areas is based on geographical issues, rather than physical aspects. Assumed is that small scale irrigation does not have any delivery costs[5]. The cost for large scale irrigation, combined with water storage is calculated.
4. The annual net revenue due to irrigation expansion is maximized across potential areas and crops. The experience with irrigation is taken into account together with the investment potential for each country.
5. The internal rates of return (IRRs) to irrigation are calculated. These results show that the IRR is quite high (7%) in Kenya and probably Sudan, for the other NEL countries this number is much lower at about 2%.

The mainly economic report tries to give a better understanding of the conditions under which irrigation investments will yield their full potential. According to the study 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. The investments can be based on pure economic considerations, such as maximizing yields and profits. Another approach could be to secure food to all countries, or to limit the area for instance by targeting the poorer regions. Investment decisions seldom depend on physical or economic criteria alone. Other non-irrigation related factors, like policies, drinking water, energy, rural development or donor suggestion may play an important role. Furthermore, irrigation is one of more productivity improving measures. Other measures include fertilizer use, advanced seed delivery systems, postharvest processing facilities, and access to markets.

[5] There are questions whether this reported statement is correct.

1.2.2 Other relevant studies

Allen, Richard G. et al. Crop Evapotranspiration (guidelines for computing crop water requirements) FAO Irrigation and Drainage Paper No. 56:

The study provided a methodology to calculate the reference evapotranspiration in a more accurate manner as has been done since the publication of FAO Irrigation and Drainage Paper No. 24 in 1977.

Beyene, T., D. P. Lettenmaier and P. Kabat. (2007) Hydrologic Impacts of Climate Change on the Nile River Basin: Implications of the 2007 IPCC Climate Scenarios:

A multi-model ensemble method was used to asses climate change inducted changes in hydrology, for the IPCC’s A2 and B1 scenarios. Precipitation is expected to increase up to 117% till 2040 compared to 1950-1999, and from 2040-2100 the average will be below 100% of the reference period.

Camberlin, P. (1996) Rainfall Anomalies in the Source Region of the Nile and Their Connection with the Indian Summer Monsoon. Journal of Climate Volume 10:

The author examined both the inter-annual and intra-seasonal variability of the July–September rains and compares them to the Indian summer monsoon. Analysis indicated that a direct statistical link exists between monsoon variations in these two regions, independent of the Southern Oscillation.

Camberlin, P. (2009) Nile Basin Climates:

The climate was characterized by a gradual transition between the dry north of Sudan and the increased monsoon precipitation south in the Nile basin. The inter-annual climate variation was strong, but is only indirect influenced by El-Nino. Furthermore, the NEL region can be characterized by the occasional very wet years. (e.g. 1961, 1997).

Conway, D. and M. Hulme (1993) Recent fluctuations in precipitation and runoff over the Nile Sub-basins and their impact on main Nile discharge. Climatic Change 25:

Substantial fluctuations in precipitation and runoff have occurred over the Nile Basin in recent decades. Ten-year mean flows of the Blue Nile (Khartoum gauge) during the 20th century have ranged from 42.2 to 56.7 km^3 and for the White Nile (Malakal gauge) from 25.5 to 36.9 km^3. These fluctuations have been responsible for changes in decade-mean Main Nile discharge of up to ± 20% which have had important consequences for water resource management in both Egypt and Sudan.

FAO (2003) Review of world water resources by country. Water Reports 23:

This review, based on climate and hydrological data sets, of the renewable resources per country presented an overview of the physical internal and external water resources in the current situation. An attempt was made to estimate the exploitable water resources per country.

Inocencio, A. et al. (2005) Costs and Performance of Irrigation Projects: A Comparison of Sub-Saharan Africa and Other Developing Regions. IWMI research report 109:

This study aimed to establish systematically whether costs of irrigation projects in SSA were truly high, determine the factors influencing costs and performance, and recommend cost-reducing and performance-enhancing options. Among other recommendation special attention should be paid to the size of the irrigation schemes, the type of crops grown, the farmer's involvements and the integration of irrigation projects. The high failure rate of irrigation projects in SSA contributes to the fact that irrigation projects in SSA are more expensive than those in other developing regions.

Kay, M. (2001). Smallholder irrigation technology: Prospects for Sub-Saharan Africa:

Experience in sub-Saharan Africa had shown that successful smallholders generally use simple technologies and have secure water supplies over which they have full control. The most successful technologies are those that improve existing farming systems rather than those that introduce radically new ideas. Speeding up development does not necessarily mean building irrigation schemes faster but building many more of them. An important lesson learned over the past 20 years is that smallholder schemes develop through a slow incremental process of improvement, usually in response to farmer demand. Unfortunately this is at odds with the way in which most donor and government agencies work to specific time schedules.

Mohamed, Y. A., B. J. J. M. van den Hurk, H. H. G. Savenije, and W. G. M. Bastiaanssen. (2005) Hydroclimatology of the Nile: results from a regional climate model. Hydrol. Earth Syst. Sci. Discuss: 2:

A regional climate model was applied in order to reproduce the regional water cycle as close as possible. Observations on runoff, precipitation, evaporation and radiation were used to evaluate the model results.

Probst, J.L. and Y. Tardy. (1987) Long range streamflow and world continental runoff fluctuations since the beginning of this century. Journal of Hydrology, 94

Fifty major rivers, distributed all around the world, were selected and since the beginning of this century their mean annual discharge fluctuations have been studied by filtering methods. The global runoff has been fluctuating but as an average has only increased about 3% during the last 65 years (1910–1975). The humid years seem to be centred around 1915, 1927, 1950, 1960 and 1972. On the contrary, the dry periods seem to be located around 1920, 1940, 1955 and 1965.

Rosegrant, M.W. and N. D. Perez. (1997) Water resource development in Africa: a review and synthesis of issues, potentials, and strategies for the future. EDTP discussion paper no.28:

The literature review examined how water resources development and water policy reform could be deployed to address the twin problems of food insecurity and water scarcity in Africa. Agricultural water use accounts for approximately 85% of the water withdrawals municipal for 14% and industrial for 3%. The total makes up about 2.5% of the internal water resources in eastern Africa region. Several policy reforms can stimulate and contribute to efficient water (re)use.

Svendsen M., M. Ewing and S. Msangi. (2009) Measuring Irrigation Performance in Africa. IFPRI Discussion Paper 00894:

The study for Sub-Saharan Africa looked at six indicator categories —institutional framework, water resource use, irrigation area, irrigation technology, agricultural productivity, and poverty and food security — to assess the potential for improving performance in the agricultural food security sector through increasing irrigation sector investments. With these indicators a baseline was set to assess the improvements in the irrigation performance with extra investments. Average groundwater utilization in Sub-Saharan Africa was less than 20 percent of renewable supplies. Groundwater was considered as a resource particularly well suited for small-scale irrigation and for multiple-use systems.

Tate, E., J. Sutcliffe, D. Conway, F. Farquharson. (2004). Water balance of Lake Victoria: update to 2000 and climate change modelling to 2100. Hydrological Sciences 49:

Change in precipitation and to a lesser extent temperature over the Nile basin, could have serious consequences on regional water resources throughout the basin. To understand runoff the processes of precipitation and evapotranspiration should be understood first.

Taye, M. T., V. Ntegeka, N. P. Ogiramoi, and P. Willems (2011) Assessment of climate change impact on hydrological extremes in two source regions of the Nile River Basin. Hydrol. Earth Syst. Sci., 15.

The potential impact of climate change was investigated on the hydrological extremes of Nyando River and Lake Tana catchments, which are located in two source regions of the Nile River basin. The results reveal increasing mean runoff and extreme peak flows for Nyando catchment for the 2050s while unclear trend is observed for Lake Tana catchment for mean volumes and high/low flows. The unclear impact result for Lake Tana catchment implies that the GCM uncertainty is more important for explaining the unclear trend than the hydrological models uncertainty.

Yates, D. N., and K. M. Strzepek. (1998) Modeling the Nile basin under climate change. Journal of hydrologic engineering:

A monthly water balance model was used to assess the potential climate change impacts on Nile runoff. Almost all models gave a significant increased discharge for the NEL region.

You, L. et al. (2007) Generating Plausible crop distribution and performance maps for Sub-Saharan Africa using a spatially disaggregated data fusion and optimization approach. IFPRI discussion paper 00725.

Agricultural production statistics reported at country or sub-national geopolitical scales were used in a wide range of economic analyses, and spatially explicit (geo-referenced) production data are increasingly needed to support improved approaches to the planning and implementation of agricultural development. However, it was extremely challenging to compile and maintain collections of sub-national crop production data, particularly for poorer regions of the world. Using the modified spatial allocation model, a 5-minute (approximately 10-km) resolution grid maps for 20 major crops across Sub-Saharan Africa was generated The approach provided plausible results but also highlights the need for much more reliable input data for the region, especially with regard to sub-national production statistics.

1.2.3 Irrigation potential NEL countries[6]

Both **Burundi** and **Rwanda** are characterized by a rolling topography with a continuous pattern of hills and valleys, with lakes and marshy lowlands at the bottom of the valleys. Improving the drainage network in part of the swamp areas, combined where possible with an irrigation network, would allow year-round cultivation, which is important for these small, but very densely populated countries. The total area of these valley bottoms in the Nile basin is estimated at 105,000 ha for Burundi and 150,000 ha for Rwanda (FAO, 1997a).

In the Nile Basin part of **Tanzania** the irrigation potential has been estimated at 30,000 ha, but this would require the construction of considerable water conveyance works. In addition to this, at the beginning of the century settlers from Germany, the then colonial power in the country, proposed a plan to transfer water from Lake Victoria to the Vembere Plateau in the Manonga River basin in central Tanzania to irrigate between 88,000 and 230,000 ha of cotton. Though this project is still on the table, it would be very expensive. The transfer would be affected by gravity as the plateau lies below the water level of the lake (FAO, 1997a).

The Lake Victoria basin in **Kenya** covers only 8.5% of the total area of the country but it contains over 50% of the national freshwater resources. The national water master plan identified an irrigation potential of 180,000 ha based on 80% dependable flow. As part of the plan, dams and water transfers to other (sub) basins are proposed. At present only about 6,000 ha are irrigated. Moreover, in Kenya there has been lengthy debate as to whether, given adequate technology, Lake Victoria basin water should be transferred to arid areas of the country for irrigation. It is considered that perhaps the most appropriate location for such an experiment would be the Kerio Valley (located in the Rift Valley), for which a special development authority has been established by the Kenyan Parliament. The feasibility of such a project is a question of engineering and several observers consider it possible. Such an undertaking would use significant quantities of water (FAO, 1997a).

The Nile basin in **DRC** covers less than 1% of the area of the country. The area is hilly and does not really lend itself to irrigation. This area is rather densely populated with most people engaged in cattle rearing and fishery activities around Lake Albert. It is considered that about 10,000 ha could be developed for irrigation (FAO, 1997a).

[6] Summarized from FAO 1997

Uganda has large swamp areas covering about 700,000 ha. The irrigation potential is estimated at 202,000 ha, requiring, however, major works such as storage, river regulation and large-scale drainage. At present only 5,550 ha are irrigated (FAO, 1997a).

Irrigation potential in **Sudan** has been estimated at over 4.8 million hectares, but this figure does not take into consideration the available water resources. The irrigated area was about 1.6 million hectares in 1979 and 1.9 million hectares in 1990. There are plans to increase irrigation to about 2.8 million hectares by the year 2000, almost all to be irrigated by Nile water (FAO, 1997a).

2 Study Objectives, Area and Main Issues

2.1 Study objectives

With a rapid rate of population increase and high pressure on arable land, increased food production is one of the main concerns and priorities of the governments of the seven countries involved in the Irrigation Potential study. Improved irrigation technology and better water resources management have been suggested as mechanisms for increased production. One of the constraints identified is the reliance on rain fed agriculture as well as low mechanization.

The **goal** of the study is to ensure household food security, improve farmers' income and alleviate poverty through increase in agricultural production and productivity resulting from accessibility to irrigation water; and as such, it will contribute to NBI's overall objective of achieving sustainable socio economic development through equitable utilization of and benefits from the common Nile Basin water resource.

Within the NELSAP, planning for water use is carried out on the basis of river basins or sub basins. On the other hand, land use is usually computed or planned according to political boundaries. This study has therefore determined the irrigation potential of the proposed countries considering the physical resources of 'soil' and 'water', combined with the irrigation water requirements as determined by the cropping patterns and climate. This will inform the subsequent preparation process and resource mobilization for the preparation phase.

The **general objective** of this study is to assess the irrigation potential of seven Nile Countries (Burundi, Eastern DRC, Kenya, Rwanda, South Sudan, Tanzania and Uganda) in order to fill gaps in the NBI and member country information bases on agriculture water use. This assignment will be carried out under the RATP project, with the support of NELSAP and the Directorate of Irrigation in the Ministries in charge of Water and Irrigation in the seven countries.

The **specific objectives** of this study are to: (i) determine the irrigation potential of the proposed countries considering the physical resources of 'soil' and 'water', combined with the irrigation water requirements as determined by the cropping patterns and climate; (ii) provide a preliminary assessment of probable environmental and socioeconomic constraints to be considered to ensure sustainable use of physical resources within the Nile basin, as well as (iii) an indication of required resources for the preparation and investment phase. The study can be categorized as preparation for a development program.

2.2 Overview[7,8]

There is a fascination about the Nile River which has captured human imagination throughout history. Some five thousand years ago a great civilization emerged depending on the river and

[7] This section is derived from various sources and is included as generic background
[8] Numbers mentioned in this Report are all taken from existing references. Some inconsistency in numbers might therefore occur.

its annual flooding cycle. The Nile River Basin is probably one of the world's most famous river basins (Figure 4). The Nile is one of the world longest rivers, flowing south to north 6,850 kilometers, over 35 degrees of latitude. Its catchment basin covers approximately 10% of the African continent, with an area of about 3,100,000 km^2, and spreads over 10 countries (Table 4)[8].

The Nile is distinguished from other great rivers of the world by the fact that half of its course flows through countries with very limited effective rainfall (Table 3). Almost all the water of the Nile is generated on an area covering only 20 percent of the basin, while the remainder is in arid or semi-arid regions where the water supply is minimal and where evaporation and seepage losses are very large.

The shape of the Nile we know today is complex and is the result of the interconnection of several independent basins by rivers which developed during the last wet period which affected Africa after the retreat of the ice of the last glacial age, some 10,000 years ago. The basins which constitute part of the present river were disconnected, forming internal lakes. At times when the climate was wet, they overflowed their banks and became connected to other basins. At other times, when the climate was very dry, they ebbed, shrank into saline pools or dried altogether. The basins stand out in the longitudinal section of the river, as flat stretches or landings with very little slope, which are connected today with rivers, which have considerably steeper slopes (Sutcliffe, 2009).

The basin of the Nile is characterized by the existence of two mountainous plateaus rising some thousands of meters above mean sea level. The Equatorial or Lake Plateau in the southern part of the Nile basin (Figure 5), situated between the two branches of the Great Rift Valley, is at a level of 1,000 to 2,000 meters and has peaks of 5,100 and 4,300 meters. This plateau contains Lakes Victoria, George, Edward and Albert, which slope gently toward the north at an average rate of one meter for every 20 to 50 km of stretch. In contrast the rivers which connect these lakes fall at an average rate of one meter every kilometer or less of length.

The Ethiopian or Abyssinian Plateau, which forms the eastern part of the basin, has peaks rising to 3,500 meters. North of the Lake plateau the basin descends gradually to the Sudan plains where the Nile runs at altitudes lower than 500 m in its northerly direction. The enormous Sudd and Central Sudan basins extend for a distance of 1,800 km from Juba to Khartoum and form a gently sloping region with a small rate of slope of one meter for every 24 kilometers of stretch. About 200 km south of the Egyptian border the river cuts its channel in a narrow trough bounded from each side by the contour line of 200 m ground surface level. Almost 200 km before discharging into the sea, the river bifurcates and its two branches encompass the Nile Delta.

The basin of the present-day Nile can be divided into six major regions: the Lake Plateau, the Sudd, the White Nile, the Ethiopian Plateau, the Main Nile and the Nile Delta.

Table 3. World's Major River Systems[8]

River	Length (Km)	Drainage Area (10^3 Km^2)	Annual Discharge (10^9 m^3)	Discharge/unit area (10^3 m^3/Km^2)
Nile	6,850	3,110	84	28
Amazon	6,700	7,050	5518	728
Congo	4,700	3,820	1248	326
Mekong	4,200	795	470	590
Niger	4,100	2,274	177	78
Mississipi	970	3,270	562	170
Danube	2,900	816	206	252
Rhine	1,320	224	70	312
Zambezi	2,700	1,200	223	185

Source: UNEP, 2000.

Table 4. Countries in Nile Basin[9]

Country	Country Area[1] (km^2)	Area within the Nile Basin[2] (km^2)	% of the total Nile Basin Area	% of the country in the Nile Basin
Burundi	27,835	13,260	0.4	47.6
DR Congo	2,345,410	22,143	0.7	0.9
Egypt	1,001,450	326,751	10.5	32.6
Eritrea	121,320	24,921	0.8	20.5
Ethiopia	1,127,127	365,117	11.7	32.4
Kenya	582,650	46,229	1.5	7.9
Rwanda	26,340	19,876	0.7	75.5
Sudan	2,505,810	1,978,506	63.6	79.0
Tanzania	945,090	84,200	2.7	8.9
Uganda	236,040	231,366	7.4	98.0
Total	8,919,072	3,112,369	100.0	34.9

[1]*Source: CIA World Factbook, 1999.*
[2]*Source: FAO, 199a7.*

[9] Note that figures might vary slightly from source to source and here the original numbers are presented.

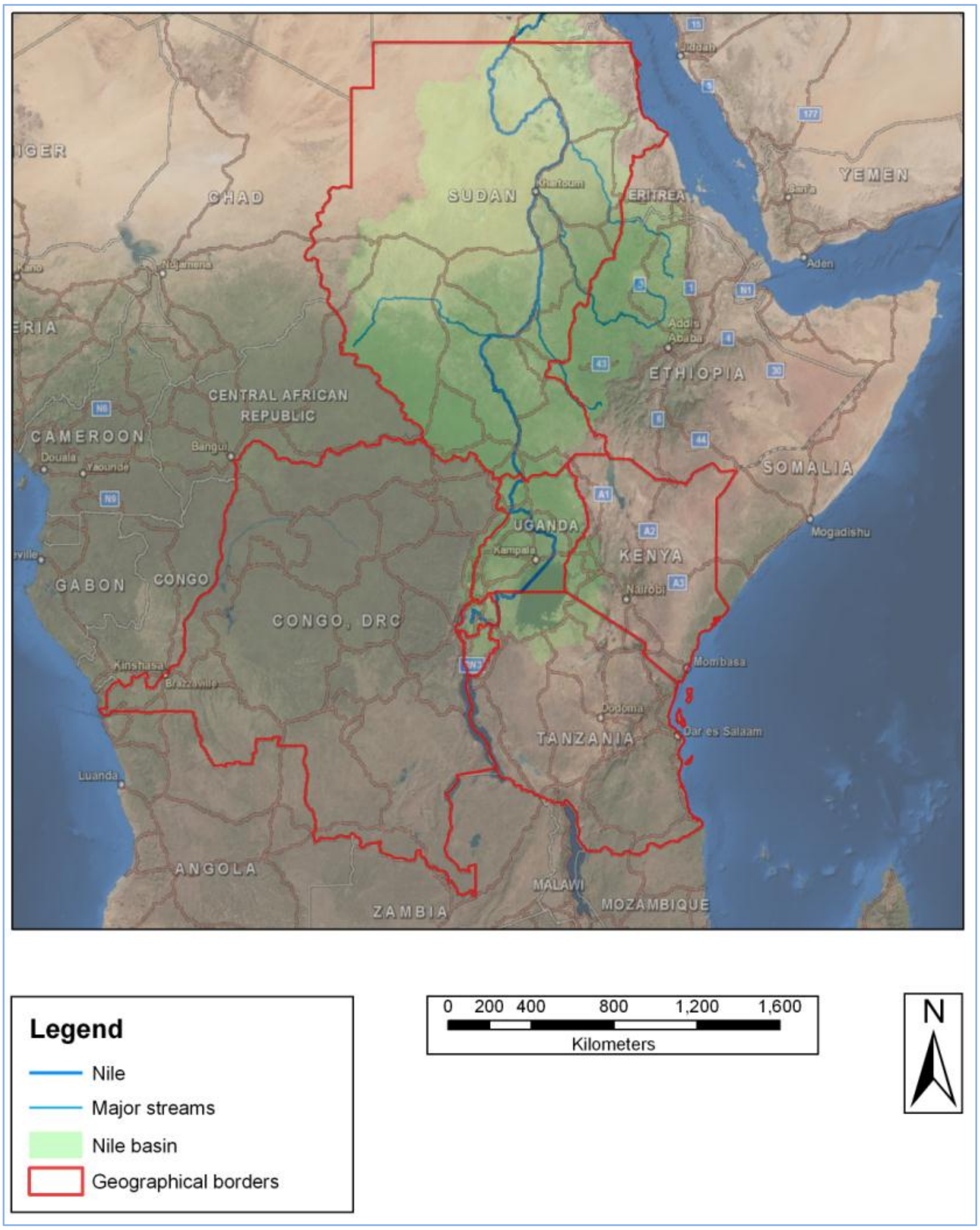


Figure 4: Overview Nile Basin.

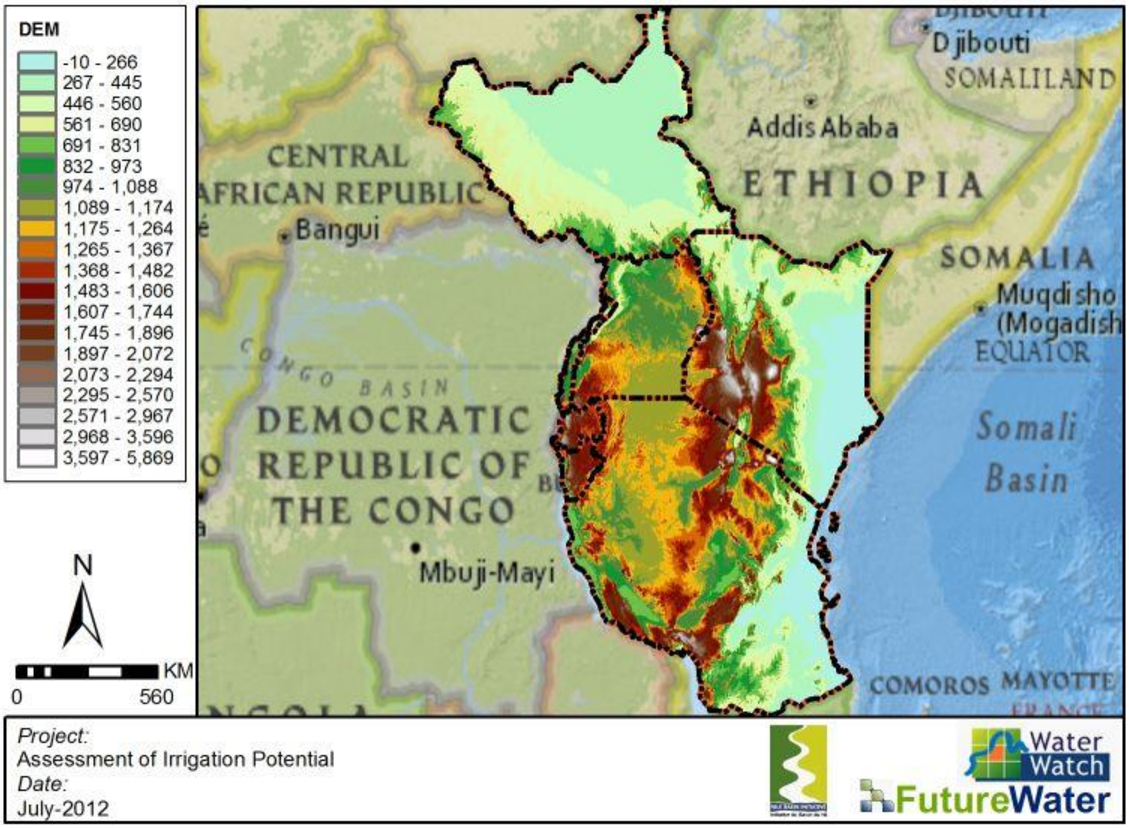


Figure 5: Overview study area and digital elevation. (Source: ASTER)

Figure 6: Sub-basins in NELarea. (Source: NBI)

3 Methodology and Tools

3.1 Introduction

The overall study aim is to provide a perspective strategy to support policy and decision making and can therefore be categorized as “preparation for development programs” or as “pre-feasability”. The study has followed a two stage approach where Phase 1 resulted in a unique overview of the irrigation potential of the seven Nile Equatorial Lake (NEL) countries. The study is unique since: (i) similar methodology applied to all countries, (ii) quantitative and qualitative aspects are included, (iii) high spatial resolution is used, (iv) monthly approach and (v) integrations of all irrigation potential determining aspects.

This Chapter will focus on the methodological approach used in this study to assess the potential for irrigation in the seven NEL countries. The Work Program was divided into two distinct phases. During the first phase focus was on all the physical components of the assessment and will be undertaken at an intermediate level of detail. During this phase also preliminary analysis on potential crop yields, socio-economic and policy issues were studied. During the second phase 34 so-called focal areas were studied using a mixture of physical analysis and taken into consideration environmental, institutional and legal frameworks.

3.2 Land suitability assessment

3.2.1 Current land productivity

An important characteristic and component, often ignored in irrigation potential studies, is the current land productivity. Current land productivity is a very good proxy of all integrated features like soils, slopes, water, management, and vegetation. Especially in regions where rainfall is available during some months, these periods provide an overall picture of the potential of the region.

The current land productivity is quantified using the NDVI, which stands for Normalized Difference Vegetation Index. The NDVI is derived using satellite imagery. The fraction of solar radiation which is reflected by a surface, instead of being absorbed, is called the albedo. The albedo of the earth’s surface partially determines the amount of available energy for heating and evaporation. Reflection of an object or surface is different for each wavelength in the electromagnetic spectrum. The average reflection for all wavelengths is the broadband albedo. A few different reflection profiles of typical surfaces are shown in Figure 7. Humans can only see the visible part of the electromagnetic spectrum, typically between 0.4 and 0.75 micrometer (µm). It can be seen from the profiles below that vegetation reflects little radiation in the visible part of the spectrum, making it appear relatively dark compared to for example (dry) bare soil.

Spectral profiles of reflectance clearly show distinct patterns for different surface types. Vegetation for example has a low reflection in the red part (+/- 0.65 µm), but high in the near-infrared part of the spectrum (+/- 0.86 µm). This can be explained by examining the process of photosynthesis taking place in vegetation. During this process, radiation is used to convert CO_2 to organic compounds like sugars, which are needed for growth. The amount of energy per photon decreases as the wavelength increases, leaving the incoming radiation from wavelengths of 0.75 micrometer and above of insufficient energy to be used in the photosynthetic process. Since it cannot be used for growth, absorbing the radiation would result in heating, and possibly damaging the tissue. It is therefore beneficial for plants to reflect as much radiation which cannot be used for growth, but absorbing all radiation which can be used, hence the steep slope in the reflection profile between red an infrared.

The difference between the near-infrared and red reflection can be used to detect photosynthetically active crops. This difference is often expressed as the Normalized Difference Vegetation Index (NDVI):

NDVI = (NIR – Red) / (NIR + Red)

Figure 8 shows a schematic example of the NDVI for lush and dry vegetation. While the equation of the NDVI has a theoretical range of -1.0 to 1.0, values for vegetation are usually found from 0.1 till 0.85. Negative values correspond with water pixels.

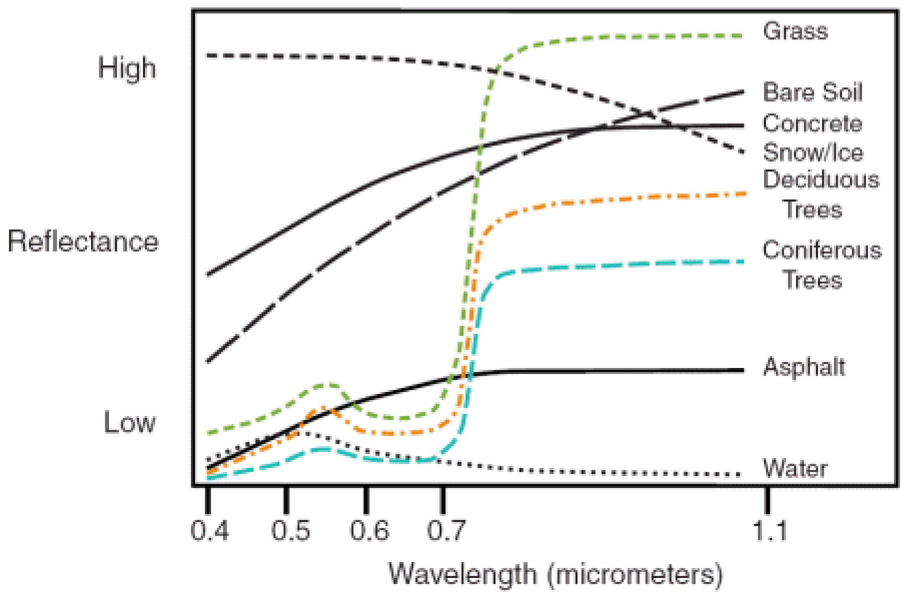
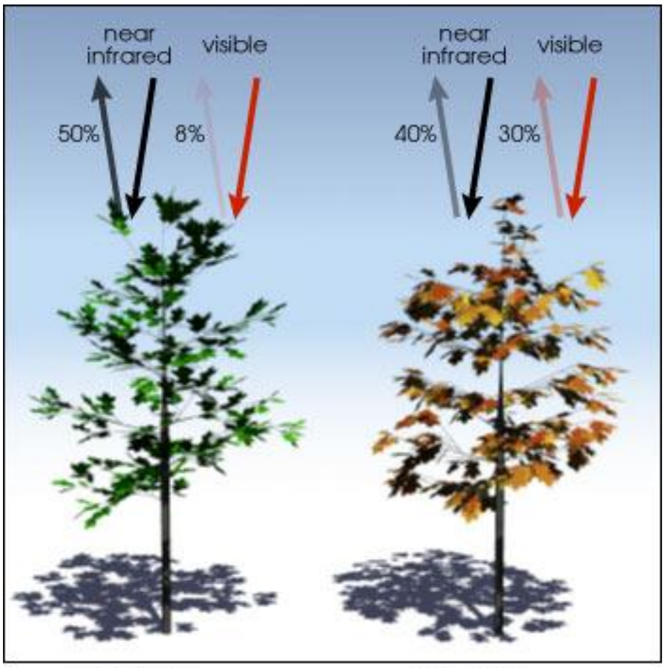


Figure 7: The amount of reflection by wavelength (source: www.NASA.gov accessed 8-2011).

The NDVI and albedo data used in this study come from the NASA MODIS products. NASA offers readily available products for both the NDVI (MOD13Q1 and MYD13Q1) and albedo (MCD43A2 and MCD43A3) through the Distributed Active Archive Centers (DAACs). These centers process, archive, document, and distribute data from NASA’s past and current research satellites and field programs. The NDVI and albedo products are composites of several atmospherically corrected radiance images. There is a new albedo composite image (plus quality information) every eight days. For the NDVI there is a new composite (plus quality) image every sixteen days for each sensor (Aqua MYD + Terra MOD). The NDVI series for both sensors have a temporal shift of eight days compared to each other, so for the NDVI there is as

well an image every eight days. More information about the MODIS products used can be found on this website: https://lpdaac.usgs.gov/lpdaac/products/modis_products_table.
For the NDVI the MOD13Q1 and MYD13Q1 products are merged together to create a smooth NDVI profile with a higher temporal resolution than the individual products. For the albedo the already combined MCD43A3 product is used. For this project the 8-days NDVI and albedo composites have been translated into monthly composites for the assessment of land productivity.



$$\frac{(0.50 - 0.08)}{(0.50 + 0.08)} = 0.72 \qquad \frac{(0.4 - 0.30)}{(0.4 + 0.30)} = 0.14$$

Figure 8. Schematic example of the NDVI for lush and dry vegetation (Source: www.NASA.gov accessed 8-2011).

Based on a representative year we derive two maps that are used in the assessment of land productivity: the average NDVI and the monthly coefficient of variation. The rationale behind this is that areas with healthy natural vegetation with limited monthly variation are most suitable for irrigation development. For an average climate year (2010) twelve monthly NDVI images are derived using the approach above. First the average annual NDVI and standard deviation based on the twelve monthly images are calculated. The monthly average coefficient of variation is then determined by dividing the standard deviation by the average NDVI. Subsequently the average NDVI and is scaled between 0 and 100 where we assume that pixels with an average NDVI lower than 0.2 are unsuitable (0) and higher than 0.6 (100) are perfectly suitable for irrigation development. For the coefficient of variation we assume pixels with a CV higher than 50% to be unsuitable (0) and areas with a CV equal to 0 to be perfectly suitable (100). The final land productivity potential map is the product of the two scaled maps.

3.2.2 Terrain suitability evaluation

A better use of land and water resources by the development of irrigation facilities could lead to substantial increases in food production in many parts of the world. The process whereby the suitability of land for specific uses such as irrigated agriculture is assessed is called land evaluation.

Land evaluation provides information and recommendations for deciding 'Which crops to grow where' and related questions. Land evaluation is the selection of suitable land, and suitable cropping, irrigation and management alternatives that are physically and financially practicable and economically viable. The main product of land evaluation investigations is a land classification that indicates the suitability of various kinds of land for specific land uses, usually depicted on maps with accompanying reports.

FAO has developed a framework for land suitability assessment in 1976 (FAO, 1976) and this approach has been tailored specifically towards irrigated agriculture (FAO, 1985). In this study a similar approach is followed as outlined in this chapter.

Similar to several other authors in this study a fuzzy approach instead of the Boolean approach first proposed by FAO (either suitable or not suitable) will be used (Burrough, 1989; Kalogirou, 2002). Each factor will be scaled between 0 and 100 and integrated into a final suitability maps for irrigated agriculture. All analyses are performed on a grid basis for the entire region at a spatial resolution of 250 meter.

The terrain slope is a key characteristic for assessing irrigation potential. Steeper slopes evidently are less suitable for irrigation. Different types of irrigation also have different associated slope suitability. We distinguish two different irrigation types in the suitability analysis: drip irrigation and border/furrow/sprinkler irrigation (Figure 9). Original slope classes were presented in 1988 by FAO and were updated later and used here (Green et al. 1996). It is assumed that drip irrigation may occur up to slopes of up to 20% and furrow, border and sprinkler types of irrigation require nearly flat surfaces and this is not possible on slopes steeper than 3%. Below these thresholds the suitability is linearly scaled.

A special case of irrigation is the sometimes called “hill-side irrigation”. In fact, this should not be considered as a specific case of irrigation as it refers to the application of regular irrigation on hill sides. This irrigation on hills (“hill-side irrigation”) is widely promoted in mainly especially Rwanda and Burundi. In Rwanda a few hundred hectares on hills are currently irrigated. For practical reasons we will use the term “hill-side irrigation” in this report, although it should be read as irrigation on hill-sides. Especially for hill-side irrigation access to power is important. This will be taken into consideration during Phase 2.

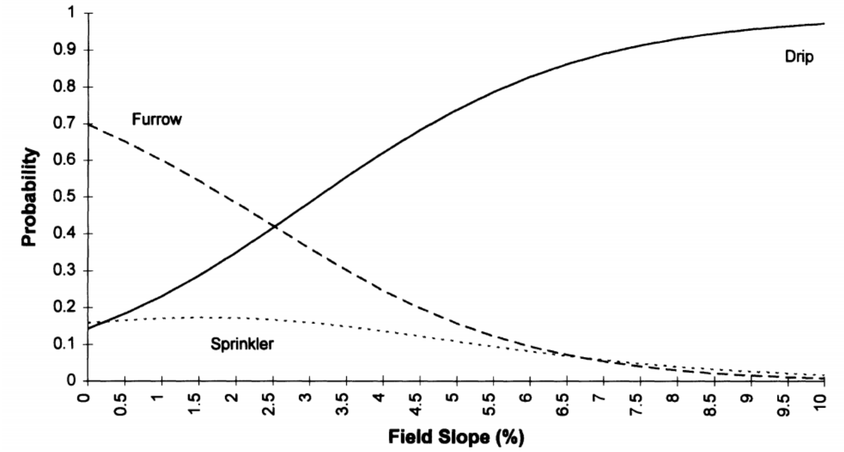


Figure 9: Irrigation methods used under a ranging slope.

3.2.3 Soil suitability assessment

The Harmonized World Soil Database (HWSD) is used to assess the soil qualities and suitability for irrigation. The Harmonized World Soil Database (HWSD) is considered as the best and most accurate available soil data set based on local soil inventories. Soil suitability for irrigation is based on six factors: (i) drainage classes and water logging, (ii) available water holding capacity, (iii) organic matter, (iv) texture, (v) pH and (vi) salinity. These factors have been assessed for the top soil (0-30cm) and the sub soil (30-100cm). Water logging is an important factor and reflected by the drainage classes. For paddy rice poorly drained soils are required, while for non-rice crops drainage should be good otherwise water logging will occur.

Each soil characteristic is assessed separately and finally combined in a soil suitability map based on the criteria as described by FAO (1985, 1996) and by IIASA. Given the quite different soils characteristics required for paddy rice compared to other crops, two different soil suitability maps have been be created. The classes which are used to assess each soil characteristic can be found in the following Tables.

Table 5. Conversion from values to suitability for organic carbon in top- and sub-soil.

Class	Non-Rice	Rice
< 0,2%	0%	0%
0,21 - 0,6 %	↓	↓
0,61 - 1,2 %	↓	↓
1,21 - 2,0 %	↓	↓
> 2,1 %	100%	100%

Table 6. Conversion from values to suitability for soil water holding capacity.

Class	Non-Rice	Rice
> 150 mm/m	100%	100%
125 - 150 mm/m	↑	↑
100 - 125 mm/m	↑	↑
75 - 100 mm/m	↑	↑
50 - 75 mm/m	↑	↑

15 - 50 mm/m	0%	0%
0 – 15 mm\m	N\A	N\A

Table 7. Conversion from values to suitability for drainage capacity.

Class	Non-Rice	Rice
Excessively drained (open water)	0%	0%
Somewhat excessively drained	0%	0%
Well drained	100%	50%
Moderately well drained	75%	50%
Somewhat poorly drained	50%	50%
Poorly drained	50%	100%
Very poorly drained	0%	50%

Table 8. Conversion from values to suitability for pH top- and sub-soil

Class pH	Non-Rice	Rice
<4	30%	30%
4 - 5.5	60%	60%
5.5 - 7.3	100%	100%
7.3 - 8.5	60%	60%
> 8.5	30%	30%

Table 9. Conversion from values to suitability for texture in top- and sub-soil.

Class	Non-Rice	Rice
No Data (open water)	-	-
Clay (heavy)	0%	100%
Silty clay		
Clay		
Silty clay loam		
Clay loam		
Silt		
Silt loam	100%	
Sandy clay		
loam		
Sandy clay loam		
Sandy loam		
Loamy sand		
Sand	0%	0%

Table 10. Conversion from values to suitability for salinity, CEC for top- and sub-soil

Class dS/m		Non-Rice	Rice
0	Non-saline / NoData	100%	100%
<0,7	Non-saline	100%	100%
0,7 – 2	Slightly saline	100%	100%
2 – 10	Moderatly saline	50%	50%
10 – 25	Highly saline	25%	25%
24 – 45	Verhy highly saline	0%	0%

3.3 Assessment of irrigation water requirements

3.3.1 Irrigation efficiencies

The amount of water needed during a growing season depends on the crop, yield goal, soil, temperature, solar radiation, and other bio-physical factors. In general, long-season crops require more water than short-season crops. Some crops benefit from irrigation during the entire season, while others are more sensitive during specific growing periods.

In general, the irrigation water requirements is determined using tools like FAO's CropWat or ClimWat, or software provided by many others. The overall approach is however based on the so-called FAO56 approach (Allen et al., 1998). However, with the advantage of satellites more and more location specific information is being used to assess water balances including, ETpot, ETact and ETshort. In this study we use the SEBAL/ETLook approach (Bastiaanssen et al., 1998) to assess the irrigation requirements, based on the following equations:

$$Irr_{req} = [(ET_{ref} * Kc_{irr} - ET_{act}) / Irr_{eff}$$

with

IRR_{req} = irrigation water requirement (mm/d)
ET_{ref} = reference evapotranspiration (mm/d)
Kc_{irr} = crop factor for irrigated agriculture (-)
Irr_{eff} = irrigation efficiency (-)
ET_{act} = actual evapotranspiration (mm/d)

During Phase 1 of the project a generic value for the Kc_{irr}. is taken based on FAO 56 (Allen et al. 1998) using the so-called dual crop coefficient. This approach consists of splitting Kc into two separate coefficients, one for crop transpiration, i.e., the basal crop coefficient (Kcb) and one for soil evaporation (Ke). This dual crop coefficient is especially important in areas where irrigation is mainly supplied as surface/border application. The Ke factor represents the evaporation from soil and standing water on the field. Based on FAO56 general values were used for Kc (1.1) and for Ke (0.1). Also, during Phase 1 of the project it is assumed that the irrigation efficiency is a function of the average efficiency of the three main irrigation systems:

Irrigation type	Area (%)	Efficiency (%)	Weighted
Surface	60	50	0.30
Sprinkler	20	70	0.14
Drip	20	80	0.16
Average efficiency			**60%**

3.3.2 ETLook

3.3.2.1 Introduction

ETLook is an algorithm developed by WaterWatch to compute the evapotranspiration of large areas on the basis of remote sensing data. ETLook has been developed in addition to the SEBAL algorithm. The SEBAL algorithm is less suitable for larger areas where differences in surface temperature cannot be explained alone by differences in the surface energy balance. Also, to avoid reliance on thermal infrared sensors that are sensitive to cloud free conditions, ETLook has been developed. Instead of using surface temperature as the main driving force for calculation of the surface energy balance, ETLook uses soil moisture derived from passive microwave sensors. Another distinguishing feature of ETLook is the possibility to separate between soil evaporation and crop transpiration. This is possible by solving the Penman-Monteith equation separately for canopy and soil.

ETLook can be run with varying spatial and temporal resolutions. Depending on the quality of the input data and available computer power, daily ETLook runs with a spatial resolution of 250 meter on continental scale are possible.

The ETLook algorithm uses soil moisture estimates from the passive microwave sensor AMSR-E[10] (Pelgrum et al., 2010). The advantage of using passive microwave sensor data is that its signal is not affected by clouds, which is the case for visible and thermal infrared images. Downscaling in ETLook is achieved by linking the soil moisture estimates from the AMSR-E sensor to a global soil map with known hydrological properties per soil type. The result is a topsoil estimate on the relative moisture content for smaller discrete areas. ETLook also uses moderate resolution (250m) visible and near infrared data from the MODIS sensor for determining surface albedo and vegetation cover (NDVI). Routine meteorological measurements (wind speed, air temperature, relative humidity and solar radiation) at a number of stations within the area are used to infer the meteorological conditions. Because the main driving force of the algorithm is soil moisture derived from passive microwave sensors, the algorithm is applicable under all weather conditions.

Figure 10 illustrates the main concepts of ETLook. A pixel is divided in two compartments: one for the canopy and one for the soil. They share the same meteorological forcing: air temperature (T_{air}), wind speed (u), relative humidity (RH) and atmospheric transmissivity (t). The latter term determines how much solar radiation reaches the earth's surface. The soil is divided into two sections: the top soil and sub soil. On the basis of AMSR-E soil moisture measurements and knowledge on soil types it is possible to calculate the effective saturation for both top soil ($S_{e,top}$) and sub soil ($S_{e,sub}$). The leaf area index (LAI), derived from the NDVI, is used to separate the net radiation R_n into a soil and canopy part. The two resistance types: the surface resistance (r) and aerodynamic resistance (r_a) are solved separately for soil and canopy. This approach enables to calculate the transpiration T for the canopy part and evaporation E for the (top) soil part using the Penman-Monteith equation (Allen et al., 1998):

$$T = \frac{s(R_{n,canopy}) + \rho c_p \frac{\Delta e}{r_{a,canopy}}}{s + \gamma(1 + \frac{r_{canopy}}{r_{a,canopy}})} \left(\frac{86400}{\lambda}\right) \qquad [\text{mm day}^{-1}]$$

$$E = \frac{s(R_{n,soil} - G) + \rho c_p \frac{\Delta e}{r_{a,soil}}}{s + \gamma(1 + \frac{r_{soil}}{r_{a,soil}})} \left(\frac{86400}{\lambda}\right) \qquad [\text{mm day}^{-1}]$$

where s is the slope of the saturation vapor pressure curve [mbar K^{-1}], De vapor pressure deficit [mbar], ρ is the air density [kg m^{-3}], c_p is the specific heat of dry air [J kg^{-1} K^{-1}], γ is the psychrometric constant [mbar K^{-1}], G is the soil heat flux [W m^{-2}], $R_{n,canopy}$ and $R_{n,soil}$ [Wm^{-2}] are the net radiation for canopy and soil respectively, r_{canopy} and r_{soil} [s m^{-1}] are the canopy and soil

[10] AMSR-E: Advanced Microwave Scanning Radiometer - EOS (AMSR-E) is a one of the six sensors aboard MODIS-Aqua. AMSR-E is passive microwave radiometer. It observes atmospheric, land, oceanic, and cryospheric parameters, including precipitation, sea surface temperatures, ice concentrations, snow water equivalent, surface wetness, wind speed, atmospheric cloud water, and water vapor (http://weather.msfc.nasa.gov/AMSR/).

resistance respectively, $r_{a,canopy}$ and $r_{a,soil}$ [s m^{-1}] are the aerodynamic canopy and soil resistance, respectively.

The soil resistance r_{soil} is a function of the soil moisture content in the topsoil and is therefore a strong reflection of the AMSR-E observations. The canopy resistance r_{canopy} is a function of the LAI and four dimensionless stress functions. Three of these stress functions are related to meteorological conditions: temperature stress, vapor pressure stress and radiation stress. The fourth stress factor is related to the soil moisture content in the subsoil. The aerodynamic canopy and soil resistance, $r_{a,canopy}$ and $r_{a,soil}$ are a function of wind speed and surface roughness. An iteration procedure is needed to correct for the atmospheric stability. The Monin-Obukhov theory (1954) is used to parameterize the effects of shear stress and buoyancy.

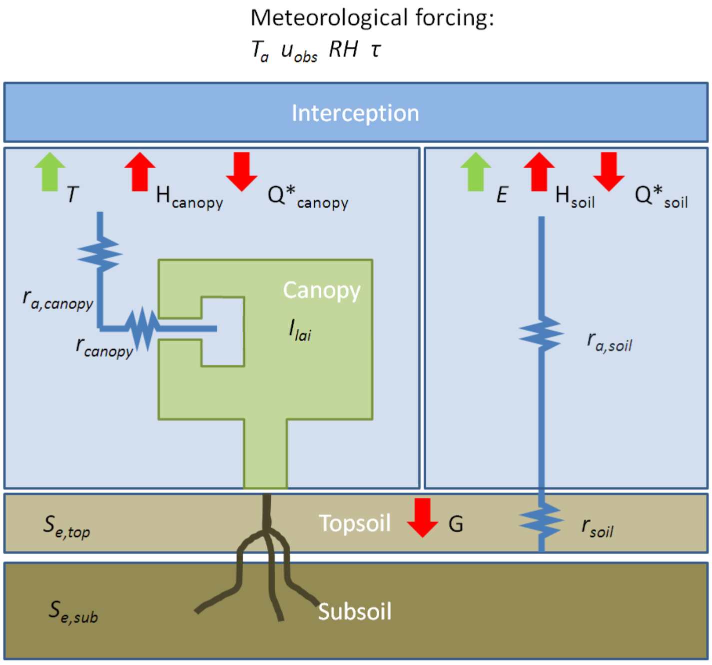


Figure 10: Overview ETLook algorithm.

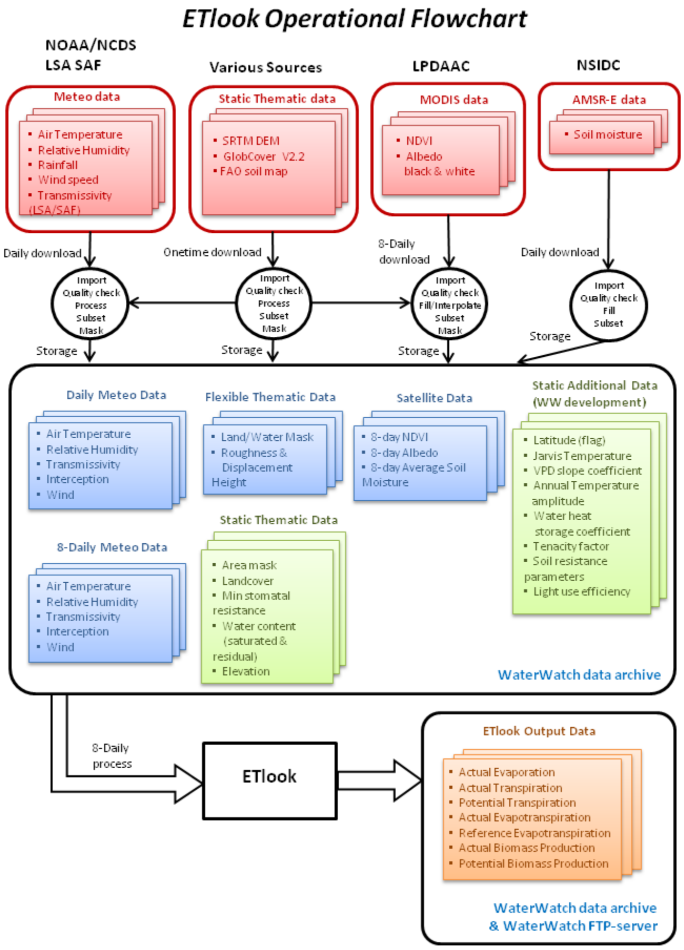


Figure 11: ETLook flowchart.

The outputs of ETLook consist of reference evapotranspiration ET_{ref}; actual and potential transpiration T_{act} and T_{pot}, actual evaporation E_{act} for soil, water and wet leaves. ETLook is also capable of calculating the potential and actual biomass production Bio_{act} and Bio_{pot}. Details on ETLook including references to other literature and validations are summarized by Perlgrim et al. 2010.

3.3.2.2 Input requirements ETLook

Surface albedo

The surface albedo determines how much solar radiation is reflected by the soil and/or canopy. It is an important parameter in determining the amount of energy (net radiation R_n) available for soil evaporation and crop transpiration. The following surface albedo products have been used: MODIS product MCD43B2 (quality product) and MCD43B3 (white sky and black sky albedo product). Both products have a spatial resolution of 500m and are a 16-day global product based on MODIS-Aqua and -Terra observations (https://lpdaac.usgs.gov/lpdaac/products/modis_products_table).

Pre-processing of the albedo products consisted of the following steps:

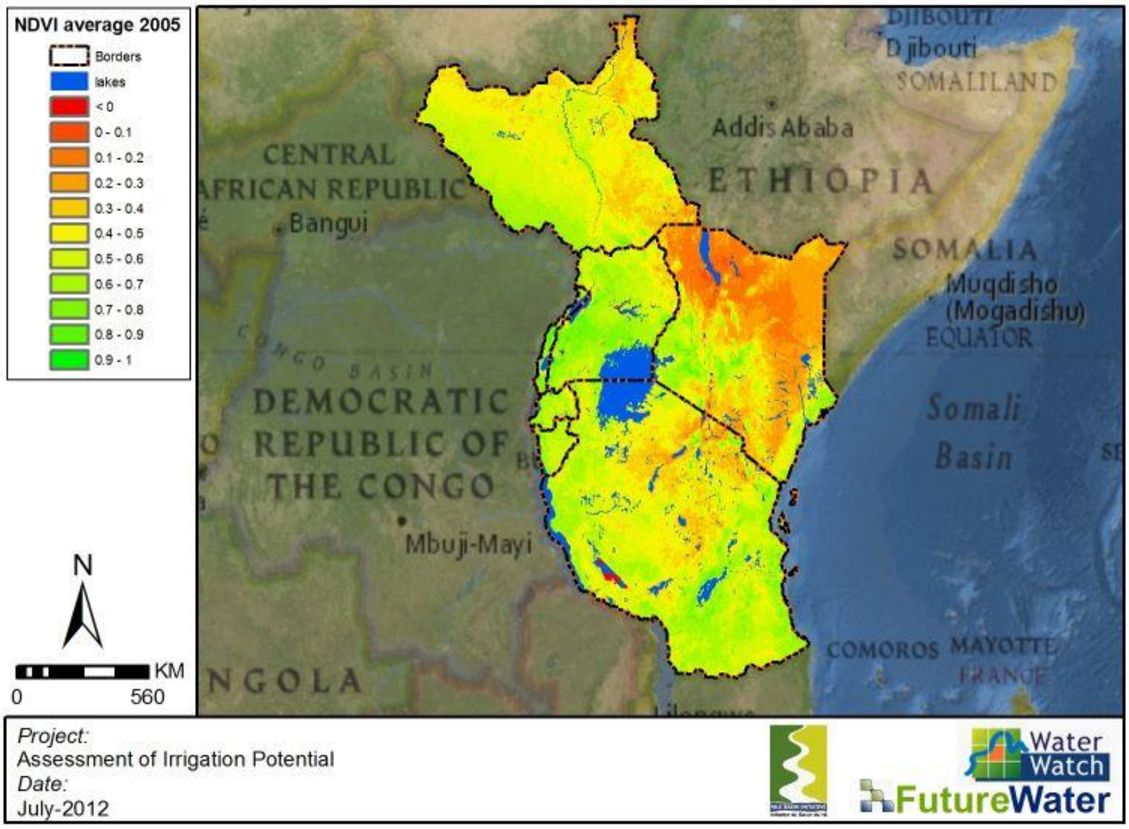
- Removal of bad pixels (mostly due to clouds) by (averaged) pixel data from previous and following images
- Downscaling of spatial resolution to 250m
- Rescaling of temporal resolution (16-days) to 10 days (as listed in Figure 11)

NDVI

The Normalized Difference Vegetation Index (NDVI) is a measure on the amount of green vegetation present at the surface. The values can range between -1 and 1. A negative NDVI value is an indicator of water. NDVI values between 0 and 0.2 indicate bare soil conditions. Values between 0.2 and 0.9 will have green vegetation ranging from almost bare (0.2) to fully covered (0.8 - 0.9). The following NDVI products have been used: MODIS product MOD13Q1 (Terra) and MYD13Q1 (Aqua). Both are 16-daily 250m global products (https://lpdaac.usgs.gov/lpdaac/products/modis_products_table).

Pre-processing of the NDVI products consisted of the following steps:

- Combining 16-day Terra and Aqua product in order to have a 8-day temporal resolution, as both products are shifted by 8 days
- Removal of bad pixels (mostly due to clouds) by (averaged) pixel data from previous and following images
- Rescaling of temporal resolution (8-days) to 10 days (as listed in Figure 12)



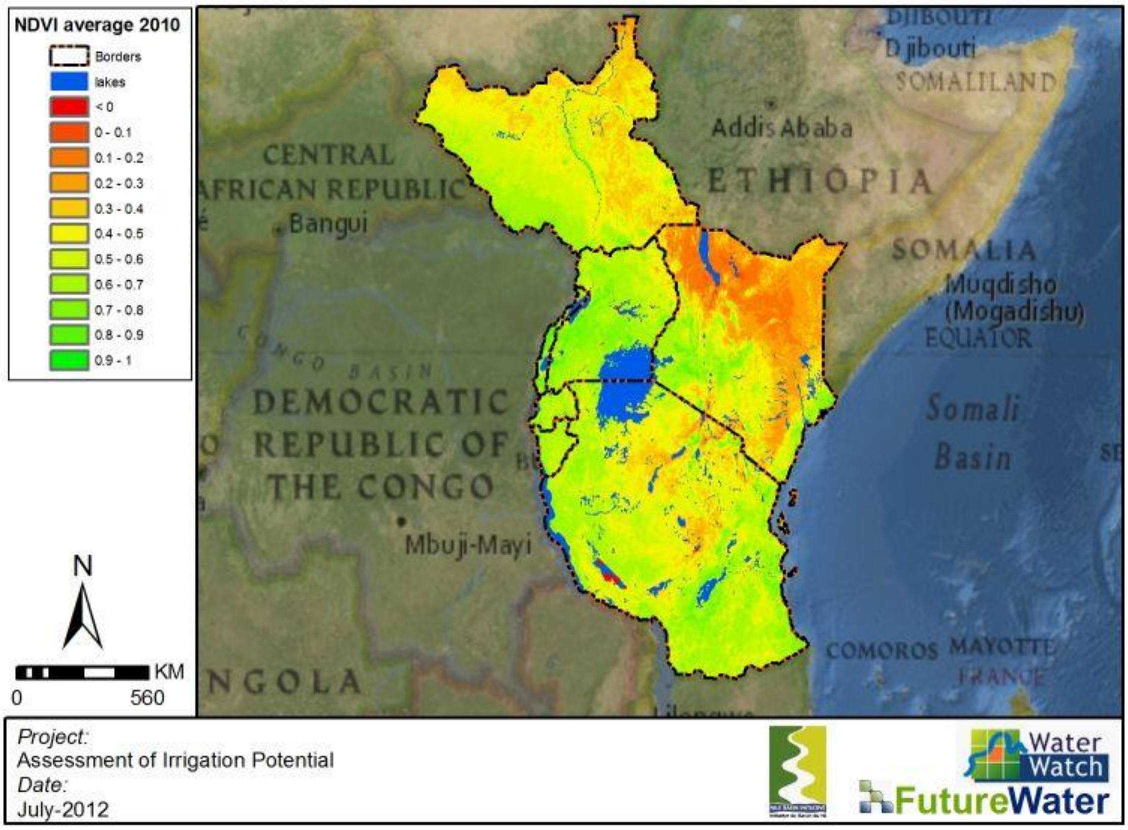


Figure 12. Annual mean NDVI for 2005 (top) and 2010 (bottom).

Soil moisture (AMSR-E)

Soil moisture data of the top soil layer is taken from the National Snow and Ice Data Center (Denver), which is derived from the AMSR-E passive microwave sensor. The daily soil moisture data (25km resolution) can be downloaded from the NSIDC site ftp://n4ftl01u.ecs.nasa.gov/SAN/AMSA/AE_Land3.002/. At this moment this is the one of the few operational data source that provides real-time global soil moisture data.

Pre-processing of the AMSR-E data consisted of the following steps:

- Averaging of daily data to 10-day intervals, as listed in Figure 11
- If necessary filling of gaps
- Resampling to 250m (using nearest neighbor). Further downscaling of AMSR-E is done in ETLook by combining with higher resolution soil and NDVI data.

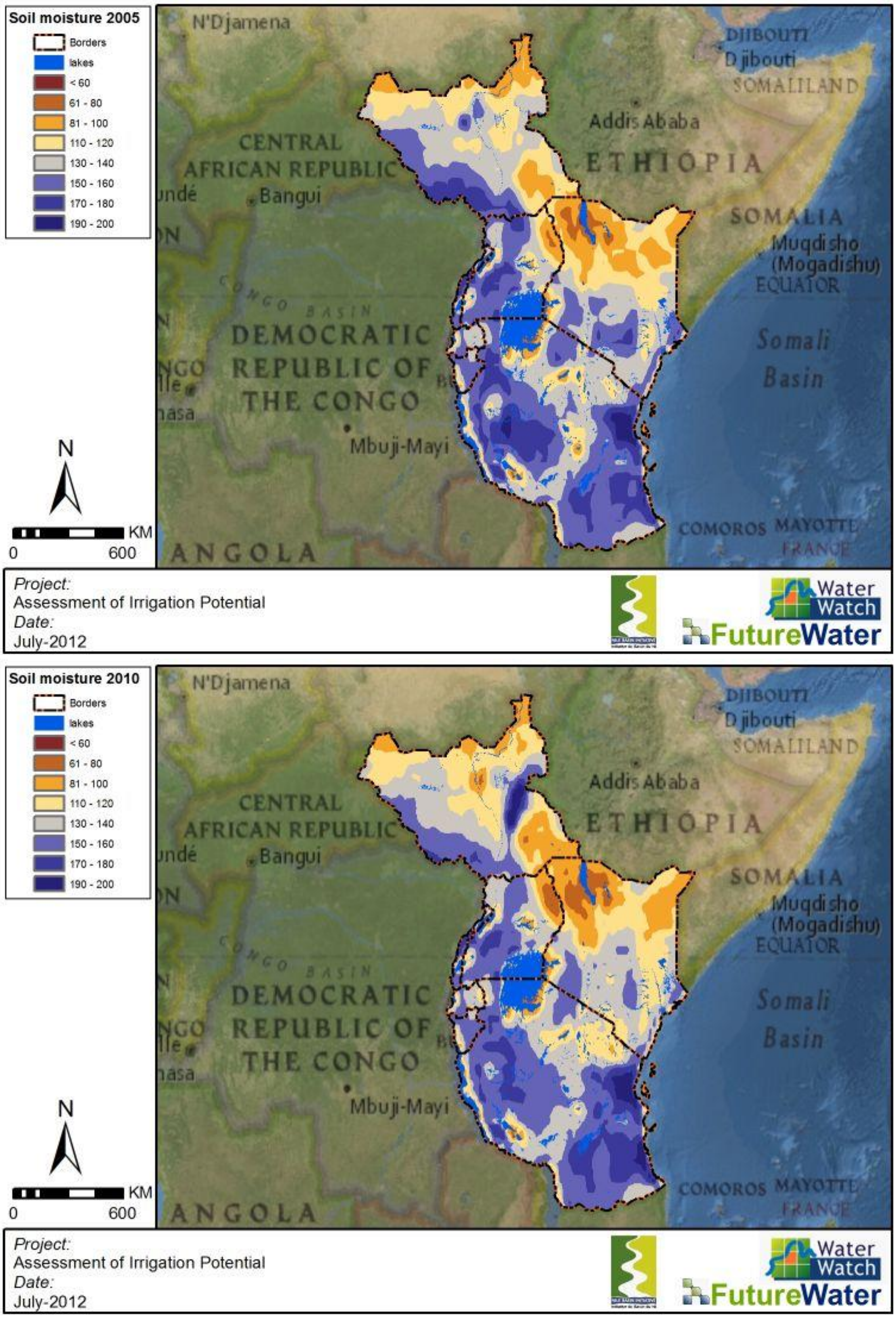


Figure 13: Annual mean soil moisture (25 km resolution) according to AMSR-E NSIDC data base for 2005 (top) and 2010 (bottom).

Radiative Forcing

The meteorological data (daily mean air temperature and relative humidity) is taken from available weather stations in the study area (approximately 127 stations). The air temperature and relative humidity are spatially gridded, in order to have meteorological information at 250m resolution. The spatially gridding is done using the DAYMET-model (Thornton et al., 1997). The wind speed and atmospheric transmissivity (and air temperature and relative humidity for days insufficient weather station data was available) is taken from the MERRA database (http://gmao.gsfc.nasa.gov/research/merra/intro.php). MERRA is a NASA reanalysis for the satellite era using a major new version of the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5). The spatial resolution is 0.5 degrees North-South and 0.6 degrees West-East.

In order to have monthly ET products all data: daily meteorological and AMSR-E data and the 16-daily MODIS products have been averaged/resampled to ~10-daily steps as listed in Figure 14. This means that both 2005 and 2010 consist of 36 periods. Finally, these 36 periods of ET are summarized to monthly (and annual) ET-results. A complete overview of all processing steps is shown in Figure 11.

Start DOY	End DOY	Length [days]	Month	Start DOY	End DOY	Length [days]	Month
1-Jan	10-Jan	10		1-Jul	10-Jul	10	
11-Jan	20-Jan	10	January	11-Jul	20-Jul	10	July
21-Jan	31-Jan	11		21-Jul	31-Jul	11	
1-Feb	10-Feb	10		1-Aug	10-Aug	10	
11-Feb	20-Feb	10	February	11-Aug	20-Aug	10	August
21-Feb	28-Feb	8		21-Aug	31-Aug	11	
1-Mar	10-Mar	10		1-Sep	10-Sep	10	
11-Mar	20-Mar	10	March	11-Sep	20-Sep	10	September
21-Mar	31-Mar	11		21-Sep	30-Sep	10	
1-Apr	10-Apr	10		1-Oct	10-Oct	10	
11-Apr	20-Apr	10	April	11-Oct	20-Oct	10	October
21-Apr	30-Apr	10		21-Oct	31-Oct	11	
1-May	10-May	10		1-Nov	10-Nov	10	
11-May	20-May	10	May	11-Nov	20-Nov	10	November
21-May	31-May	11		21-Nov	30-Nov	10	
1-Jun	10-Jun	10		1-Dec	10-Dec	10	
11-Jun	20-Jun	10	June	11-Dec	20-Dec	10	December
21-Jun	30-Jun	10		21-Dec	31-Dec	11	

Figure 14. Begin- and end-DOY for each ETLook time step (2005 and 2010).

Vegetation Characteristics

Three vegetation characteristics are required as input for ETLook namely the surface roughness, zero-displacement height and minimum stomatal resistance. The first two are required to estimate the aerodynamic resistance ($r_{a,canopy}$ and $r_{a,soil}$) from wind speed data. The surface roughness and zero-displacement height are derived from the LAI and pre-defined maximum obstacle height for each land cover type as listed in Table 11. By incorporating the LAI the roughness and displacement height will vary depending on the vegetation dynamics during the growing season.

The minimum stomatal resistance describes the resistance to Transpiration for a canopy under ideal and non-stressed conditions. The $r_{s,min}$ can have different values per land use and land cover class. Spatially variable grids for minimum stomatal resistance have been developed by WaterWatch based on literature and modeling experience. The set values per land use class are listed in Table 11. The light gray listed classes are not present in the study area (NAN-values).

Table 11. Land use classes and corresponding maximum obstacle height and minimum stomatal resistance.

Land use class	Maximum obstacle height [m]	Minimum stomatal resistance [s m^{-1}]
Irrigated croplands\post flooding	NAN	NAN
Rainfed croplands	1	140
Rice - irrigated	0.5	90
Plantations	2	180
Herbaceous	0.75	150
Mosaic, forest and crop	4	160
Bare areas	0	400
Open water	0	0
Grassland	1	180
Shrubland --> open	1	200
Shrubland --> closed	2	225
Closed forest --> ever green	9	250
Closed forest --> deciduous	9	225
Open forest --> ever green	9	350
Open forest --> Decideous	9	275
Snow and ice	0	0
Urban	5	400
Open/sparse mixed vegetation	1	180
Irrigated - herbaceous	1	90
Rainfed - herbaceous	1	140
Rainfed - maize	2	120
Rainfed - coffee	1.5	140
Rainfed - cereal	1	120
Rainfed - tea	1.5	140
Rainfed - Wheat	1	120
Rainfed -shurb crop	1	120
Rainfed - pineapple	2	120
Rainfed - Sisal	2	120
Irrigated - citrus	2	110
Rainfed plantation	2	180
Irrigated plantation	NAN	NAN
Rainfed - shrub crop	0.5	140
Irrigated - suger cane	2	90
Rainfed -banana	2	120
Rainfed - oil palm	2	120
Rainfed plantation - pinus & Cupressus	2	120
Rainfed plantation - Acacia mearnsi	9	180
Rainfed plantation - Teak	9	180
Rainfed plantation - Cashew	5	120
Irrigated - Cotton	NAN	NAN
Irrigated - cereal	NAN	NAN
Irrigated plantation - Eucalyptus	NAN	NAN

3.4 Water resources assessment

3.4.1 Introduction

One of the paramount factors whether irrigation can be developed is the availability of water in a particular location and at the required time. Classically approaches are often based on observations on streamflow and/or groundwater availability. Given the vast area explored in this study, and the limited time available, setting-up monitoring networks is impossible. In general, the feeling is that discharge from rivers has been reduced over the last decades. Dai et al. (2009) confirmed this global trend, although for the entire Nile he noticed a small increase in flows since 1948. Changes in river flows can have multiple reasons such as changes in rainfall, evapotranspiration, land use, land management etc. . It was therefore selected to use a modeling approach that will give a good estimation of the water resources availability.

Rainwater harvesting can be seen as an additional option to overcome water shortage. Multiple studies have been undertaken on rainwater harvesting (e.g. EWUAP studies). In the current study a detailed analysis of the potential of rainwater harvesting is beyond the scope of the study.

The model as setup is used to determine the three major potential sources of irrigation: (i) from a stream, lake, or reservoir, (ii) from groundwater, and/or (iii) from reservoir to be developed. The NELmod model (see hereafter) is used to estimate whether sufficient water is available if irrigation would be developed in a particular area.

3.4.2 Hydrological model setup and calibration

3.4.2.1 Introduction to hydrological modeling

A huge number of hydrological models exits, applications are growing rapidly and a relevant question for hydrological model studies is therefore related to appropriate model selection. An important issue to consider here is the continuum between physical detail and spatial scale. In general it can be stated that the larger the spatial scale the less physical detail can be included (Figure 15). A field scale model that aims at simulation crop growth, water transport through he unsaturated zone, percolation to the groundwater and atmosphere land surface interaction requires a lot of data and is computational intensive and can therefore only be applied at the field scale. If one wants to study for example the impact of climate change at the continental scale, then different algorithms are used which are less data intensive. If we consider irrigation schemes, then we are looking at the spatial scale of a system (Figure 15), which can include more physical detail than modeling at the basin scale, but less detail than modeling at the field scale.

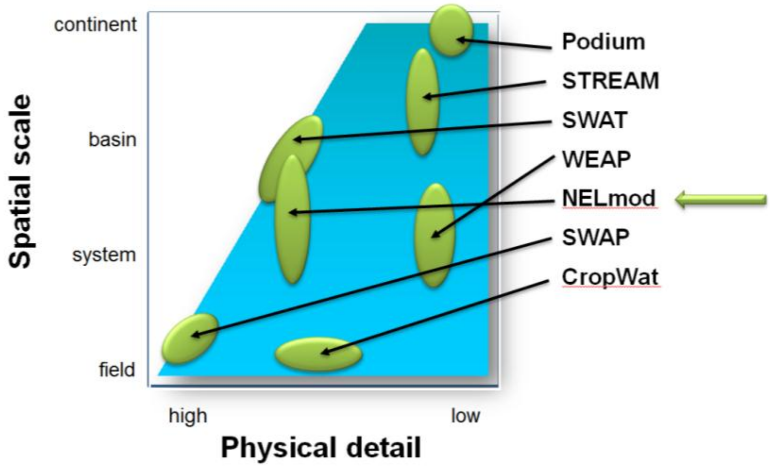


Figure 15: Relation between spatial scale and physical detail. The green ellipses show the key strength of some well-known models.

Besides these important considerations there are a number of other factors influencing the appropriate choice of model such as the availability of source code, documentation, support, user friendliness, resources, data availability and inclusion of crucial processes relevant to a particular study.

Hydrological models use input data and parameters that must be assessed for each computational segment of the model. They must be estimated either by some relationship with physical characteristics or by tuning the parameters so that model response approximates observed response, a process known as calibration. The process of model calibration is often required because of limitations of the models and especially of data. An example of a limitation is the mathematical description that can be imperfect and/or the understanding of the phenomenon may not be complete. Another example of model limitations is that the mathematical parameters used in models to represent real processes are often uncertain because these parameters are empirically determined or represent multiple processes. Also the initial conditions and boundary conditions in a model may not be known.

The use of remote sensing in hydrological modeling is a growing field and proves to be highly relevant, especially in areas where data are scarce, unreliable or unusable. This situation is regularly encountered in many areas across the world in developing countries. Obviously, ground truthing is an important aspect of quality and will in general improve accuracy of the data. Remote sensing provides objective and continuous information on relevant variables and could provide a solution for date shortage. As far as the link with models is concerned a distinction should be made in applications aimed at model parameterization and in applications aiming at model calibration. Remotely sensed parameterization is more common, and could for example include land cover classification, inclusion of digital elevation model in catchment delineation, use of vegetation indices to derive surface roughness and the use of precipitation radar data as input to a model. In the current study a combination of remote sensing data, global data and local data are used to setup and to calibrate the model.

For the assessment of the irrigation potential in in Burundi, Eastern DRC, Kenya, Rwanda, South Sudan, Tanzania and Uganda a hydrological model will be used and a number of criteria are important in the selection of the model and these include:

- The model should include a reasonable level of physical detail and include all major hydrological processes at the basin and sub-basin scale at a level of data availability.
- The model should be applied on a very large scale (~ 2.4 million km^2).
- The model should be run on a daily timescale.
- The model should be fully distributed and raster based to provide as much detail as possible.
- There needs to be a clear link with continental and global public domain data sources (climate forcing, land use and soil).
- There needs to be a clear link with remote sensing datasets to calibrate and parameterize the model.
- The model needs to be user-friendly and in the public domain.

We will first describe the PCRaster model and previous applications and then provide a justification for the use of the PCRaster based approach.

3.4.2.2 PCRaster and NELmod

Introduction

The PCRaster Environmental Modeling Language[11] (Wesseling et al., 1996) is a computer language for the construction of iterative spatial-temporal environmental models. The PCRaster Environmental Modeling Language is developed at the department of physical geography of Utrecht University in the Netherlands. An advantage of PCRaster is that it is open source software, and therefore enables it's user to easily change or extend the model code to satisfy the user's wishes as will be done for the current study. One hydrological model which is successful applied in the Middle East and North African (MENA) countries, and written in the PCRaster language, is PCR-GLOBWB. This name stands for PCRaster Global Water Balance. This model is developed at the department of physical geography of Utrecht University in the Netherlands with the explicit aim to simulate terrestrial hydrology at macro-scales, under various land use and climate conditions, with a temporal resolution of one to several days (Van Beek, 2009). FutureWater successfully applied this model in the MENA region to assess the water availability under climate change (Immerzeel et al., 2011, Immerzeel et al. (2010) also successfully applied this model in Asia with the aim to assess future water availability in large Asian river basins in relation to food security.

For the water resources assessment in the MENA study, PCR-GLOBWB was set-up at a spatial resolution of 10 km. This resolution of 10 km was considered by World Bank as very high given that previous studies focused often on basin, country or sub-basin level only. Moreover, this high resolution over such a large area was only possible given that the normal restriction of data was partly overcome by using remotely sensed data.

For the current study model result of NELmod will be at a resolution of 250m. This resolution can be obtained by running the NELmod model at a spatial resolution of 1 km and resample the results using the 250m DEM to the final output resolution of 250 m.

[11] http://pcraster.geo.uu.nl/

Previous applications

In addition to the above the PCRaster based hydrological model has been applied successfully in a number of cases under varying conditions and the results have been published in top scientific journals:

- Bierkens and van Beek (2009) have applied the model in Europe and they have developed a seasonal prediction system for river discharge based on the North Atlantic Oscillation (NAO) and anomalies in sea surface temperature.
- Loos et al. (2009) use a PCRaster based hydrological model to assess nutrient and sediment loads for the Rhine river basin and they show that this can be simulated with a relative high degree of accuracy.
- Sperna Weiland et al. (2010) tested the usefulness of GCM data for hydrological studies, with focus on discharge variability and extremes using bias-corrected daily climate data from a selection of twelve GCMs as input to the global hydrological model.
- Petrescu et al. (2010) used the hydrological model in upscaling methane emission of boreal and arctic wetlands.
- Wada et al. (2010) mapped global groundwater depletion and assess how much this contributes to global sea level rise.

Discretization

The optimal model resolution is a tradeoff between the detail of the available input data, the desired output resolution, the physical detail of the model, and the calculation time. In general, resolution of data availability is the limiting factor. Given these constraints and previous experiences for World Bank, ADB and EU, results will be presented at a resolution of 250 m. The NELmod model will run on a resolution of 1 km and results will be resampled to 250 m using the DEM.

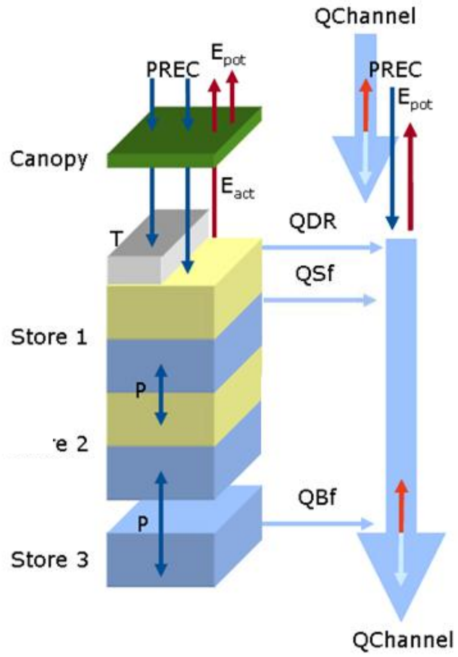


Figure 16: Hydrological model concept as will be used in this study.

Model concept

The model concept as will be used in our hydrological model is presented in Figure 16. In the remainder of this study we will refer to this model as NELmod. NELmod simulates the most direct pathways of water that reaches the earth surface back to the open water (streams, ponds, and lakes) or atmosphere; within each cell precipitation in the form of rain or snow either falls on soil or in open water surface. Additional specific cell features can be added if necessary. If there is a pumping station in a specific area for example, then this can be implemented into that grid cell. The left side of Figure 16 shows the soil compartment, which is divided in the two upper two soil (root zone and sub-soil layer) stores and the third groundwater store, and their corresponding drainage components: direct runoff (QDR), subsurface flow (QSf) (drainage) and base flow (QBf). In the center of the figure, the resulting discharge along the channel (QChannel) with lateral inflow is depicted. Any precipitation that falls on the soil surface can be intercepted by vegetation and in part or in whole evaporated. A part of the liquid precipitation is transformed in direct or surface runoff, whereas the remainder infiltrates into the soil. The resulting soil moisture is subject to soil evaporation when the surface is bare and to transpiration when vegetated. A certain amount of moisture in the root zone will contribute to subsurface flow, also known as drainage. The remaining part will percolate to the sub-soil layer. The sub-soil moisture content can recharge the groundwater layer, or it can be used for capillary rise to the root zone. Water used for recharge of the groundwater layer will eventually exit the layer as baseflow.

Runoff

Liquid water passed on to the soil surface will infiltrate if sufficient storage capacity is available, else it will drain over the surface as direct runoff. Following the concept developed by Zhao (1977) and Todini (1996), the partitioning into infiltration and direct runoff is dependent on the degree of saturation and the distribution of available storage in the soil. In other words, if the root water volume exceeds the saturation volume, then the part that exceeds the saturation volume becomes runoff. This is shown in the following equation:

$$Runoff = max(RootWater - RootSat, 0)$$

Where:	*Runoff*	=	*Runoff on a specific day [mm];*
	RootWater	=	*Moisture in root zone on a specific day [mm];*
	RootSat	=	*Saturated root water volume [mm];*

Actual evapotranspiration ETact

The amount of water which evaporates from a grid cell can be either bare soil evaporation, or transpiration from a crop. Water from bare soil or open water will evaporate at the potential rate. For vegetated areas, however, the situation will be different. Each type of crop will have a different rate of potential evapotranspiration (ETpot), depending on the crop factor and ETref (reference evapotranspiration). If the soil becomes too wet, then the roots cannot breathe and as a result there will be a reduction in potential evapotranspiration, known as the actual transpiration. The same is true for too dry conditions. If the soil is too dry, then the crop will reduce its transpiration because there is a stress situation. Therefore the model incorporates an evapotranspiration reduction for too wet and too dry conditions. These are shown in the following two equations:

$$ETreductionWet = if(RWater > RootSat\ then\ 0\ else\ 1)$$

Where: ETreductionWet = Reduction for wet conditions [-];
RWater = Moisture in root zone on a specific day [mm];
RSat = Saturated root water volume [mm];

$$ETreductionDry1 = (RWater - RDry)/(RWilt - RDry)$$

$$ETreductionDry2 = max(min(ETreductionDry1,1),0)$$

Where: ETreductionDry1 = Reduction for dry conditions [-];
RWater = Moisture in root zone on a specific day [mm];
RDry = Permanent wilting point [mm];
RWilt = Wilting point [mm];
ETreductionDry2 = Final reduction for dry conditions [-];

Then the actual evapotranspiration will be calculated as follows:

$$ETact = ETpot * ETreductionWet * ETreductionDry2$$

Where: ETact = Actual evapotranspiration [mm] on a specific day;
ETpot = Potential evapotranspiration [mm] on a specific day;

Infiltration

As mentioned before the amount of precipitation is added to the root zone. A part of that will leave the grid cell as runoff, and another part evaporates into the air. The remaining part (RootWater – Runoff – ETact) stays in the root zone and can be seen as the updated root water moisture content. This can be seen as the amount of water which has infiltrated into the root zone. Not all the infiltrated water in the root zone will stay in the root zone. A certain amount of this water will leave the grid cell as subsurface flow, also known as drainage, and another amount of this water will percolate to the sub-soil layer.

Drainage

Drainage will only be significant in areas with soils having high hydraulic conductivities and significant slopes. Drainage in the NELmod follows the concept of a kinematic storage model for subsurface flow developed by Sloan et al. (1983) and summarized by Sloan and Moore (1984). This model simulates subsurface flow in a two-dimensional cross-section along a flow path down a steep hillslope. This model is based on the mass continuity equation, with the entire hillslope used as the control volume. The excess from the root zone is considered whenever the root zone water content exceeds the root zone’s field capacity:

$$RWexcess = RWater - RFieldCap \qquad \textit{if RWater > RFieldCap}$$
$$RWexcess = 0 \qquad \textit{if RWater <= RFieldCap}$$

Where: RWexcess = Drainable volume of water in the root zone [mm];
RWater = Moisture in root zone on a specific day [mm];
RFieldCap = Field capacity of root zone [mm];

Then the lateral volume at the hillslope outlet is given by:

$$Qlat = H_0 * v_{lat}$$

Where:	*Qlat*	=	*Net drainage at hillslope outlet [mm];*
	H_0	=	*Saturated thickness normal to the hillsope at the outlet expressed as a fraction of (RootSat – FieldCap) [-];*
	v_{lat}	=	*Velocity of flow at the outlet [mm/d];*

The velocity of flow at the outlet is defined as:

$$v_{lat} = K_{sat} * slp$$

Where:	v_{lat}	=	*Velocity of flow at the outlet [mm/d];*
	K_{sat}	=	*Saturated hydraulic conductivity [mm/d] of root zone;*
	slp	=	*Slope as the increase in elevation per unit distance [-];*

In large sub-basins with a time of concentration greater than one day, only a portion of drainage will reach the main channel on the day it is generated. Therefore a drainage flow lag is incorporated in the NELmod. So once the lateral volume is calculated, the amount of drainage released to the main channel is calculated as:

$$Drainage_i = \left(\left(1 - exp\left(\frac{-1}{RootTT}\right)\right) * Qlat\right) + \left(exp\left(\frac{-1}{RootTT}\right) * Drainage_{i-1}\right)$$

Where:	$Drainage_i$	=	*Drainage [mm] on day i;*
	RootTT	=	*Lateral flow travel time [d];*
	Qlat	=	*Lateral volume generated on day I;*
	$Drainage_{i-1}$	=	*Drainage [mm] on day i-1;*

The travel time of lateral flow is calculated as:

$$RootTT = \frac{RSat - RFieldCap}{Ksat}$$

Where:	*RootTT*	=	*Travel time of lateral flow [d];*
	RSat	=	*Saturated root water volume [mm];*
	RFieldCap	=	*Field capacity of root zone [mm];*
	K_{sat}	=	*Saturated hydraulic conductivity [mm/d] of root zone;*

Percolation

Percolation occurs from the root zone to the sub-soil (second layer), and from the sub-soil into the groundwater store. Percolation from the root zone to the second soil layer will occur if the water content in the root zone exceeds the field capacity of the root zone and the sub-soil layer does not have a seasonal high water table. The equation for root water excess is already shown earlier. Then the amount of percolation from the root zone to the sub-soil layer is:

$$RPerc = if\left(SWater \geq \left(SFieldCap + 0.5 * (SSat - SFieldCap)\right) \, then \; 0 \; else \; RWexcess * \left(1 - exp\left(\frac{-1}{RootTT}\right)\right)\right)$$

Where:	*Rperc*	=	*Water percolating to the sub-soil layer [mm];*
	SWater	=	*Water content of sub-soil layer [mm];*
	SFieldCap	=	*Field capacity of sub-soil layer [mm];*
	SSat	=	*Saturated sub-soil water volume [mm];*
	RWexcess	=	*Drainable volume of water in the root zone [mm];*
	RootTT	=	*Travel time of flow in root zone [d];*

Percolation from the sub-soil to the groundwater layer is only allowed if the groundwater store water content is lower than the saturated content of the groundwater store. Then percolation is calculated as:

$$Sperc = if\left(GWater \geq GSat \; then \; 0 \; else \; \left(SWater * \left(1 - exp\left(\frac{-1}{SubTT}\right)\right)\right)\right)$$

Where:	*Sperc*	=	*Water percolating to the groundwater layer [mm];*
	GWater	=	*Water content of the groundwater layer [mm];*
	GSat	=	*Saturated groundwater store volume [mm];*
	SubTT	=	*Travel time of flow in sub-soil layer [d];*

The travel time of flow in the sub-soil layer is calculated as:

$$SubTT = \frac{SSat - SFieldCap}{Ksat}$$

Where:	*SubTT*	=	*Travel time of flow in sub-soil layer [d];*
	SSat	=	*Saturated sub-soil water volume [mm];*
	SFieldCap	=	*Field capacity of sub-soil layer [mm];*

Groundwater

The third store of the soil compartment represents the deeper part of the soil that is exempt from any direct influence of vegetation and constitutes a groundwater reservoir fed by active recharge. The water balance of the groundwater store is as follows:

$$GWater_i = GWater_{i-1} + GW_{rchrg} - Q_b - GW_{revap} - GW_{pump}$$

Where:	$GWater_i$	=	*groundwater storage on day i [mm]*
	$GWater_{i-1}$	=	*groundwater storage on day i-1 [mm]*
	GW_{rchrg}	=	*groundwater recharge on day i [mm]*
	Q_b	=	*baseflow on day i [mm]*
	GW_{revap}	=	*water moving to sub-soil due to deficiencies [mm]*
	GW_{pump}	=	*water extracted from groundwater storage [mm]*

The groundwater recharge depends on the recharge entering on the previous day and the percolation exiting the sub-soil on the current day according to:

$$GW_{rchrg,i} = \left(1 - exp\left[-1/\delta_{gw}\right]\right) * Sperc + exp\left[-\frac{1}{\delta_{gw}}\right] * GW_{rchrg,i-1}$$

Where:	δ_{gw}	=	*delay time over overlaying formations [days]*
	Sperc	=	*percolation exiting from sub-soil [mm]*
	$GW_{rchrg,i-1}$	=	*recharge entering groundwater store on day i-1 [mm]*

Baseflow from the groundwater store is related to the recharge to this groundwater store. Finally baseflow contributes to the total discharge from a grid cell. Baseflow is calculated as follows:

$$Q_{b,i} = Q_{b,i-1} * exp\left[-\alpha_{gw} * \Delta t\right] + GW_{rchrg,i} * \left(1 - exp\left[-\alpha_{gw} * \Delta t\right]\right)$$

Where:	$Q_{b,I}$	=	*baseflow on day i [mm]*
	$Q_{b,i-1}$	=	*baseflow on day i-1 [mm]*
	α_{gw}	=	*baseflow recession coefficient [*d^{-1}*]*
	Δt	=	*time step [days]*
	$GW_{rchrg,I}$	=	*recharge to groundwater store on day i*

3.4.2.3 Validation and calibration

In general models are calibrated and validated on using streamflow data only. Calibration of physically based, distributed hydrological models is complex given limitations of the input data, complexity of the mathematical representation of hydrological processes, and incomplete knowledge of basin characteristics (Immerzeel and Droogers, 2008). It was therefore decided to calibrate and validate NELmod using a combination of streamflow data as well as comparing simulated evapotranspiration to observed ones from satellite data.

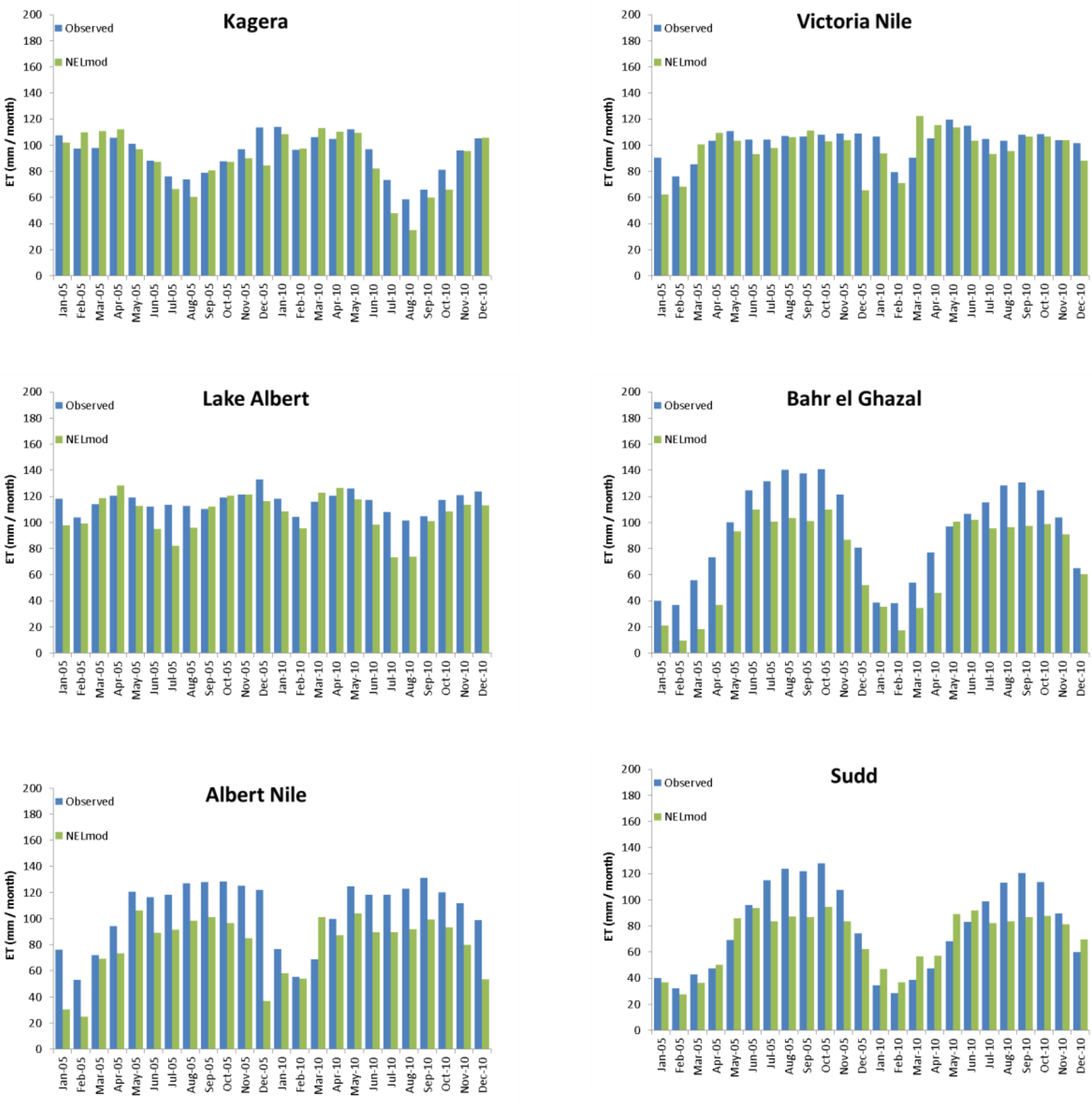


Figure 17: Comparison of NELmod evapotranspiration with observed evapotranspiration (ETlook) for 2005 and 2010.

Validation and calibration on evapotranspiration

For the current study, it is essential that especially complex land processes, such as runoff, groundwater recharge and evapotranspiration are well represented in the model. Therefore the modeled evapotranspiration is compared to the observed ones, derived from satellite data (ETLook). For each of the seven sub-basins as considered in the study, monthly evapotranspiration from the model as well as the observed ones are shown in Figure 17.

Overall the model is performing well in simulating evapotranspiration. For Bahr el Ghazal, the Sudd and the Albert Nile basin, however, the model seems to underestimate the evapotranspiration for most months. It is known that a large number of wetlands exist in the Nile basin, with the Sudd being the largest one. The hydrology in these wetlands is extremely complex (Mohamed et al., 2006) and can only be partly captured in the hydrological model. In reality, the surface area of these wetlands varies during the year, depending on the season. A larger surface area means a larger water surface area available for evaporation. This phenomena is not captured by the model, and therefore the evapotranspiration needs to be corrected for the varying wetland surface area. The correction method is described in the next Section.

The goal of the calibration is to match the NELmod evapotranspiration with the observed evapotranspiration (ETlook). The observed evapotranspiration is available for each of the seven basins of Figure 17 on a monthly time-scale for the years 2005 and 2010. Then the correction is based on a simple mass balance:

$$E_{ETlook} * A_{basin} = E_{NELmod} * A'_{basin}$$

Where:	E_{ETlook}	=	*Evapotranspiration from ETlook [mm]*
	A_{basin}	=	*Basin area [L^2]*
	E_{NELmod}	=	*Evapotranspiration from NELmod [mm]*
	A'_{basin}	=	*Variable basin area, consisting of a static area and a variable wetland area [L^2]*

The evapotranspiration from NELmod can be seen as the sum of evapotranspiration from a static area, and the evapotranspiration from a variable wetland area. Therefore the right-hand side of the previous equation can be rewritten as:

$$E_{NELmod} * A'_{basin} = E_{static} * A_{static} + E_{wetland} * A_{wetland}$$

Where:	E_{static}	=	*NELmod evapotranspiration as calculated for the static landuse surface (as shown in Figure 17) [mm]*
	A_{static}	=	*Static landuse area, from which the wetland surface area has been extracted [L^2]*
	$E_{wetland}$	=	*Evapotranspiration from the variable sized wetlands [mm]*
	$A_{wetland}$	=	*Wetland surface area, which can vary in size throughout the year [L^2]*

The above equation can be solved using the monthly averages of 2005 and 2010. The wetland evapotranspiration is based on the reference evapotranspiration from ETlook, and the crop factor (Kc) for wetlands, which is 1.2 (Allen et al., 1998). Then the wetland evapotranspiration is calculated as:

$$E_{wetland} = ET_{ref} * K_c = ET_{ref} * 1.2$$

Based on the previous equations we can calculate for each month the wetland area. The calculation of the wetland area is based on averages from 2005 and 2010. Because ETlook results were only available for these two years, it is assumed that this monthly varying wetland area is the same for the other years. The corrected basin evapotranspiration is finally calculated as:

$$E_{basin} = \frac{E_{static} * A_{static} + E_{wetland} * A_{wetland}}{A_{basin}}$$

Results of the calibration can be seen in Figure 18 and Figure 19. It is clear that the impact of varying wetland sizes over the year in the model is required to model evapotranspiration correctly. The final calibration results indicate that the model is able to mimic reality quite well. Based on this, it can be concluded that NELmod is able to provide accurate information on water availability. It is important that NELmod result are on a scale (spatial as well as in time) that can never be achieved using observations.

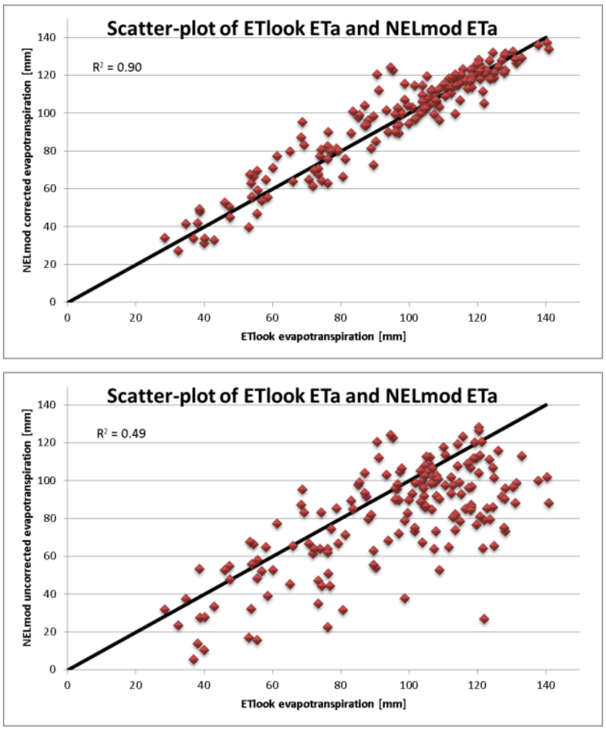


Figure 18: Scatter-plot of ETlook evapotranspiration vs. the corrected NELmod evapotranspiration (top), and ETlook evapotranspiration vs. the uncorrected NELmod evapotranspiration.

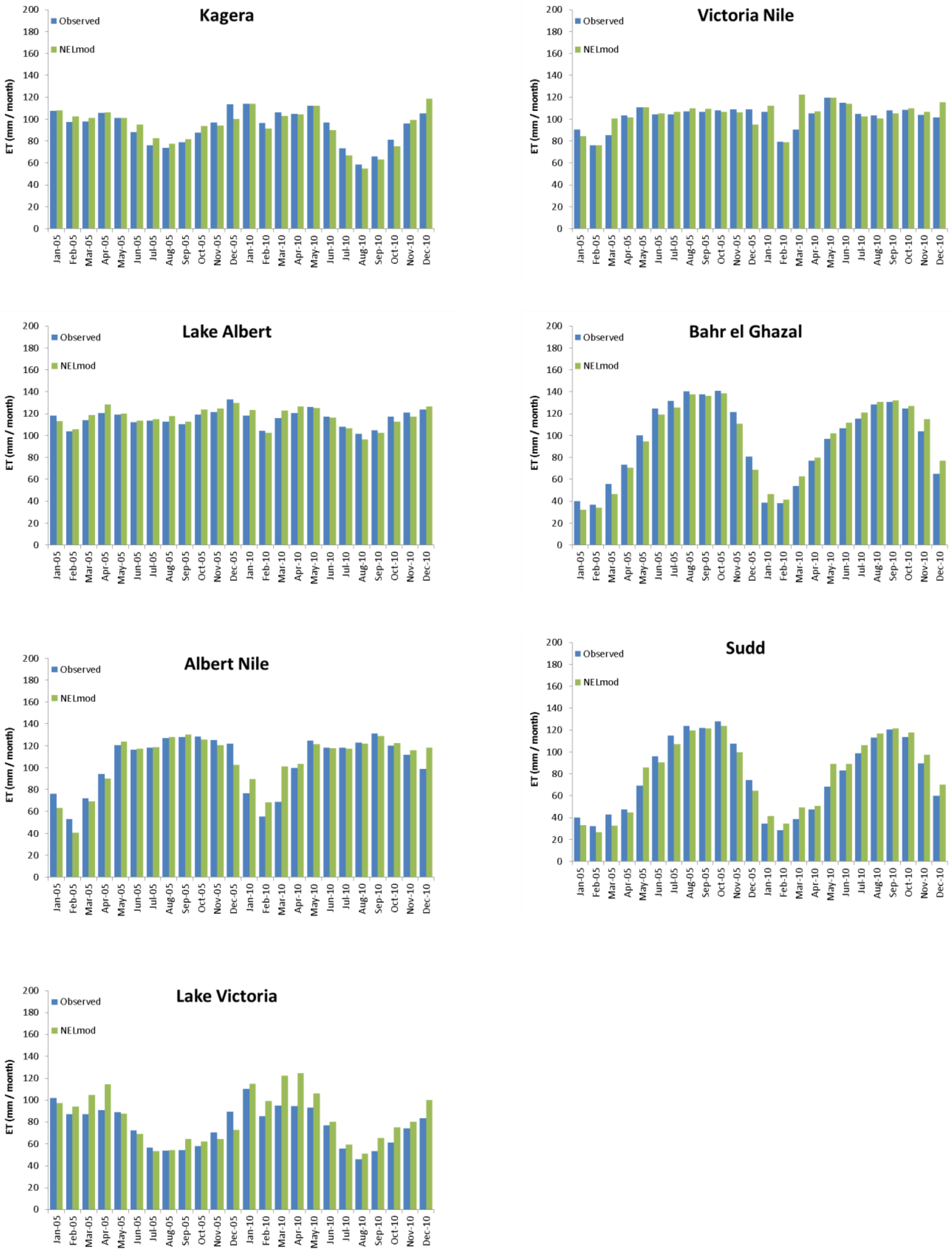


Figure 19: Comparison of calibrated NELmod evapotranspiration with observed evapotranspiration (ETlook) for 2005 and 2010.

Validation and calibration on streamflow

Data from 370 streamflow stations were available for validation and out of these a selection was made based on two criteria: (i) ten years or more of data, (ii) average flow over 100 $m^3\ s^{-1}$. Using these criteria 11 stations (Figure 20 and Table 12) were available and distributed throughout the study area. Most of these stations do not have very recent data and therefore the minimum, maximum and average stream flow was determined for each station. These flows were compared to the flows as simulated with the NELmod model.

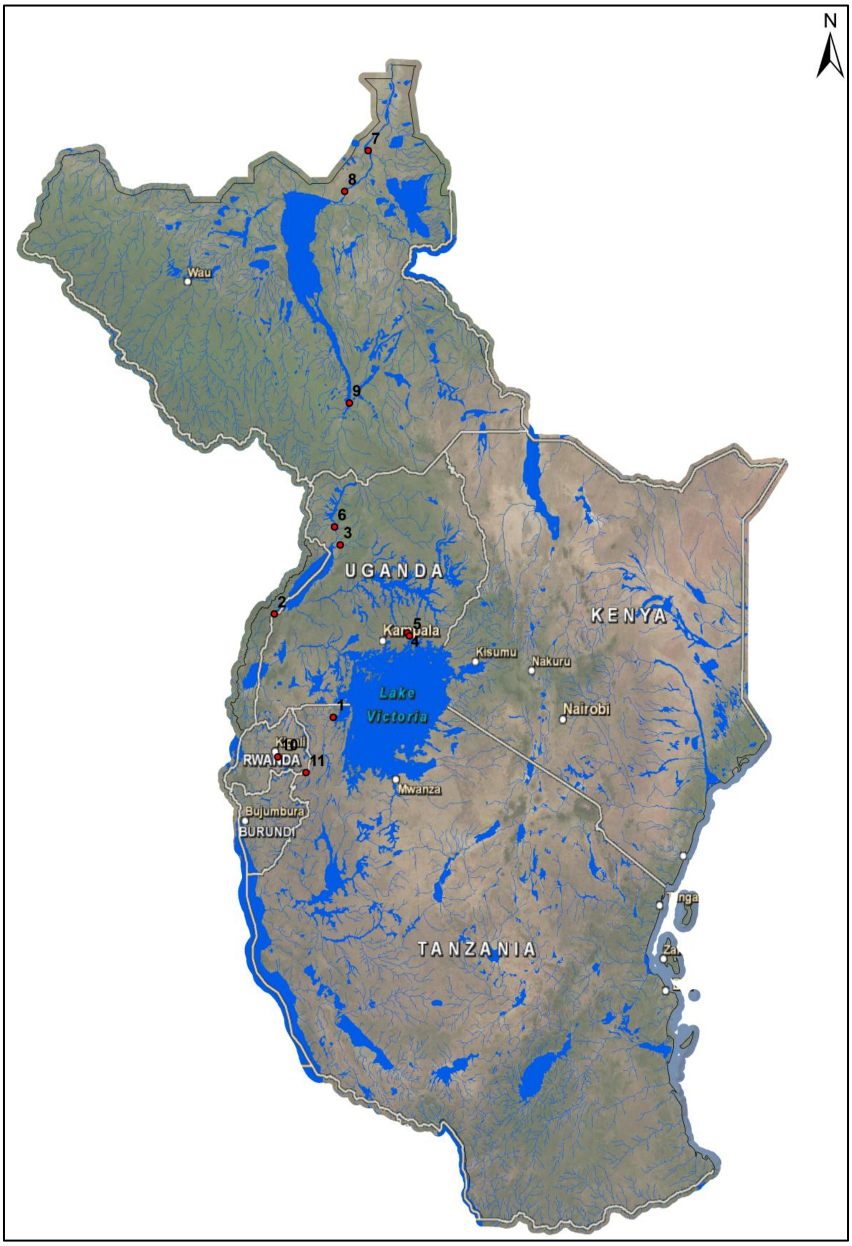


Figure 20: Location of 11 selected streamflow stations (red circles) used for NELmod validation.

In the previous section we applied a correction to the evapotranspiration from wetlands. The wetland surface area depends on the inflow from upstream, the evapotranspiration from the wetland, and rainfall onto the wetland area. A well-known concept in hydrology is the Rational Method (Dooge, 1957; Mulvany, 1850), which is a way to relate precipitation to the resulting streamflow from a catchment. The underlying concept is that each catchment has a time of concentration, which is the time needed for the water to flow from the most distant point of the catchment to the outlet. Then the peak discharge takes place when the entire catchment area contributes to the outflow. Thus for a mean rainfall over that period, the peak rate of flow is:

$$Q = C * I * A$$

Where:	Q	=	*Peak rate of flow* $[L^3\ T^{-1}]$
	I	=	*Rainfall* $[L\ T^{-1}]$
	A	=	*Basin area* $[L^2]$
	C	=	*Runoff coefficient*

Considering the equation above, the runoff coefficient relates the rainfall and basin area to the peak rate of flow. If we take the wetland as the control volume, and we know that the size varies throughout the year, then we need to apply a correction to the runoff coefficient. This means the correction has been applied to the routed streamflow. In other words, the correction has been applied to the right-hand side of the previous equation.

Table 12: Selected streamflow stations used for validation of the model.

id	name	country	latitude	longitude	Average Flow (m3/s)	Records
1	KYAKA FERRY	TZ	-1.27	31.42	194	384
2	BWERAMULE	UG	0.93	30.00	147	273
3	PAARA	UG	2.28	31.57	946	276
4	OWEN RESERVOIR	UG	0.47	33.12	1,176	120
5	JINJA	UG	0.43	33.20	909	300
6	PANYANGO	UG	2.65	31.65	1,079	276
7	MELUT	SD	10.43	32.20	1,014	120
8	MALAKAL	SD	9.58	31.62	939	852
9	MONGALLA	SD	5.20	31.77	1,050	852
10	KANZENZE	RW	-2.06	30.11	109	231
11	RUSUMO	RW	-2.38	30.79	223	228

The corrected simulated monthly streamflow and average, minimum and maximum observed monthly streamflow are shown in Figure 21 for station Malakal. The simulations for the other stations are discussed in Phase 1 Report. Streamflow simulations are shown for the period 2002-2010, where 2001 is used to initialize the model.

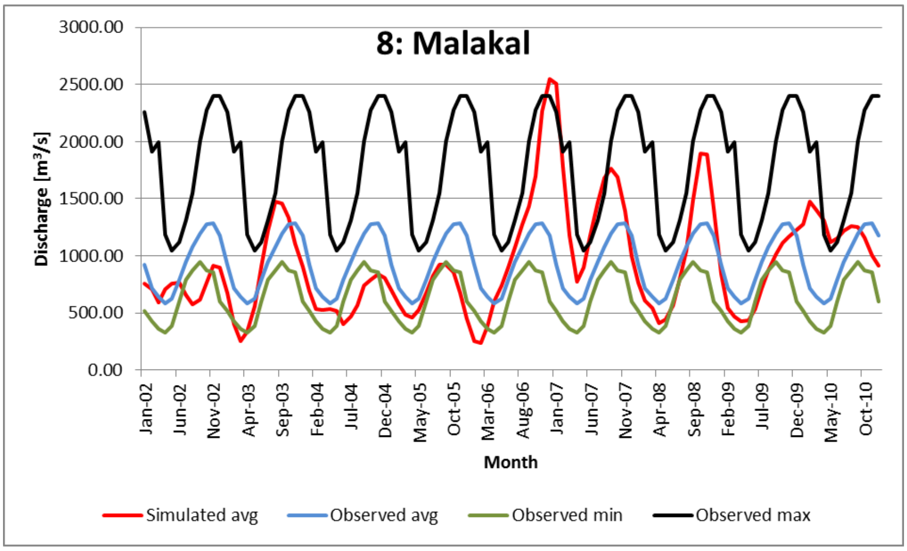


Figure 21: Typical example of NELmod analysis. Simulated monthly streamflow (2002-2010) compared to long-term observed average, minimum and maximum monthly streamflow at Malakal.

Overall the streamflow at the stations is well simulated by NELmod. It is simulated between the range of observed minimum and maximum streamflow. NELmod overestimates the maximum observed streamflow at the end of 2006 and the beginning of 2007. This may be due to a very wet period which is not present in the observed streamflow records.

3.4.2.4 Water availability

Water availability for irrigation is assessed using information from the NELmod model in combination with the irrigation water requirements from ETLook/SEBAL. The NELmod model provides daily results on all aspects of the water balance at a resolution of 250 x 250 meter. This is by far the most advanced and detailed resolution ever done before for the entire region. Most relevant output for this irrigation suitability study is: (i) percolation to groundwater, (ii) runoff and base flow to streams, (iii) flows in streams. Specific results of these components can be seen in the seven country Appendices.

For water availability for irrigation the following method has been followed for the three sources of water (groundwater, streamflow source, potential reservoirs).

For each location the annual irrigation water requirement as originating from ETLook has been compared with the long-term groundwater recharge. This long-term groundwater recharge can be considered as a sustainable use of groundwater resources as withdrawals are compensated by this recharge. If more than three subsequent months groundwater pumping can sustain irrigation demand, the indication of suitable for irrigation was given.

Irrigation water can also originate from existing streamflow. NELmod provides for every stream daily streamflow records. For irrigation from a stream no buffer (like in groundwater or reservoirs) exists and therefore the monthly flow must match the monthly irrigation water requirements. For each stream a buffer of 5 km was assumed around a stream and it was calculated for how many months sufficient water was available. Again if for more than three subsequent months water was available the indication suitable for irrigation was given.

Finally, it was assumed that the option exists to construct a reservoir so that water can be stored during wet seasons. Obviously, construction of reservoirs is only possible if other physical and social aspects allow. Based on the assumption that a reservoir might supply water to an area of 20 km from the reservoir and that the reservoir will be used for at least 5000 ha, suitability has been calculated.

For irrigation directly from the stream as well as from the reservoir downstream flow requirements were included. The issue of downstream flow requirements is very complex and involves environmental as well as political issues. Following various literature on downstream flow requirements we assumed a maximum abstraction following a logarithmic functions of 5*ln(flow) + 1 is used. This equation leads that for large flows never more than 3.6% of the flow can be diverted.

3.4.3 Access to potential water source

A crucial component in assessing the potential for irrigation is the distance from the potential irrigation scheme to natural course of a river, stream or lake or to an existing reservoir. In some cases a canal network will be constructed when the irrigation scheme is developed, however even then access to the natural drainage network is crucial. In addition it is important to assess how much the water needs to be lifted potentially as there are high energy costs associated in the transport of water and in particular to lifting water. The costs for transporting 1 m^3 water 100 km horizontally is approximately equal to lifting 1 m^3 by 100 meter at 0.05 US$/$m^3$ (Zhou and Tol, 2005).

First a raster is created a 250 meter resolution of all streams and reservoirs. The stream network is based on the vector file of the HydroSheds database (Lehner et al., 2008) and the lakes and reservoirs are selected from the level 1 dataset of the Global Lakes and Wetlands Database (Lehner and Döll, 2004). Both vector datasets are reprojected, clipped and rasterized at the nominal resolution of 250 meter. Then for the entire domain the distance and elevation above the nearest stream is calculated as a first order estimate for irrigation potential.

Locations which are further away than 20 kilometer from a natural stream, lake or reservoir are deemed unsuitable for irrigation. Locations which have more than 200 meter of elevation difference to the nearest natural stream, reservoir or lake are also deemed unsuitable. Between 0 and those threshold values the suitability scores vary between 100 and 0. Obviously, water flowing by gravity in existing streams has no restriction at all. The final suitability score for water access is the product of the distance suitability score and the elevation difference suitability score.

3.4.4 Groundwater trends

Groundwater provides most of the domestic water in rural Africa and might supports poverty reduction through irrigation. Reliance on groundwater is likely to increase as rainfall becomes more variable and demand for water becomes greater. Unfortunately, African groundwater resources are poorly understood and lack of borehole data combined with limited efforts on combining these data collectively, makes assessment of potentials difficult.

Based on a collection of locally available data a groundwater resources map for Africa has been developed (Richts et al., 2010). This map (Figure 22) has very limited level of detail and provides just a broad overview of the larger aquifer systems. Moreover, this map is static and is missing information about dynamics in groundwater extraction and recharge. The map also lacks an indication of the amount of water that can be extracted sustainably. In the results of NELmod this sustainability is specifically emphasized by looking at the long-term groundwater recharge as indicator of the sustainable extraction rates.

Recent developments in satellite techniques have led to observations of large scale groundwater fluctuations based on the so-called GRACE satellite. GRACE stands for Gravity Recovery And Climate Experiment (GRACE) and is a twin-satellite mission, developed to measure changes in the Earth's time-variable gravity field (Longuevergne, 2010).

GRACE consists of two polar orbiting satellites that are developed to fly at an altitude ranging from 300 to 500 km and are separated by a distance of about 200 km along track. The Earth's gravity field causes accelerations of the satellites where they approach an area of relatively high mass concentration, and decelerations where they move away from them (see Figure 23). The raw measurements consist of extremely accurate distances between the two satellites, measured by the High Accuracy Intersatellite Ranging System (HAIRS). The acceleration - deceleration behavior of both satellites causes changes in these distances that can be translated back into mass (or gravity) configurations of the Earth.

GRACE data are recovered since May 2002. However results before July 2003 are not very accurate because of a relatively high level of noise in the signal. Also the GRACE data of September and October 2004 are of lower quality due to repeated tracks of the satellites. GRACE data are nowadays processed in three data centers: the Center for Space Research Texas (CSR), the GeoForschungsZentrum Potsdam (GFZ) and the Jet Propulsion Laboratory (JPL). Data from GRACE is presented by University of Colorado GRACE Data Analysis Website (UoC, 2011).

Annual groundwater trends based on GRACE in the entire Nile Basin are plotted in Figure 24. It is clear that for some countries, like Kenya and Uganda, groundwater levels are decreasing by about 10 to 20 mm per year. For some parts of Tanzania and Burundi and Rwanda groundwater levels are somewhat increasing. For the entire Nile (Figure 25) monthly variation is clearly visible and a small downwards trend can be seen for the entire Nile. Country specific trends will be presented in the Appendixes for the individual countries.

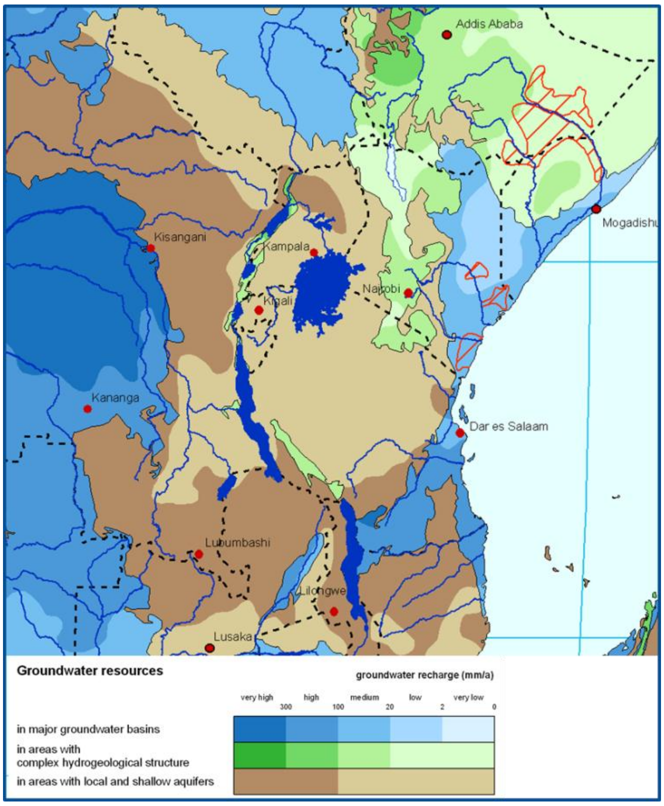


Figure 22: Groundwater resources for Africa (Source: Richts et al., 2010)

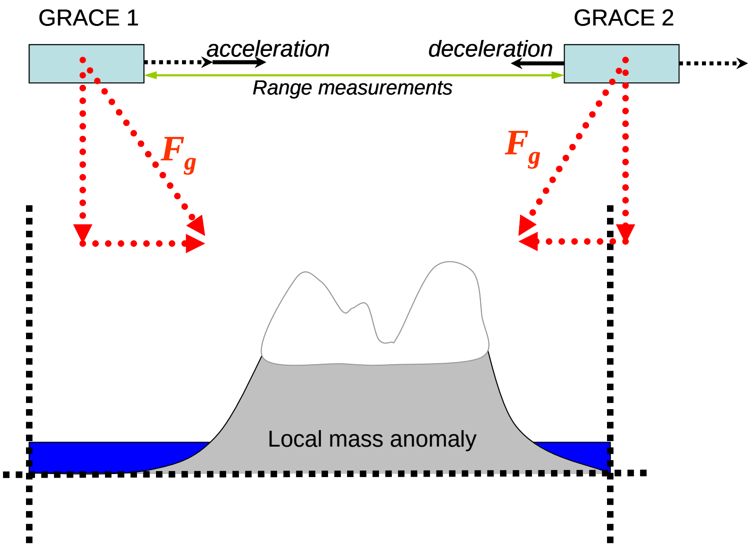


Figure 23: A schematic representation of the way in which GRACE measures the gravity field.

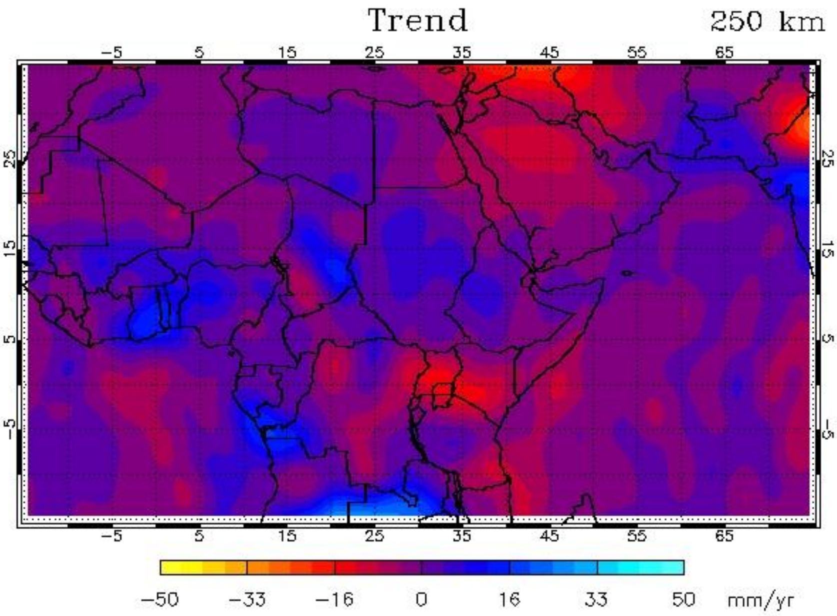


Figure 24. Mean annual groundwater storage trends (Source: UoC, 2011).

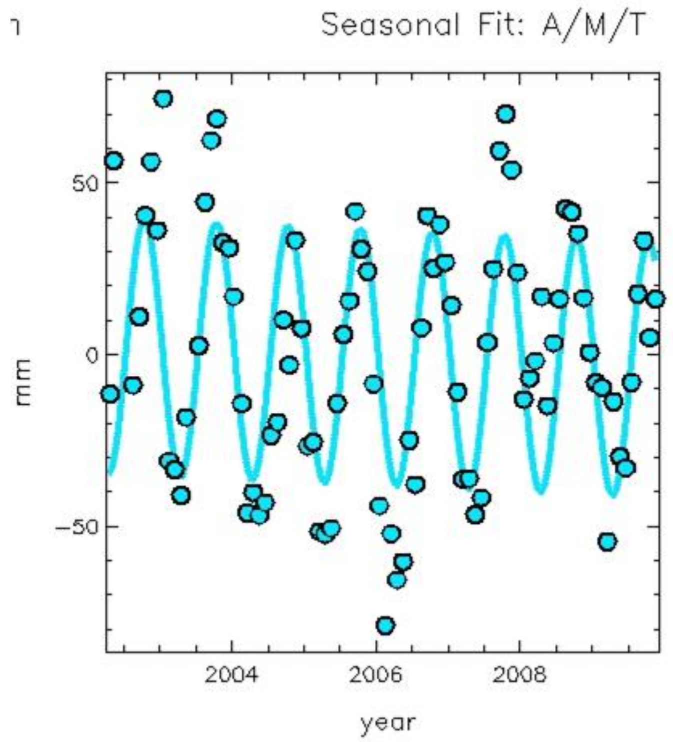


Figure 25: Annual groundwater storage trends for the entire Nile Basin based on GRACE (Source: UoC, 2011)

3.5 Potential crop yield assessment

Potential crop yield assessment is based on the so-called yield-gap analysis. Yield-gap is defined as the difference between the actual yield and the maximum obtainable yield. In general five production constraints can been identified that contribute to explaining the yield gap, i.e. (i) limited water availability, (ii) limited nutrient availability, (iii) inadequate crop protection (iv) insufficient or inadequate use of labor or mechanization, and (v) deficiencies in knowledge and investments (Hengsdijk,, 2009). Water shortages during the growing season can be reduced using irrigation; nutrient limitations can be lifted by applying organic or inorganic fertilizers. Yield reductions due to inadequate control of weeds, pests and diseases can be avoided by introduction of proper crop protection including the use of biocides, phytosanitary methods and crop rotations. Mechanization and labor can be substituted. Insufficient or inadequate application of labor and machinery may contribute to the current yield gap. Especially for operations where timeliness is crucial, such as sowing or planting, limited application may result in yield reductions, e.g. when delayed sowing is done under unfavorable weather conditions (e.g. Cirilo and Andrade, 1994). In other cases, seasonally-specific cultivation patterns may cause temporal labor shortages that, in their turn, reduce the adoption of new technologies. In Africa, where many production situations are based on manual labor, the availability of labor may be limited during the period crucial for weeding. Under these conditions, poorly controlled weed populations may reduce crop yields (e.g. Riches et al., 1997). The fifth production constraint is the most important one, and in fact the dominant factor in many developing countries. Untrained farmers and lack of access to investments is by far the most important factor and highly correlated to the other factors. This may affect crop yields in many ways, e.g. by applying poor quality seed or planting material, inappropriate plant densities, or by selecting poorly adapted crop varieties, damaging plants by inadequate applications of fertilizers or crop protection agents, etc. It may also include incorrect, premature or late harvesting, etc.

Obviously, these production constraints are interrelated and their effects difficult to separate. For example, weather conditions may limit the accessibility of fields to fertilizer application machinery, resulting in decreased nutrient availability and thus reduce crop yields. It is, however, not possible to identify or account for possible interactions and synergies and the production constraints are treated as independent constraints, each individually contributing to the yield gap in a particular region.

The yield-gap analysis is essential to show what might be an obtainable yield if all factors are optimal. In state of using a so-called theoretical yield assuming that none of the restrictions above exists, it was selected to base the yield-gap analysis on realistic and attainable yields. The analysis will therefore compare the countries involved in this study as well as the average of the continent and the highest value obtained somewhere in the world. Moreover, a trend analysis per country will indicate whether improvements can still being made. Results are presented in the seven country Appendixes.

3.6 Environmental, socio-economics

3.6.1 Access to markets

Access to markets is an important factor when irrigated agriculture would be developed. Harvest products should be sold to the local, regional, national or world market. Distance reinforces the effects of low population density on productivity in Africa. While much is made of Africa's distance from world markets, the primary problem is domestic—long distances within countries. Figure 26 indicates that Africa has one of the lowest road densities in the world. Moreover Africa has a third of its population in landlocked countries and even more far from access to global markets. Economic distance has isolated a large proportion of Africans from access to domestic and global markets. Physical factors, such as the relative absence of navigable rivers and natural harbors, have been serious barriers to trade. Low levels of domestic and international trade, in turn, limit the potential for growth.

Distance to nearest markets is therefore an important factor to determine suitability for irrigated agriculture. AfriCover data set includes two classes of towns: (i) major town and (ii) other towns. For major towns a criterion was set that at distances larger than 100 km, suitability would be very low. Between 0 and 100 km a linear suitability index is assumed. For other towns the same approach was used, but here the maximum distance was set at 30 km around a town.

Region	Trading time across borders for exports (days)[a]	Average transport costs ($ per container to Baltimore)[b]	Population in landlocked countries (%)[b]	Ratio of number countries to surface area[b]	Road density (km^2 of road per surface area) (1999)[c]
East Asia & Pacific	24	3,900	0.42	1.44	0.72
Europe & Central Asia	29	–	23.00	1.17	–
Latin America & Caribbean	22	4,600	2.77	1.52	0.12
Middle East & North Africa	27	2,100	0	1.60	0.33
South Asia	34	3,900	3.78	1.67	0.85
Sub-Saharan Africa	40	7,600	40.20	2.00	0.13

Sources: a. World Bank 2006b, p. 44; b. Ndulu and others 2007, p. 101; c. Ndulu and others 2007, p. 29; d. Fearon and Laitin 2003, pp. 7–10.
Note: – = not available

Figure 26. Trade and transport (source: Naude, 2011)

3.6.2 Access to transportation

The infrastructure in developing countries is limited, especially in rural areas. The link between infrastructure and rural development is obvious, through an adequate road network the transportation time and cost can be reduced, this will increase competition and reduce marketing margins. In this way farm incomes and investment opportunities can be improved. FAO (1996) concludes: "infrastructure services are limited in all rural areas, although they are of key importance to stimulate agricultural investment and growth".

The importance of infrastructure for rural development is well established, a recent report states (Andersen and Shimokawa, 2006): "Since the 1960s the importance of agriculture to drive the overall economic growth has been emphasized. Agricultural productivity increase is an important driver for poverty reduction. The productivity increase depends on good rural infrastructure, well-functioning domestic markets, appropriate institutions, and access to appropriate technology.”

Development of irrigation should take into consideration distances to roads for transportation of harvested products. For this, the distance to the nearest transportation option is used. It is assumed that areas further away from a road, railway and/or waterway are less suitable for irrigation. A criterion of 20 km was used. All areas within this 20 km range are scaled between 0 and 100 as suitability score.

3.7 Integration

During Phase 1 of the project focus will be on creating for each country a map at a resolution of 250 x 250 m indicating suitability for irrigation. Some of these maps will be used as general reference while other maps will be used quantitatively. The latter is combined to one map indicating an overall “suitability for irrigation”. A wide range of maps and data resulted from the study (over 500GB). Most relevant maps and tables are presented in this report and especially in the seven country Appendixes. Other maps and data can be found in the digital database attached to the report (for description see Report Phase 1).

Some of these maps are used to create an overall map of “suitability of irrigation”. These maps (determining factors) are all scaled between values of 0 (not suitable) to 100 (very suitable). By combining this information a total suitability map per country is produced. The following maps are used for this:

- Terrain suitability
- Soil suitability
- Water availability
- Distance to water source
- Accessibility to transportation

As indicated before, these maps have to be considered using the other (non-determining) maps and other factors like expert knowledge, existing policies etc. Results can be found in the seven country Appendixes attached to this report.

Based on these country results a total of 34 so-called focal areas were selected for a more detailed analyses and field visits. Selection of this specific focal area was based on results of Phase 1 of this study, while final selection was the responsibility of the relevant country representatives. Results of the 34 focal areas can be found in the seven country Appendixes attached to this report.

4 Data

4.1 Elevation and river network

Elevation data is the basis for the hydrological modeling. Based on the elevation data the streams and watersheds are delineated. Various sources of elevation data are available. As was mentioned in the Inception Report (Droogers et al., 2011), the SRTM DEM is recommended as the source for digital elevation data. Another source of (better) quality elevation data, however, is the **Hydro**logical data and maps based on **SH**uttle **E**levation **D**erivatives at multiple **S**cales (HydroSHEDS[12]). This dataset is based on the SRTM DEM, but is corrected for hydrological applications.

HydroSHEDS (Lehner, 2005) provides hydrographic information in a comprehensive and consistent format for both local and global-scale applications. The goal of developing this database was to generate key data layers in support of regional and global watershed analyses, hydrological modeling, and freshwater conservation planning at previously inaccessible quality, resolution, and extent. HydroSHEDS offers a suite of geo-referenced data sets (vector and raster), including stream networks, watershed boundaries, drainage directions, and ancillary data layers such as flow accumulations, distances, and river topology information. Available resolutions range from 3 arc-second (~ 90 meter) to 5 minute (~ 10 km) at seamless near-global extent.

HydroSHEDS is based on elevation data of the Shuttle Radar Topography Mission (SRTM) at 3 arc-second (~ 90 meter) resolution. To generate HydroSHEDS, the original SRTM elevation data have been hydrologically conditioned in a sequence of automated procedures. Both standard methods of data improvement and newly developed algorithms have been applied, including customized gap filling, filtering, stream burning, and upscaling techniques. Manual corrections were added where necessary. Preliminary quality assessments indicate that the accuracy of HydroSHEDS significantly exceeds that of existing global watershed and river maps.

HydroSHEDS has been developed at the Conservation Science Program of the World Wildlife Fund US (WWF-US), Washington DC, in collaboration with the U.S. Geological Survey (USGS), the International Centre for Tropical Agriculture (CIAT), The Nature Conservancy (TNC), and the Center for Environmental Systems Research (CESR) of the University of Kassel, Germany.

For the current study the 3 arc-second (~90 m) river network was extracted from HydroSHEDS. The 3 arc-second elevation data was resampled to 250 m. Accordingly the 90 m stream network was burned into the resampled 250 m Digital Elevation Model (DEM). This result is shown in Figure 27 for a small part of the study area to verify the high spatial detail. Figure 28shows the Digital Elevation Model of the study area.

[12] http://hydrosheds.cr.usgs.gov/index.php

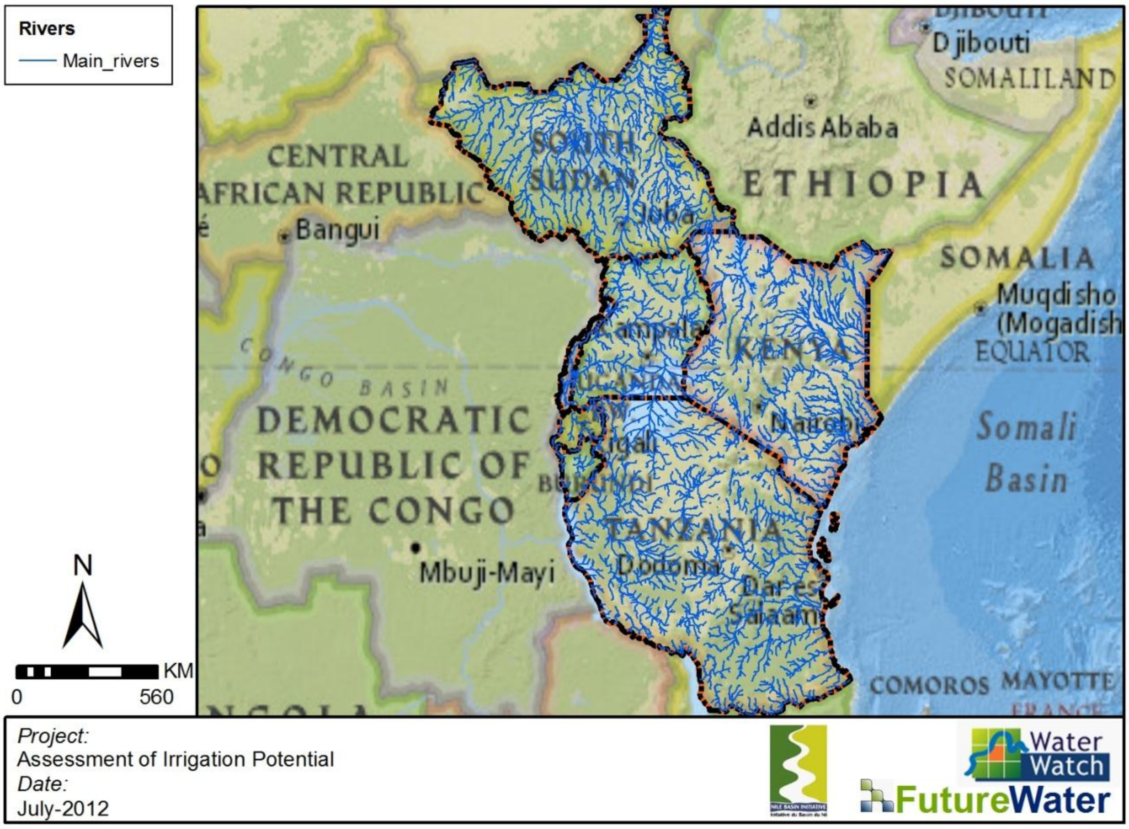


Figure 27: Stream network based on HydroSHEDS.

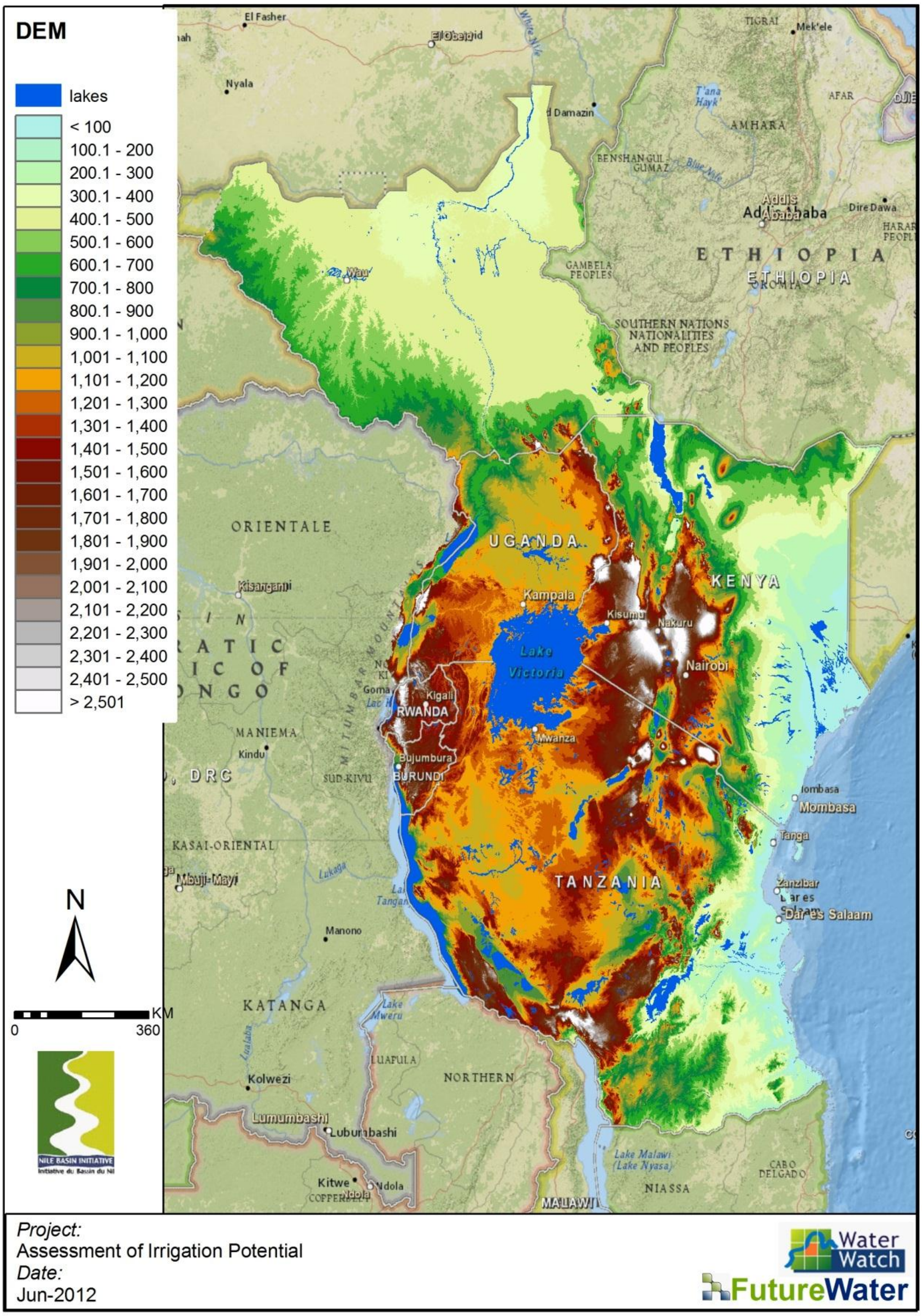


Figure 28: Digital Elevation Model (DEM) based on HydroSHEDS.

It is clear that the spatial variation in elevation throughout the study area is large. Elevation ranges between 5837 m MASL and -8 m MASL. Burundi, Rwanda, Tanzania, and Kenya are relatively mountainous, while Southern Sudan and Uganda are relatively flat.

4.2 Land use

4.2.1 AfriCover

As was mentioned in the Inception Report (Droogers et al., 2011), various sources of land use data are available. The AfriCover land use data is considered to be the best source of land use data for the current project. It's most reliable, because it was formulated to meet the countries requests for a reliable geo-referenced database on natural resources.

The AfriCover Project[13] developed a combined approach to promote the sustainable use of natural resources. The purpose of the AfriCover Project is to establish a digital geo-referenced database on land cover and a geographic referential for the whole of Africa including:

- Geodetically homogeneous referential
- Toponomy
- Roads
- Hydrography

The Multipurpose AfriCover Database for the Environmental Resources (MADE) is produced at a 1:200,000 scale (1:100,000 for small countries and specific areas).

The Eastern Africa module is the first operational component of the AfriCover Project. It was formulated to meet several African countries request for assistance in the set-up of reliable and geo-referenced data-bases on natural resources. It is part of FAO assistance to the Nile Basin countries. The Project has been operational in the period 1995-2002 and was signed by ten countries, including the seven NEL countries. For these seven NEL countries the map scale is 1:100,000.

The AfriCover Database has been downloaded for each of the seven NEL countries. For the purpose of the current study the AfriCover Database has been reclassified, because there was a huge overlap between the original land use classes. This is mainly because AfriCover is generated for each of the countries separately using their own country specific classification system. Therefore these classes were reclassified to have a uniform system for all the NEL counrties. The final result is a land use map with 37 land use classes as is shown in Figure 29. This map forms the basis for the hydrological modeling.

For the water resources assessment the rooting depths are extracted, based on the land use classes as shown in Figure 18. For the water resources assessment, however, it is of major importance to know the growing periods of the various crops. The different growing periods throughout the year are translated to different crop factors within a year, meaning that the potential evapotranspiration will be variable, and not based on a single crop factor. These growing periods are not provided by AfriCover, because in AfriCover it is assumed that the

[13] http://www.africover.org/index.htm

vegetation is present all year round. For this reason, additional information related to the growing periods of the agricultural crops is required. This information is taken from the MIRCA database.

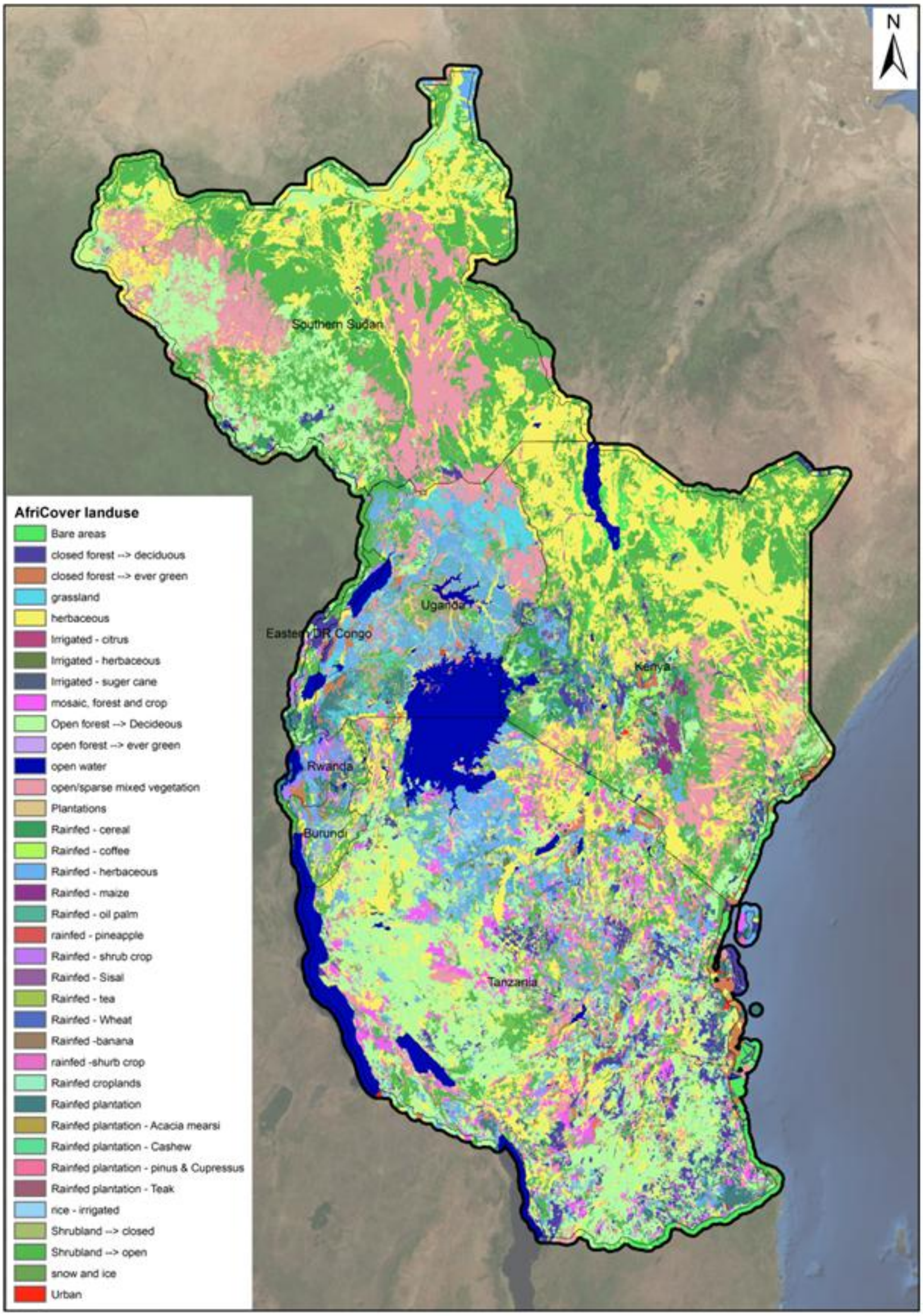


Figure 29: Land use map of the NEL countries, based on reclassified AfriCover.

4.2.2 MIRCA

The Institute of Physical Geography of the University of Frankfurt, Germany, developed a data set of monthly growing areas of 26 irrigated and rainfed crops and related crop calendars (Portmann et al., 2010). The selection of the crops consisted of all major food crops including regionally important ones (wheat, rice, maize, barley, rye, millet, sorghum, soybeans, sunflower, potatoes, cassava, sugar cane, sugar beet, oil palm, rape seed/canola, groundnuts/peanuts, pulses, citrus, date palm, grapes/vine, cocoa, coffee), major water-consuming crops (cotton), and unspecified other crops (other perennial crops, other annual crops, fodder grasses). The data set refers to the period 1998-2002 and has a spatial resolution of 5 arc-minutes by 5 arc-minutes which is about 9.2 km by 9.2 km at the equator. An overview of all the MIRCA crop classes is shown in Table 13.

Table 13: MIRCA crop classes (rainfed and irrigated)

MIRCA crop code	*MIRCA crop name*
1	Wheat
2	Maize
3	Rice
4	Barley
5	Rye
6	Millet
7	Sorghum
8	Soybeans
9	Sunflower
10	Potatoes
11	Cassava
12	Sugar cane
13	Sugar beet
14	Oil palm
15	Rape seed / Canola
16	Groundnuts / Peanuts
17	Pulses
18	Citrus
19	Date palm
20	Grapes / Vine
21	Cotton
22	Cocoa
23	Coffee
24	Others perennial
25	Fodder grasses
26	Others annual

It is the first time that a global data set distinguishing growing areas of irrigated and rainfed crops were created at this spatial resolution. The data set is consistent to the irrigated area statistics of the AQUASTAT programme of the FAO[14] and to version 4.0.1 of the Global Map of Irrigation Areas[15] (GMIA). At the cell-level it was tried to maximize consistency to total cropland extent and harvested crop areas provided by the Center of Sustainability and the Global

[14] http://www.fao.org/nr/water/aquastat/main/index.stm
[15] http://www.fao.org/nr/water/aquastat/irrigationmap/index.stm

Environment[16] (SAGE) of the University of Wisconsin at Madison. The development of monthly growing area grids and related crop calendars for irrigated crops is documented in Portmann et al. (2010).

As mentioned before, the MIRCA dataset can be seen as an refinement of the AfriCover dataset, because AfriCover assumes a crop to be present throughout the entire year. With MIRCA the crop factor (Kc) can be made variable throughout the year, which in the end will improve the calculation of the potential evapotranspiration and thus our model results.

4.3 Soils

4.3.1 General

Soil information is the basis for all environmental studies. Soil science has been the dominant factor in many of these studies for a long time. Over the last two decades a huge leap forward has been made on using quantitative methods for environmental studies, based on three major developments (i) increased computer power, (ii) satellites, and (iii) concerns on global changes. Soil science was not able to cope to this move towards quantitative analysis, because of the nature of soils science itself (e.g. not visible from satellites) and the long-term tradition of soil scientists. This has led to an unacceptable gap in quantitative soils data in global environmental studies.

Various initiatives to overcome this data gap have been started, but so-far no concrete results have been delivered. To overcome this data gap various best-estimates data sets have been developed (e.g. Droogers, 2002). Most of these global best-estimates datasets were based on the well-known The FAO/UNESCO Digital Soil Map of the World.

The last few years, some additional global soil information has become available. Unfortunately, these products are often still missing the quantitative information required for environmental studies.

For the current study, various sources of soil data are available. These sources of soil data are described in detail in the Inception Report (Droogers et al., 2011). Therefore the Harmonized World Soil Database was considered to be the best source of soil data for this study.

[16] http://www.sage.wisc.edu/pages/datamodels.html

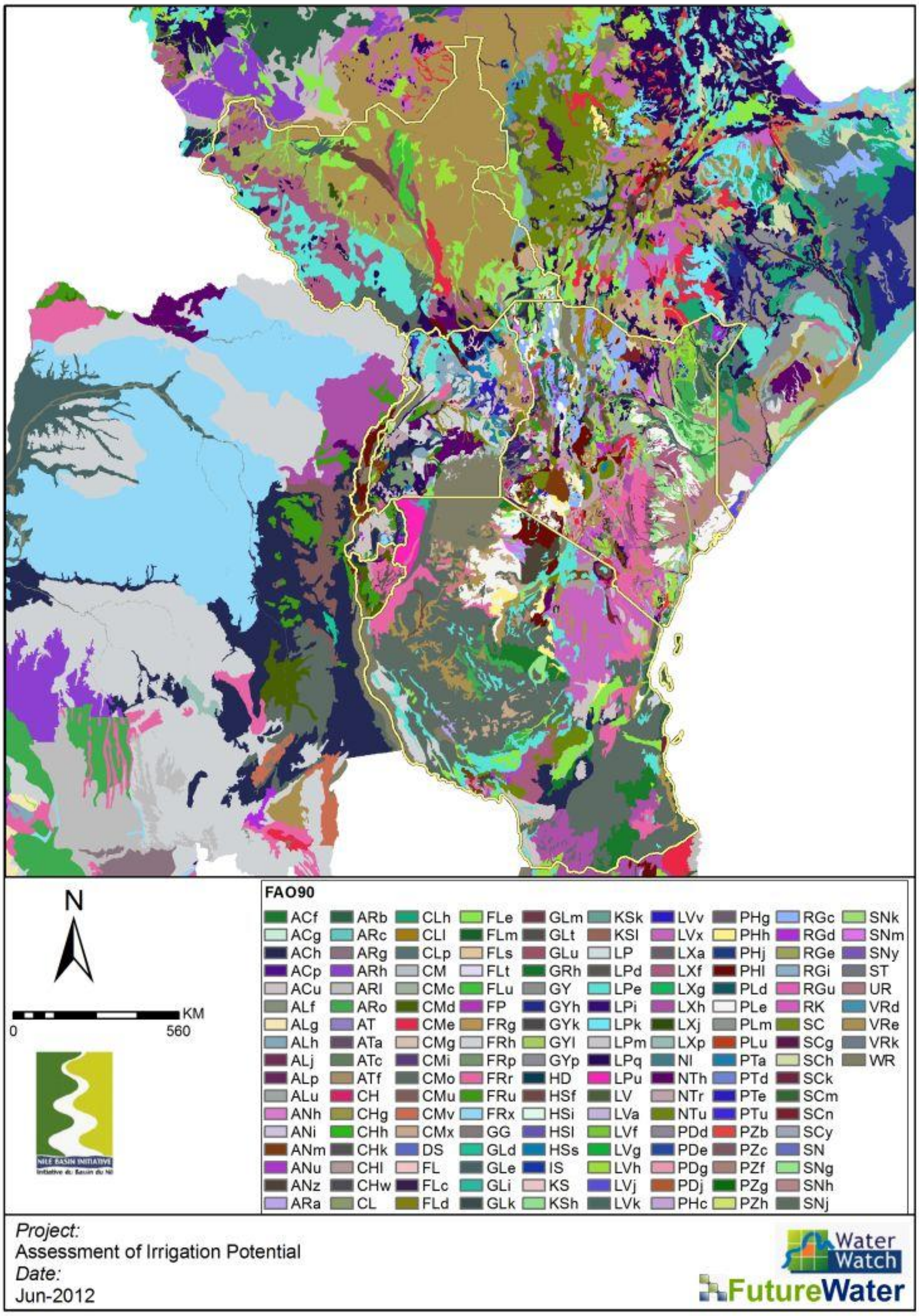


Figure 30: Harmonized World Soil Database of the study area. (Legend: FAO, 1990)

4.3.2 Harmonized World Soil Database

In 2008 a new global dataset was developed under the name “Harmonized World Soil Database” (HWSD) (FAO, 2009) existing out of a 30 arc-second (~1 km resolution) raster database with over 15000 different soil mapping units that combines existing regional and national updates of soil information worldwide (SOTER, ESD, Soil Map of China, WISE) with the information contained within the 1:5 000 000 scale FAO-UNESCO Soil Map of the World (FAO, 1974). The Harmonized World Soil Database is considered to be the most detailed available. The resulting global raster database consists of 21600 rows and 43200 columns, which are linked to harmonized soil property data. The use of a standardized structure allows for the linkage of the attribute data with the raster map to display or query the composition in terms of soil units and the characterization of selected soil parameters (organic Carbon, pH, water storage capacity, soil depth, cat-ion exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry). The HWSD of the NEL countries is shown in Figure 30.

4.3.3 Soil texture parameters

A basic soil parameter is the soil texture. This parameter is also required to obtain the soil hydraulic characteristics as required in NELmod. HWSD has for a small number of soil-unit no values and in these cases the texture is determined based on the soil-unit name. FAO textures are “coarse”, “medium”, or “fine”, and are designated with a “1” (coarse), “2” (medium), or “3” (fine) following the soil-unit symbol. These textures are defined in the FAO documentation based on the soil texture classes form the USDA Soil texture triangle (FAO/UNESCO, 2003). The USDA Soil Texture Triangle is shown in Figure 31 an these textures can be redefined as illustrated on the keft side of Figure 31. The corresponding texture names are shown in Figure 14.

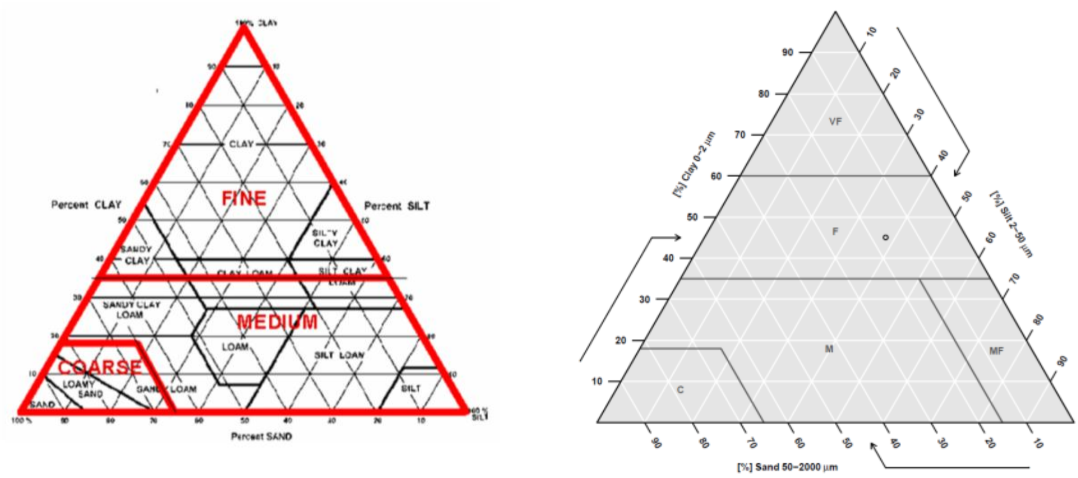


Figure 31: USDA Soil Texture Triangle with FAO soil textures outlined (left) and USDA (right).

Table 14: Names soil textures, based on the USDA Soil Texture Triangle.

Abbr	*Description*
O	Organic
VF	Very Fine
F	Fine
M	Medium
MF	Medium Fine
C	Course

The soil textures where defined as:

Organic soils: OM > 20%

Mineral soils: Clay > 60%: VF

else

Clay > 35%: F

else

Sand < 15%: MF

else

Clay < 18% and Sand > 65%: C

else M

4.3.4 Soil physical parameters

Additional physical soil parameters were derived using the van Genuchten function (Van Genuchten, 1980):

$$\theta(\Psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\Psi|)^n]^{1-1/n}}$$

Where: $\theta(\Psi)$ = the water retention curve $[L^3L^{-3}]$;

$|\Psi|$ = suction pressure ($[L^{-1}]$ or cm of water);

θ_s = saturated water content $[L^3L^{-3}]$;

θ_r = residual water content $[L^3L^{-3}]$;

α = related to the inverse of the air entry suction, $\alpha > 0$ ($[L^{-1}]$, or cm^{-1});

n = measure of the pore-size distribution, $n > 1$ [-];

The van Genuchten soil-water retention and hydraulic conductivity functions with the Mualem (Mualem, 1976) substitutions are:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha VG * h)^n]^{-m}$$

$$K = K_s \frac{\left[1 - (\alpha VG * h)^{n-1}[1 + (\alpha VG * h)^n]^{-m}\right]^2}{[1 + (\alpha VG * h)^n]^{-m/2}}$$

$$m = 1 - \frac{1}{n}$$

Where: θ = the volumetric water content [-];

h = pressure head [L];

θ_r	=	residual water content [-];
θ_s	=	saturated water content [-];
n	=	empirical parameter relating to the pore-size distribution [-];
m	=	empirical parameter relating to the pore-size distribution [-];
K_s	=	saturated hydraulic conductivity [L T^{-1}];
K	=	unsaturated hydraulic conductivity as a function of pressure head;
αVG	=	a constant [L^{-1}];

The final soil parameters, which were added to the HWSD, are shown in Table 4.

Table 15: Soil attributes which were added to the original HWSD.

Attr	*Description*	*Unit*
T_Class	Soil class (top soil)	O, VF, F, M, MF, C
S_Class	Soil class (sub soil)	O, VF, F, M, MF, C
T_ ALFA	MVG alpha (top soil)	cm^{-1}
T_N	MVG n (top soil)	-
T_WCSAT	MVG sat water content (top)	$m^3\ m^{-3}$
T_WCRES	MVG res water content (top)	$m^3\ m^{-3}$
T_KSAT	MVG Ksat (top)	cm d^{-1}
T_L	MVG L (top)	-
S_ ALFA	MVG alpha (sub soil)	cm^{-1}
S_N	MVG n (sub soil)	-
S_WCSAT	MVG sat water content (sub)	$m^3\ m^{-3}$
S_WCRES	MVG res water content (sub)	$m^3\ m^{-3}$
S_KSAT	MVG Ksat (sub)	cm d^{-1}
S_L	MVG L (sub)	-
T_pF2	Field capacity (top)	$m^3\ m^{-3}$
T_pF3	Wilting point (top)	$m^3\ m^{-3}$
T_pF4	Permanent wilting point (top)	$m^3\ m^{-3}$
T_avail	Soil water holding capacity (top)	$m^3\ m^{-3}$
S_pF2	Field capacity (sub)	$m^3\ m^{-3}$
S_pF3	Wilting point (sub)	$m^3\ m^{-3}$
S_pF4	Permanent wilting point (sub)	$m^3\ m^{-3}$
S_avail	Soil water holding capacity (sub)	$m^3\ m^{-3}$

4.4 Climate

4.4.1 Precipitation

In this study, precipitation will be used as input to the hydrological modeling. Because precipitation is known to be spatial highly variable, it is preferred to have a dense network of precipitation stations, or to use high resolution satellite-based precipitation products (TRMM, PERSIANN, FEWS-NET). During the Inception Phase it was proven that the FEWS-NET rainfall data are the most accurate one. Moreover, FEWS-NET is already corrected by local data.

Given the importance of rainfall, it was however decided to undertake additional correction by using local data as collected by the German Weather Services and distributed in the GPCC database.

4.4.1.1 FEWS-NET

One day estimates of precipitation for the African continent are prepared operationally at the Climate Prediction Center (CPC) for the United States Agency for International Development (USAID) as a part of the Famine Early Warning System Network (FEWS-NET[17]). The algorithm for the rainfall estimates uses Meteosat 7 geostationary satellite infrared data that are acquired in 30-minute intervals, and areas depicting cloud top temperatures of less than 235K are used to estimate convective rainfall. Two other satellite rainfall estimation instruments are incorporated into the algorithm, being the Special Sensor Microwave/Imager (SSM/I) on board of the Defense Meteorological Satellite Program satellites, and the Advanced Microwave Sounding Unit (AMSU). All satellite data are first combined using the maximum likelihood estimation method, and then GTS station data are used to remove bias. Warm cloud precipitation estimates are not included in the algorithm. The most recent version available is the RFE2.0 version, which is compared to version RFE1.0 more accurate. This version produces daily precipitation output on a 0.1 degree (~10 km) spatial resolution, and on a spatial extent from 40°S-40°N and 20°W-55°E. An example of one day output of RFE2.0 is shown in Figure 32.

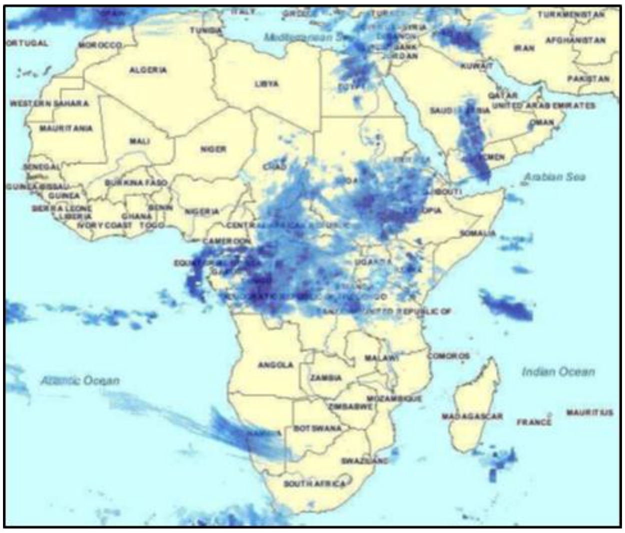


Figure 32: Rainfall estimate obtained from FEWS-NET (24/11/2000).

4.4.1.2 Global Precipitation Analysis Product of the GPCC

For the correction of FEWS-NET precipitation we have used the Global Precipitation Climatology Centre's (GPCC[18]) Full Data Reanalysis Product. The GPCC has been established in 1989 on request of the World Meteorological Organization (WMO). It is operated by the Deutscher Wetterdienst (DWD[19], National Meteorological Service of Germany) as a German contribution to the World Climate Research Programme (WCRP).

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[17] http://www.fews.net/Pages/default.aspx
[18] *gpcc.dwd.de*
[19] http://www.dwd.de

All GPCC products are gauge-based gridded monthly precipitation data sets for the global land surface. Available spatial resolutions are 1.0° x 1.0° and 2.5° x 2.5° geographical latitude by longitude. Non-real-time products are based on the complete GPCC monthly rainfall station database (the largest monthly precipitation station database of the world with data from ca. 85,000 different stations) are also available in 0.5° x 0.5° resolution. GPCC's new global precipitation climatology based on data from ca. 64,400 stations is used as background climatology for GPCC analyses. The different GPCC products are used world-wide by various institutions, in particular in context of water- and climate-related research and monitoring activities of WMO, WCRP, GCOS, FAO, and UNESCO.

The Full Data Reanalysis Product, which is used in the current study to correct FEWS-NET, is of the highest accuracy of all GPCC products. Therefore, its application is recommended for hydro-meteorological mode verification and water cycle studies. This analysis product is based on all stations, near real-time and non-real-time. It covers the period 2001-2009 on a spatial resolution of 0.5 degrees. An overview of the spatial distribution of the stations in Africa is shown in Figure 33. This product is used because it is based on real station data, and therefore the best available source to correct the FEWS-NET precipitation. The GPCC product cannot directly be used for our hydrological modelling because its spatial resolution is to coarse, and it only contains monthly precipitation data.

Other references to GPCC related studies are [Beck et al., 2004], [Huffman et al., 1995], [Legates and Willmott, 1990], [Rudolf and Schneider, 2005], [WMO, 1985] and [Xie and Arkin, 1997].

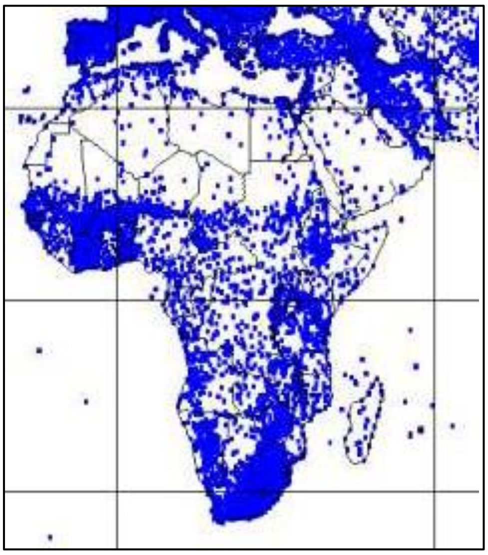

Figure 33: Spatial distribution of GPCC's monthly in-situ stations available in the GPCC database.

4.4.1.3 Correction method

As mentioned in Section 4.4.1.2 we will use the 0.5 degrees gridded Full Data Reanalysis Product of the GPCC to correct the daily FEWS-NET precipitation. The correction factors are derived on a monthly basis, because precipitation is known to be different throughout the year. To achieve this, the daily FEWS-NET precipitation was aggregated to monthly precipitation grids. This resulted in 108 monthly precipitation grids for the period 2001-2009. These grids were then averaged over the 9 years, resulting in 12 precipitation grids representing the average monthly precipitation sums for 2001-2009. The GPCC precipitation was already in the correct monthly format. The remaining steps for the determination of the correction factors are illustrated in Figure 34. The descriptions of these steps are given below:

1. For each month we need a FEWS grid with the average precipitation sum over the period 2001-2009. This data is in a WGS1984 coordinate system at a spatial resolution of 0.1°;
2. The grid of step 1 needs to be projected to the African Albers Equal Area projection and rescaled to a resolution of 1 km for our hydrological model. This results in the figure as shown in the arrow;
3. For each month we need a GPCC grid with the average precipitation sum over the period 2001-2009. This data was in a WGS1984 coordinate system at a spatial resolution of 0.5°;
4. The grid of step 3 needs to be projected to the African Albers Equal Area projection and rescaled to a resolution of 1 km for our hydrological model. This results in the figure as shown in the arrow;
5. To derive the monthly correction factor we need to divide the GPCC grid (result of step 2) by the FEWS grid (result of step 4). This results in a monthly correction grid, which will be applied to all FEWS-NET daily precipitation grids for the corresponding month. FEWS-NET is then corrected according to:

$$FEWS_{corr,i} = FEWS_{uncorr,i} \times CORFAC_m$$

where:	$FEWS_{corr,i}$	=	*corrected FEWS on day i;*
	$FEWS_{uncorr,i}$	=	*uncorrected FEWS on day i;*
	$CORFAC_m$	=	*correction factor for month m;*

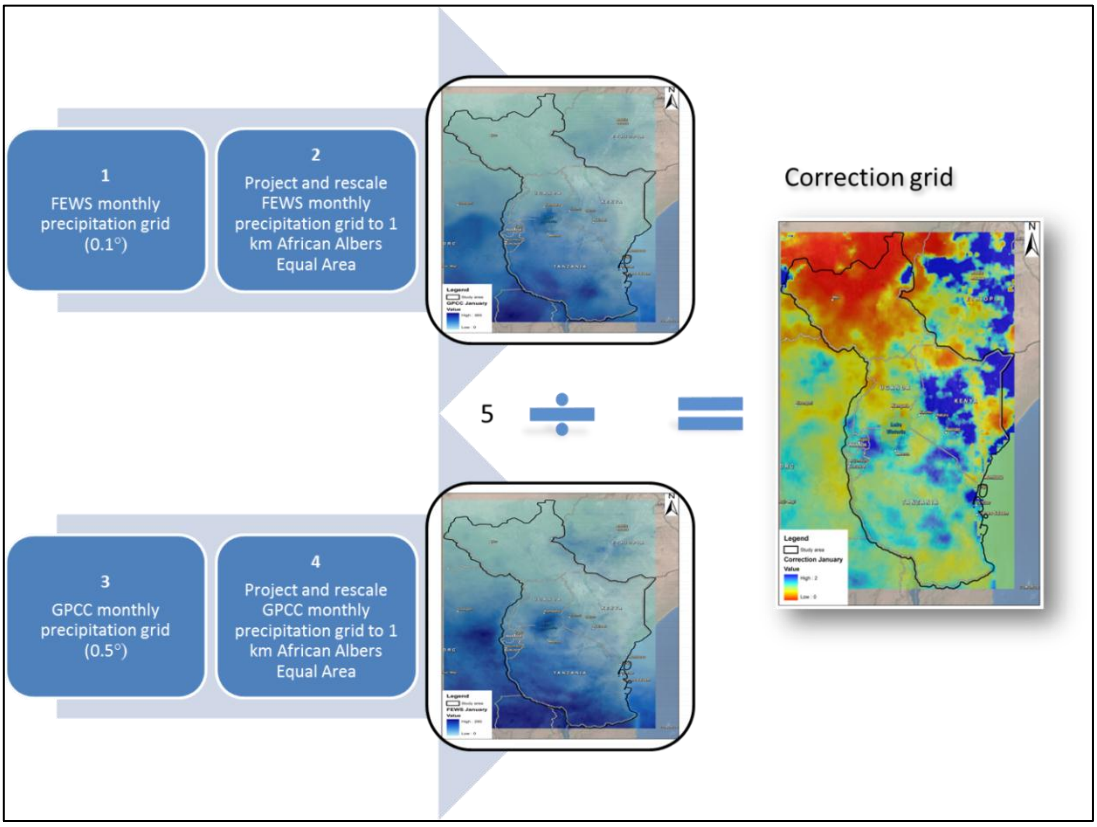

Figure 34: Steps to be taken to derive the correction grids for FEWS-NET.

4.4.1.4 Evaluation of corrected FEWS-NET

Annual precipitation pattern

The annual precipitation for the NEL countries is shown in Figure 35for the period 2001-2010. This figure is based on the corrected FEWS-NET precipitation. There is a clear precipitation pattern present throughout the years; an arid region in the east and southeast, and a more humid climate in the west and southwest of the NEL countries. Kenya is known to be the country with the lowest annual precipitation, having less than 100 mm of precipitation in some regions. The wettest part of the study area is the region around Lake Victoria. Mainly Uganda and the western part of Kenya are relatively wet. Based on this figure it is clear that 2005 is the year with the lowest annual precipitation, and 2006 is the year with the largest precipitation amount. This is also shown in Figure 36, in which the annual precipitation is averaged over the NEL countries. The horizontal line in this graph represents the overall annual average, which is 900 mm.

The annual precipitation has also been analyzed for each of the NEL countries separately. Figure 37 represents the average annual precipitation per country for the period 2001-2010. The vertical bars in this plot represent the within country variation of precipitation (mean plus/minus one standard deviation). The variation in precipitation within a country is larger if these bars are larger. It is clear that 2005 is not the driest year for all NEL countries. This is only true for Kenya, Uganda, and Southern Sudan. For Burundi, Rwanda, and Tanzania, 2003 seems to be the driest year. Eastern DR Congo was driest during 2008. Figure 10 also indicates that the within country variation in precipitation is quite constant over the years. Burundi has the smallest within country variation in precipitation (ca. 200 mm), and Kenya has the largest within country variation of precipitation (ca. 600 mm). This is of course related to the sizes of these countries. Besides the evaluation of annual precipitation patterns it is relevant to analyze the monthly precipitation as well, because precipitation is known to be season varying. Section 4.5.3.2 describes the monthly precipitation analysis.

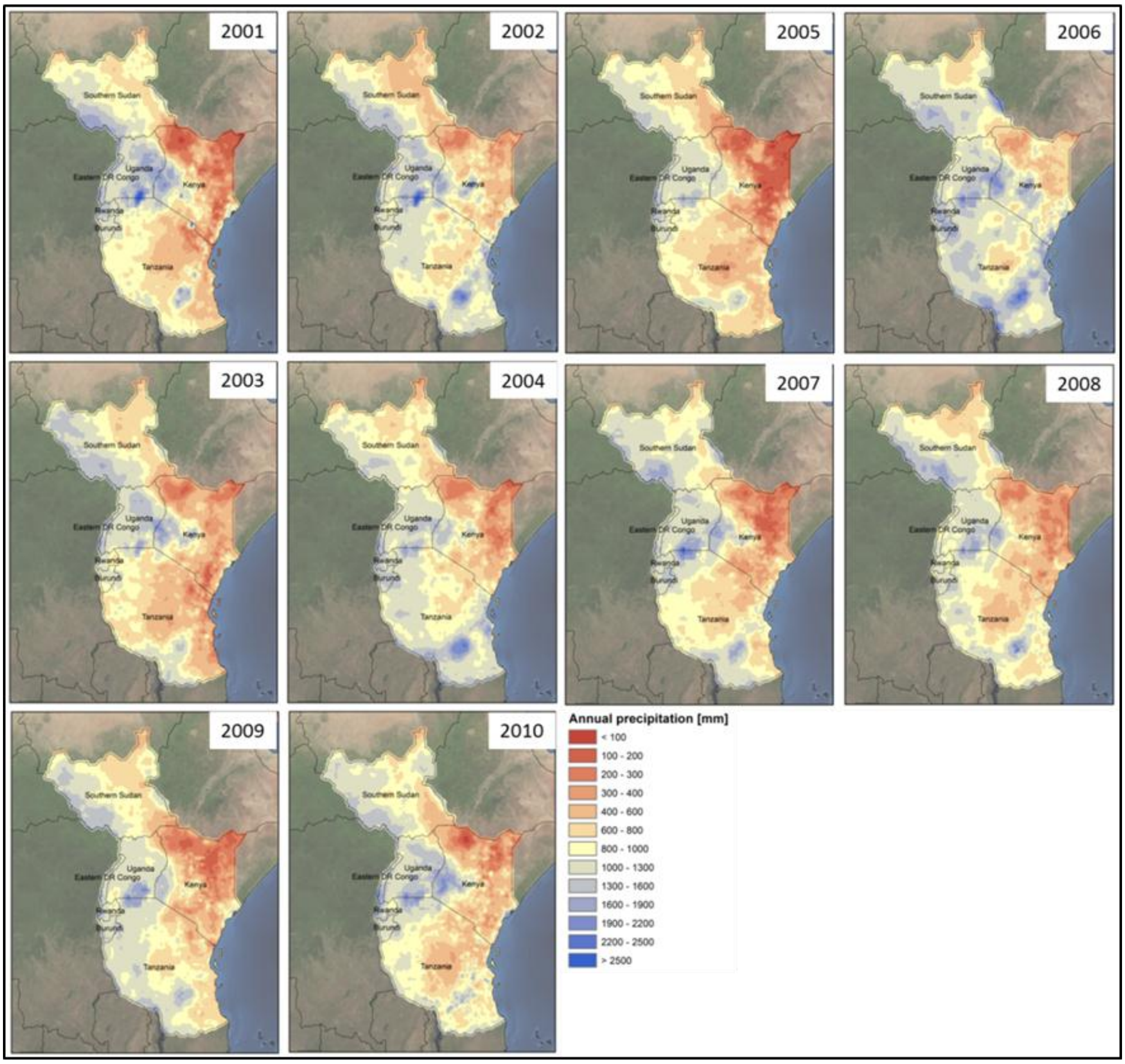

Figure 35: Annual precipitation for the NEL countries for the corrected FEWS-NET precipitation product.

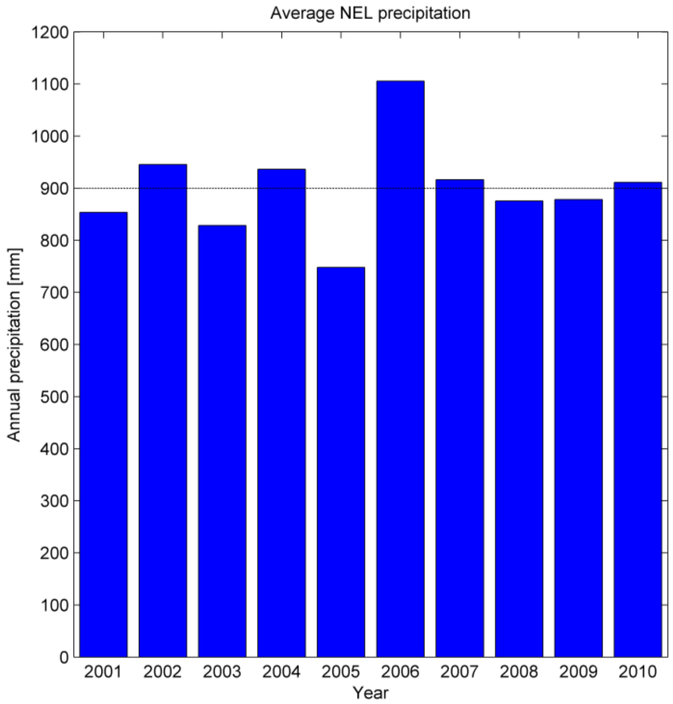

Figure 36: Average annual precipitation over all NEL countries.

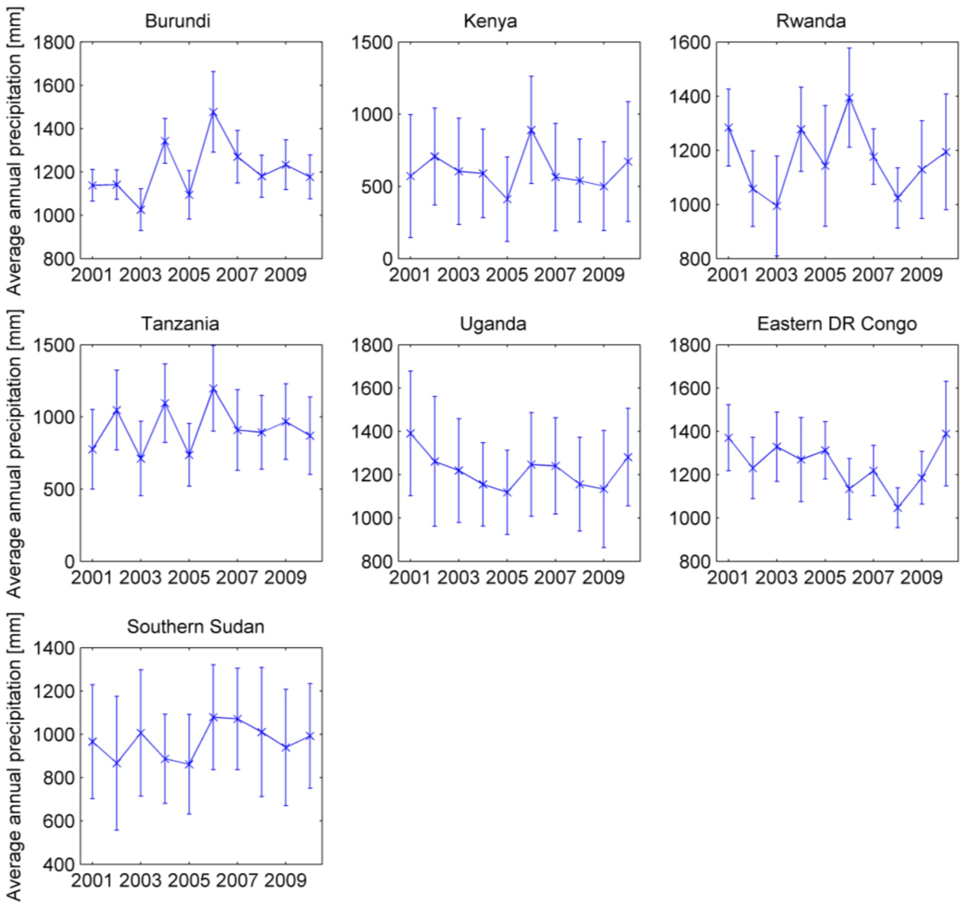

Figure 37: Average annual precipitation per country. The bars indicate the within country variation of precipitation (mean +/- one standard deviation).

Monthly precipitation

Figure 38shows the average monthly precipitation for the period 2001-2010 for the NEL countries. A clear seasonal precipitation pattern is present for the NEL countries. From December through April the northern and eastern part of the study area are dry, while the central and southern part are relatively wet. Then from May through October the pattern more or less shifts, with the eastern and southern part being the driest, and the northern and western part being the wettest. In November the northern and southern part are dry when compared to the eastern and western part of the study area. The driest region is Kenya, which was also concluded in the previous section. It is clear that April is the wettest month for most countries. June seems to be the driest month for most NEL countries.

The monthly precipitation analysis has also been performed for each of the NEL countries individually. Figure 39shows the average monthly precipitation for each of the NEL countries, and the within country variation of precipitation (as indicated with the bars). Kenya, Rwanda, Uganda, and Eastern DR Congo seem to have two rain seasons with two drier periods in between. June-August and December-February are more or less the drier periods for these countries, while September-November and March-May are the wetter periods. Burundi and Tanzania have a clear dry period which runs from June through September. The precipitation pattern in Southern Sudan is the opposite of what is noticed in the other countries, with June-September being relatively wet, and the remaining months being relatively dry. The within country variation of precipitation can be large, and is largest for Kenya, as was already noticed in the previous section. The within country variation of precipitation varies throughout the year, and is for most countries largest during the high precipitation months, and lowest during the drier months.

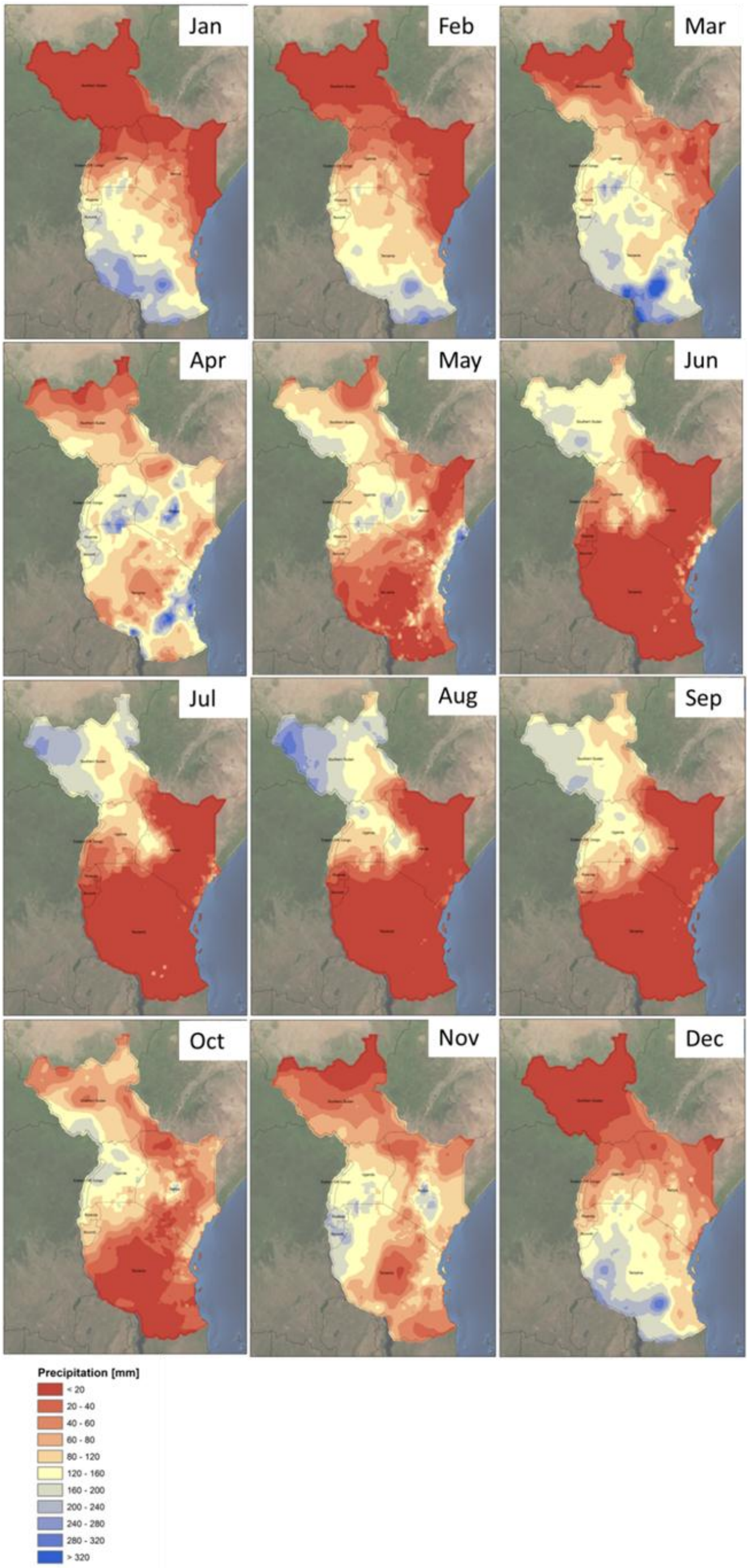

Figure 38: Average monthly precipitation for the period 2001-2010.

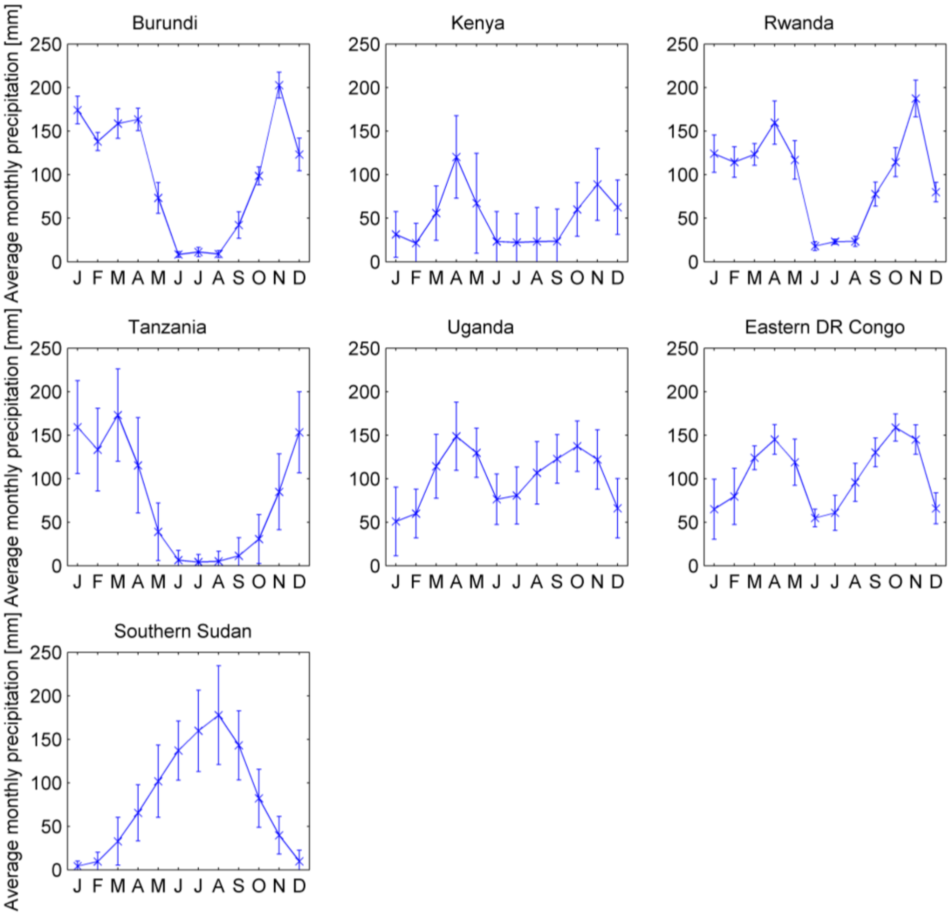

Figure 39: Average monthly precipitation per country. The bars indicate the within country variation of precipitation (mean +/- one standard deviation).

4.4.2 Evapotranspiration

4.4.2.1 Reference Evapotranspiration

For the calculation of the reference evapotranspiration the Penman-Monteith (Allen et al., 1998) equation will be used:

$$ET_{ref} = \frac{s(R_n)+\rho c_p(e_s-e_a)}{s+\gamma(1+\frac{r_s}{r_a})}\left(\frac{86400}{\lambda}\right)$$

Where:	*ET_{ref}*	=	*Reference evapotranspiration [mm];*
	s	=	*Slope vapor pressure curve [kPa oK-1]*
	Rn	=	*Daily net radiation [W m-2]*
	r	=	*Air density [kg m-3]*
	cp	=	*Specific heat of air = 1004 J kg-1 K-1*
	es	=	*Saturation vapor pressure [kPa]*
	ea	=	*Actual vapor pressure [kPa]*
	g	=	*Psychrometric constant [kPa oK-1]*
	rs	=	*Bulk stomatal resistance for a grass reference crop = 70 s m-1*
	ra	=	*Aerodynamic resistance for a grass reference surface [s m-1]*

l = *Latent heat of vaporization [J kg-1]*

The daily net radiation is determined as follows:

$$R_n = (1-\alpha)R_a\tau - \sigma T_{air}^4\left(0.34 - 0.14\sqrt{e_a}\right)(1.35\tau - 0.35) \quad \text{[W m-2]}$$

Where:	R_n	=	*Net radiation [W m-2];*
	Ra	=	*Extra-terrestrial radiation [W m-2]*
	t	=	*Atmospheric transmissivity [-]*
	s	=	*Stefan Boltzman constant [-]*
	Tair	=	*Daily mean air temperature [K]*

The data requirements for the calculation of the ETref are:

- Digital elevation map (DEM) [masl, 1km resolution];
    - Radiation model for deriving daily mean extraterrestrial radiation;
    - Air density as function of height;
    - Air temperature as function of height;
    - Relative humidity as function of height;
- Daily mean air temperature [^{o}C];
- Daily mean relative humidity [%];
- Daily mean wind speed [m s-1];
- Daily mean atmospheric transmissivity [-];

These data are extracted from NOAA (station data):

- Air temperature;
- Humidity;

These data are spatially gridded using Daymet model (using DEM). Other data are extracted from MERRA:

- Air temperature (resolution: ~0.5^o);
- Humidity;
- Wind speed;
- Atmospheric transmissivity;

MERRA is a NASA reanalysis for the satellite era using a major new version of the Goddard Earth Observing System Data Assimilation System Version 5 (GEOS-5). The Project focuses on historical analyses of the hydrological cycle on a broad range of weather and climate time scales and places the NASA EOS suite of observations in a climate context (http://gmao.gsfc.nasa.gov/research/merra/intro.php).

4.4.2.2 Calculation of potential evapotranspiration

For the water resources assessment it is of major importance to know the potential evapotranspiration (ET_{pot}) from a specific area, which can be considered as a loss of water. The potential evapotranspiration is defined as the amount of evaporation that would occur if sufficient water is available. During dry seasons there is often too little water available for the crops, which causes the crop to have “stress”. This results in a reduction of the potential evapotranspiration, also known as the actual evapotranspiratiofn (ET_{act}).

To calculate the potential evapotranspiration we need a crop factor and the reference evapotranspiration (ET_{ref}). The calculation of the reference evapotranspiration is described in detail in Section 0. If both the crop factor (Kc) and the ETref are known, then the potential evapotranspiration is calculated as (Allen et al., 1998):

$$ET_{pot} = Kc * ET_{ref}$$

Where ET_{pot} = *Potential evapotranspiration [mm];*
Kc = *Crop factor [-];*
ET_{ref} = *Reference evapotranspiration [mm];*

For vegetated areas ET_{act} can be lower than ET_{pot} due to water “stress”. For the following land use classes water will always evaporate at the potential rate:

- Urban;
- Bare land;
- Open water;

This means that ET_{act} will be equal to ET_{pot} for these land use classes.

4.4.2.3 Crop factors

The MIRCA database (Section 5.3.2) gives us for each month and each crop the growing area in hectares. The corresponding crop factors for each of the MIRCA crops are defined in Allen et al. (1998). This means that for each grid cell of 1 km^2 we can define the Kc for each month. The growing area of the MIRCA crop, however, might be smaller than the total area of the grid cell (1 km^2). Therefore, the remaining grid cell area (area not covered with MIRCA crop) is filled with the AfriCover land use class. This means for one grid cell that we can have multiple MIRCA crops growing and a remaining area covered with AfriCover. As a result we have to deal with the multiple Kc factors within one grid cell. To get the most accurate result, we calculated for each month and each grid cell the weighted average of the crop factors present within a grid cell:

$$Kc = \frac{w_i * KC_i}{\sum_{i=1}^{n} w_i}$$

Where Kc = *Crop factor for a specific month and grid cell [-];*
w_i = *Area of grid cell covered by crop i [km²];*
Kc_i = *Crop factor of crop i [-];*

The crop factors of all land use classes present in the study area are based upon Allen et al. (1998).

4.5 Lakes, wetlands and reservoirs

The Nile basin is known to have a large number of lakes, wetlands, and reservoirs. These large open water areas can be useful as a source for irrigation. Besides a source for irrigation, these lakes, wetlands, and reservoirs play an important role in the hydrological modeling. Lakes and wetlands can be seen as buffers, which cause a delayed release of water from these open water bodies. Reservoirs are often managed in a certain manner, so they have to be classified as well for the hydrological model. Thus it is clear we need a reliable source of lakes, wetlands and reservoirs.

The Center for Environmental Systems Research of the University of Kassel, Germany, has created a Global Lakes and Wetlands Database (GLWD) (Lehner and Döll, 2004). The combination of best available sources for lakes and wetlands on a global scale (1:1 to 1:3 million resolution), and the application of GIS functionality enabled the generation of a database which focuses in three coordinate levels on (1) large lakes and reservoirs, (2) smaller water bodies, and (3) wetlands. Level 1 (GLWD-1) comprises the shoreline polygons of the 3067 largest lakes (area ≥ 50 km^2) and 654 largest reservoirs (storage capacity ≥ 0.5 km^3) worldwide, and includes extensive attribute data. Level 2 (GLWD-2) comprises the shoreline polygons of permanent open water bodies with a surface area ≥ 0.1 km^2 excluding the water bodies contained in GLWD-1. The approx. 250,000 polygons of GLWD-2 are attributed as lakes, reservoirs, and rivers. Level 3 (GLWD-3) comprises lakes, reservoirs, rivers and different wetland types in the form of a global raster map at 30-second resolution. For GLWD-3, the polygons of GLWD-1 and GLWD-2 were combined with additional information on the maximum extents and types of wetlands.

In a validation against documented data GLWD proved to represent a comprehensive database of global lakes and to provide a good representation of the maximum global wetland extent (Lehner and Döll, 2004). An overview of the lakes, wetlands, and reservoirs in the NEL countries is shown in Figure 40. The GLWD data is available for free download at: http://www.wwfus.org/science/data.cfm

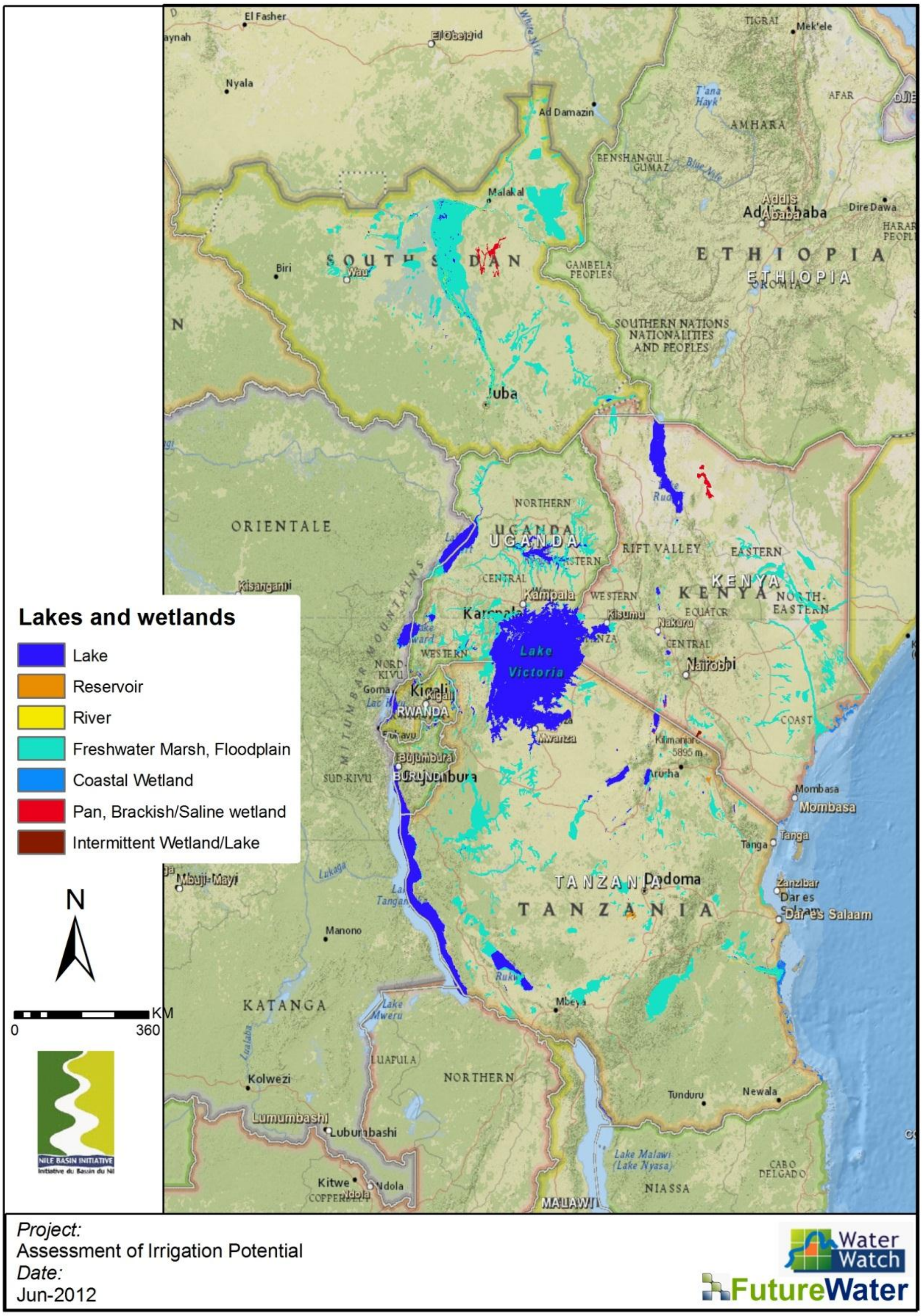

Figure 40: Global Lakes and Wetlands Database (GLWD) for the NEL countries (Lehner and Döll, 2004).

Based on Figure 40 it is clear that there is a large number of freshwater marshes (floodplains) present in the study area. Other large water bodies are the lakes like e.g. Lake Victoria in the center of the study area, and Lake Tanganyika at the western border of Burundi and Tanzania.

The rivers in the current study will not be based on the GLWD database, but will be delineated based on digital elevation data.

4.6 Socio-economic data

4.6.1 Population density

Population density should be considered as component to access suitability for irrigation. Highly-dens populated areas are not suitable for irrigation. On the contrary, areas where hardly anybody lives might face difficulties in terms of labor and markets.
The Center for International Earth Science Information Network at Columbia University provides gridded population of the world databases. Data grids are provided at a resolution of 30 arc-seconds (~1km), with population estimates normalized to the years 2000, 1995, and 1990. All eight data sets are available for download as global products, and the first five data sets are also available as continental, regional, and national subsets. Details are available at: http://www.ciesin.org/news.html#GRUMP-spotlight

4.6.2 Access to transportation

Development of irrigation should take into consideration distances to roads for transportation of harvested products. For this, the distance to the nearest road, nearest railroad and nearest lake/sea is used. It is assumed that areas further away from a road are less suitable for irrigation. A criterion of 20 km was used. All areas within this 20 km range are scaled between 0 and 100 as suitability score.

Based on a comparison between various data sources (AfriCover, Cloudmate, Mapcruzin, AfBD) the Cloudmate provides the best information (see Inception Report for details).

4.6.3 Access to Markets

Distance to nearest markets is an important factor to determine suitability for irrigated agriculture. AfriCover data set includes two classes of towns: (i) major town and (ii) other towns. For major towns a criterion was set that at distances larger than 100 km, suitability would be very low. Between 0 and 100 km a linear suitability index is assumed. For other towns the same approach was used, but here the maximum distance was set at 30 km around a town.

5 Regional Results

Results from analysis and data as described in the previous Chapters are presented in four different sections: (i) regional results, (ii) sub-basin results, (iii) country results, and (iv) focal area results. Country results and results for the 34 focal areas can be found in the seven appendixes to this main report. Summarizing results per sub-basin are presented in Chapter 6.

5.1 Economic Considerations

5.1.1 Food, irrigation, investments

Global food production will have to increase by 1-2% per year for the next generation in order to keep up with food demand (Molden et al., 2007). Increase in food demand is caused by a combination of population growth and changes in consumption patterns, especially an increase in animal-based protein in our diets. The production of biofuels may, until the advent of so-called third generation biofuels, put extra stress on grain and sugar production, although such stress will only be very localized (Hoogeveen et al., 2009). The spike in food prices in 2008 (see Figure 41) has dampened but food prices are still 70% higher than they were five years ago. It has been known for a long time that the supply elasticity of food is low. World trade without dramatic productivity rises can, therefore, only be a limited solution.

The bulk of the world's agricultural production is rainfed, not irrigated. Despite substantial increases in large-scale irrigation infrastructure over the past half century, the bulk of the world's agricultural production still comes from predominantly rainfed lands. Some 55% of the gross value of crop production is grown under rainfed agriculture on 72% of harvested land (Molden et al., 2007). Approximately 70% of the world's irrigated land is in Asia, where it accounts for almost 35% of cultivated land. Rainfed agriculture is therefore by far the most important agricultural production system in most parts of the world and a major consumer of water by evapotranspiration losses (Figure 42).

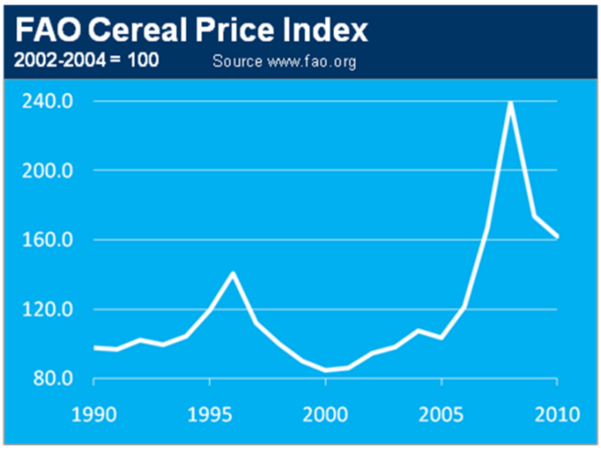

Figure 41: Cereal price development (source: www.FAO.org accessed 08-2011).

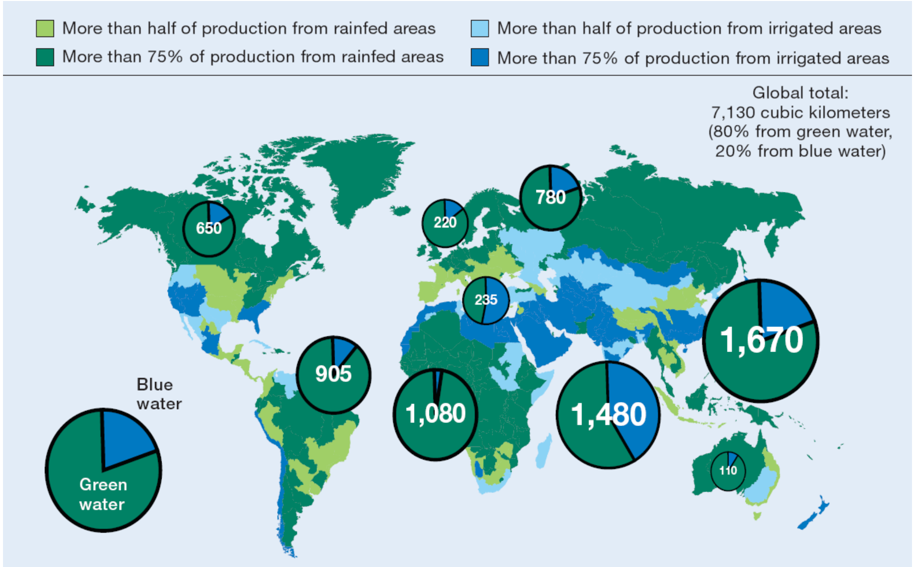

Figure 42. Food crop evapotranspiration from rain and irrigation (source Molden, 2007)

Investment in irrigation accelerated rapidly in the 1960s and the 1970s, with area expansion in developing countries at 2.2% a year reaching 155 million hectares in 1982 (Figure 43). Global irrigated area rose from 168 million ha in 1970 to 215 million ha over the same time frame. Rapid growth in irrigated area, together with other components of the green revolution package, such as improved crop varieties and substantial growth in fertilizer use, particularly in Asia, led to a steady increase in staple food production and a reduction of real world food prices. More recently, agricultural subsidizes in developed countries have helped keep food prices low (Rosegrant et al.,2001).

The annual growth rate of irrigation development, particularly in large-scale public schemes, has decreased since the late 1970s due to several factors. The areas best suited to irrigation have already been developed, leading to increased construction costs for future dams and related infrastructure, and prices of staple cereals have declined. Both of these factors have made irrigated agriculture progressively less economically attractive than in the past. The underperformance of large-scale irrigation has also reduced donor interest (Merrey, 1997). Concerns over negative social and environmental impacts, particularly the dislocation of residents in affected communities and the calls for increased in-stream flows for environmental purposes have received heavy publicity and discouraged lenders from investing in irrigation. More competition for water from other sectors has also reduced the scope for further development of irrigation (Sanmuganathan 2000).

Irrigation is particularly crucial in sustaining agriculture across dry regions. However, irrigation has remained limited in most of Sub-Saharan Africa, with a few large commercial schemes developed during the colonial period and a relatively modest small-scale irrigation subsector. The 1990s saw a substantial rise in private irrigated peri-urban agriculture in Sub-Saharan Africa in response to higher demand from growing cities for fresh fruits and vegetables (FAO 2005).

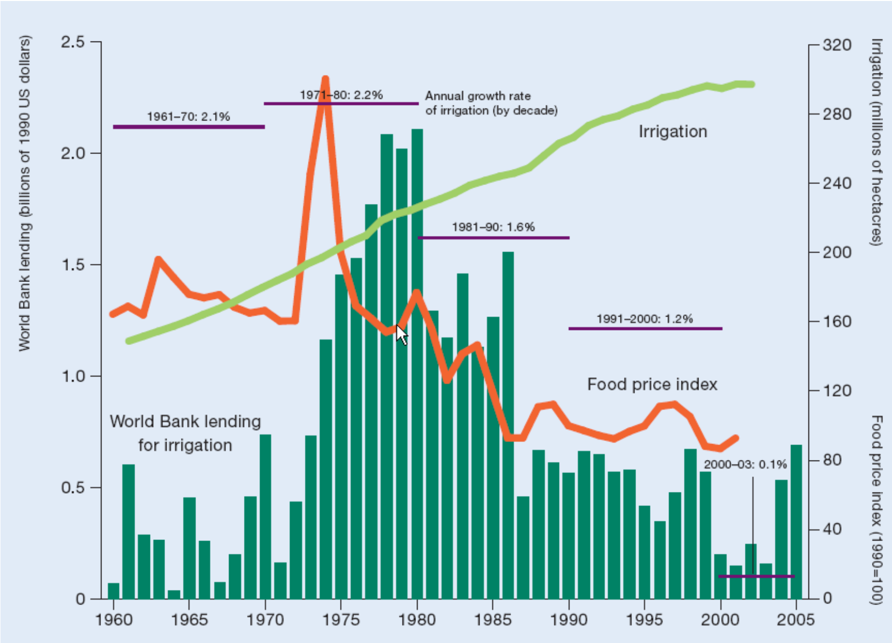

Figure 43. Trends in irrigation, investment and food prices (Source: Molden et al., 2007).

Official statistics indicate a total of 277 million ha of land under irrigation in 2002 worldwide (Table 16), but the extent of land under irrigation is likely to be higher when unreported private investment in irrigation is taken into account. Irrigation covers 20% of all cultivated land and about 40% of agricultural production. In 1995, 38% of cereals grown in developing countries were on irrigated land, accounting for about 60% of cereal production (Ringler et al., 2003). Rainfed cereal yields averaged 1500 kg per hectare in the developing world in 1995, but irrigated yields were 3300 kg per hectare (Rosegrant, et al., 2002). The difference in productivity between irrigated and rainfed agriculture varies widely, depending on the climate, combination of crops, and technologies. Typically, land productivity is two to four times higher in irrigated agriculture.

Table 16. Irrigated land, total and as share of arable land, 1980, 1990, and 2002. (Source FAO, 2004)

	Total irrigated area (thousands of hectares)			As share of arable land (percent)		
Region	**1980**	**1990**	**2002**	**1980**	**1990**	**2002**
World	*210,222*	*244,988*	*276,719*	*15.7*	*17.6*	*19.7*
Developed countries	*58,926*	*66,286*	*68,060*	*9.1*	*10.2*	*11.1*
Industrialized countries	37,355	39,935	43,669	9.9	10.5	11.9
Transition economies	21,571	26,351	24,391	7.9	9.8	10.0
Developing countries	*151,296*	*178,702*	*208,659*	*21.9*	*24.1*	*26.3*
Latin America and the Caribbean	13,811	16,794	18,622	10.8	12.5	12.6
Near East and North Africa	17,982	24,864	28,642	21.8	28.8	32.3
Sub-Saharan Africa	3,980	4,885	5,225	3.2	3.7	3.6
East & Southeast Asia	59,722	65,624	74,748	37.0	33.9	35.1
South Asia	55,798	66,529	81,408	28.6	33.9	41.7
Oceania, developing	3	6	14	0.7	1.2	2.4

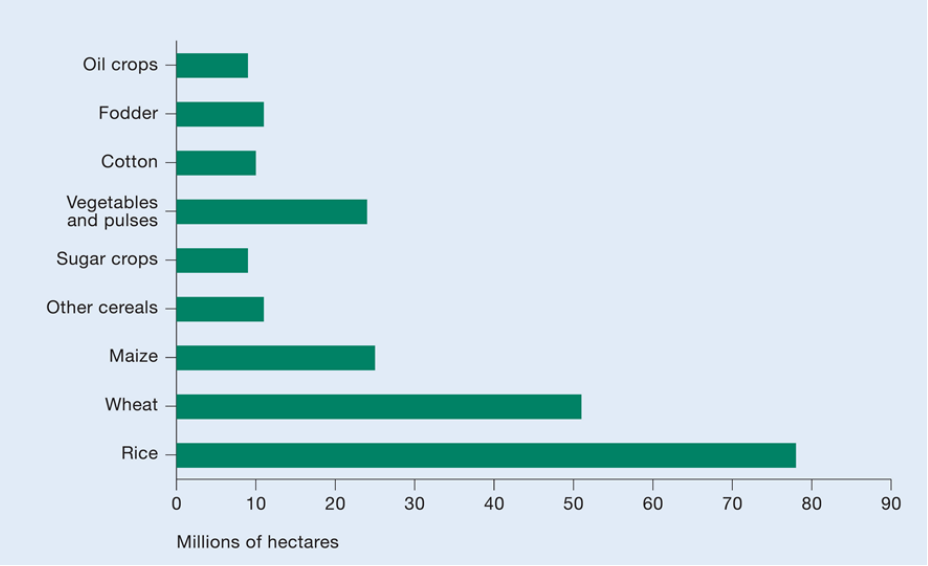

Figure 44. Global distribution of crops under irrigation, 2000 (source Molden, 2007)

5.1.2 Irrigation and return on investments

An economic assessment of the irrigation potential is often interpreted in a narrow sense, i.e. in terms of the financial profitability of irrigation systems, whereas the value which society attaches to all kinds of social concerns such as equity, sustainability and food self-sufficiency should also be considered. This means that the welfare and environmental implications of developing schemes should also be taking into account. So even if it is financially not very profitable to develop irrigation, it can still be desirable if it gets priority by the government for social reasons, such as poverty alleviation, food security or more equitable distribution of wealth. Although the values society attached to all kinds of social concerns is subject to change and often difficult to quantify, they should definitely not be ignored.

There are not many consistent studies available about the feasibility and potential payoff from irrigation investment in Burundi, Easter DRC, Kenya, Rwanda, South Sudan, Tanzania and Uganda. This is, however, not so surprising given the fact that data on investment costs to create the irrigation infrastructure and to convert fallow, rainfed and dry lands to irrigated cropland are limited and vary widely. The costs depend on irrigation technology, irrigation scheme (large scale versus small scale) and local conditions. The benefits of irrigation in terms of net annual revenues of irrigation fluctuate substantially, it depends on rainfall and commodity prices. So, even assessing the financial profitability is not that straightforward.

In a study by You et al., (2010) the internal rate of return on investments in both small- and large-scale irrigation schemes in every African country was calculated in a consistent manner. The results of this study and the sensitivity of the results to the assumptions made, such as the assumed investment costs, water costs and impact of climate change, are summarized below. The study by You et al. did not include results for Rwanda.

Despite highly variable and -in many cases- insufficient rainfall and a high incidence of droughts, food production in Africa 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. 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 areas. The African continent has ample water resources overall; however, they are spread unevenly over a wide range of agro-ecologic zones. The average rate of expansion of irrigated area over the past 30 years was 2.3 percent. In Africa, irrigated agriculture accounts for nearly 38 percent of the value of all agricultural output. Thus the potential of irrigation development for Africa is large, given existing water resources and the high value of irrigated agriculture on the continent (You et al., 2010).

A recent study of IFPRI (You et al., 2010) about the irrigation potential for Africa shows a potential increase in irrigated area in Africa of 23.6 million hectares; of which 16.3 million hectares large-scale and 7.3 million hectares small-scale irrigation. It shows a potential increase in irrigated area of 579,000 ha in Congo DRC, 42,000 ha in Burundi, 338,000 ha in Kenya, 1,012,000 ha in Tanzania, 1,151,000 ha in Uganda and 628,000 ha in Sudan. Using 12 percent as a cutoff point for Internal Rate of Return (IRR) the potential increase in irrigated area in Africa is 6.1 million hectares. In that case the potential increase in irrigated area is 43,500 ha in Congo DRC, 25,700 ha in Kenya, 196,100 ha in Tanzania, 445,000 ha in Uganda and 378,300 ha in Sudan.

The results for large- and small-scale irrigation potential reveal a striking contrast. Although the total area expansion potential is small for small-scale irrigation, IRRs are considerably higher than for large-scale irrigation expansion. The average IRR is 28 percent for small-scale compared to 6.6 percent for large-scale irrigation in Africa.

Table 17. Investment needs and increase in irrigated area for both small- and large-scale irrigation and positive IRR (Internal Rate of Return) and for IRR cutoff at 12%.

Country	Large-scale Investment cost (US$mil)	Large-scale Increase in irrigated area (1000 ha)	Large-scale IRR (%)	Small-scale Investment cost (US$mil)	Small-scale Increase in irrigated area (1000 ha)	Small-scale IRR (%)	Total increase in irrigated area (1000 ha)	Total increase in irrigated area for IRR cutoff at 12% (1000 ha)	IRR (%) for IRR cutoff at 12%
DRC	861	441	3.0	715	138	12	579	43.5	28
Burundi	31	16	2.4	135	26	2	42		
Kenya	562	288	7.0	257	50	40	338	25.7	59
Rwanda		-	-		-	-	n/a	n/a	
Tanzania	1,392	713	2.8	1,546	299	28	1,012	196.1	42
Uganda	1,035	531	2.4	3,203	620	32	1,151	445.0	46
Sudan	687	352		1,429	276	16	628	378.3	20
All Africa	31,718	16,252	6.6	37,933	7,341	28	23,593	6,143.3	35

The profitability and potential for irrigation expansion are quite sensitive to underlying assumptions, in particular to the investment costs and water delivery costs. For the large-scale investment analysis, the baseline assumptions are: low water delivery costs of $0.01/m3, on-farm irrigation investment costs of $3,000/hectare and on-farm O&M costs of $30/hectare. For the small-scale investment analysis, the assumed investment costs are $2,000/hectare.

Table 18. Sensitivity of the increase in irrigated area to the assumed investment costs.

	Large-scale Investment costs of $3,000/ha	Large-scale Investment costs of $6,000/ha	Large-scale Investment costs of $8,000/ha	Small-scale Investment costs of $600/ha	Small-scale Investment costs of $2,000/ha	Small-scale Investment costs of $5,000/ha
Increase in irrigated area in Africa (1000 ha)	16,252	8,775.	6,380	15,786	7,341	322

The assumption about the cost of water delivery for dam-based irrigation has a significant effect on profitable irrigation expansion. If the water price is $0.05/m^3 instead of $0.01/m^3, large-scale area expansion drops to 11.9 million hectares with an IRR of 5.8 percent, compared with 16.3 million hectares with an IRR of 6.6 percent for their baseline.

5.2 Political and Institutional Considerations

National governments have historically played a leading role in water development, both in supporting large-scale irrigation, hydropower, and flood control as well as in facilitating private and small-scale farmer-managed irrigation. The state was the central institution driving the boom in irrigation development in the second half of the 20th century. There are sound reasons for the state's central role, related to state authority, national welfare and development, and resource mobilization. Vital natural resources are considered public goods to be regulated, managed, and used by the state for public welfare. Large-scale development of water resources requires substantial financial and human resources and a long-term perspective on returns to the investments.

Triggered by the Asian food crises of the 1960s, governments made huge investments in new irrigation schemes, supported by bilateral donors and development banks. By the mid-1970s, however, evidence was growing that while the green revolution had significantly reduced food shortages, the new publicly constructed and managed irrigation systems were performing far below expectations (Merrey, 2007).

The initial response was to assume that the problems were largely on the farm, that farmers were mismanaging water and needed training to improve irrigation performance. In some cases farmers were perceived as illiterate, conservative, and too "traditional". This blame-the-farmers analysis conveniently defined the problem as outside the domain of the managing water agencies and placed it squarely on the farmers' shoulders. The conditions to which farmers were responding, such as unreliable water services, were not acknowledged. The educate-the-farmers attitude persists today as a component of social engineering approaches to water sector reform (Molden et al., 2007).

An important dimension of the early attention to on-farm problems was attempts to organize farmers into water user associations. Observations showed farmer-managed irrigation systems to be functioning effectively, so the hope was that organizing farmers in government-managed schemes would show similar results. Water user associations, farmer training, and on-farm infrastructure development were expected to lead to better irrigation performance while also reducing government investment and operation and maintenance (O&M) costs. At this early stage, water user associations were perceived in narrow terms: they would take responsibility for rehabilitation, maintenance, and water distribution of irrigation systems at the tertiary level (the smallest canals from which a number of farmers take water directly). Before the 1990s few attempts had been made to give farmers a voice at higher levels of irrigation schemes (Uphoff, 1992).

The following conditions have been identified as necessary for successful irrigation management transfer (Samad and Merrey (2005)):

- Firm, consistent long-term political commitment.
- Legal and political recognition of farmer organizations, including their right to raise revenue, enter into contracts, and apply sanctions.
- Clearly recognized and sustainable water rights and water service.
- Infrastructure that is compatible with the water service, water rights, and local management ca-pacities.
- Well specified management functions and assignment of authority.
- Effective accountability and incentives for management.
- Arrangements for viable and timely conflict resolution.
- Benefits that exceed costs and are proportional to farmer investments.
- Ability to mobilize adequate resources for irrigation.
- Support services to farmer organizations as they evolve from single-purpose operation and maintenance to multipurpose commercial organizations.
- Periodic financial audit of the farmer organization.
- Higher level federations of local organizations for planning, allocating, and enforcing resource use at watershed or aquifer levels.

The International Development Committee of DFID (Lankford, 2009) proposed the following five major policy issues to be considered:

1.**Canal irrigation rehabilitation and expansion.** Irrigation rehabilitation (also expansion) is a significant and worthy policy area for public and international aid. (Borehole/groundwater irrigation and micro-systems, including treadle, are better left to commercial interests). Canal irrigation offers the chance of boosting grain production via smallholders whereas other micro-techniques are suited to horticultural production.

2.**Headworks of irrigation systems re-tuned to facilitate basin water allocation.** Irrigation headworks, existing and planned, are invariably built with the irrigation system in mind, complicating downstream water allocation within river basins. This will require a redesign of intake infrastructure to alter flow rates or make them more manageable and transparent. Other options include flow measurement & proportional intakes.

3.**Large-scale water storage is not necessarily the priority**. Irrigation infrastructure to manage water (the previous two points) must be emphasised prior to, or alongside, efforts to increase water storage. Demand and share management are more relevant, though institutionally more difficult to implement and sustain.

4.**Diverse and comprehensive policies are required.** If expansion of irrigation is envisaged, this should be via multiple methods and approaches rather than through the application of a narrow set of technologies.

5.**Creative institutional arrangements for irrigation.** Benefits arising from new cooperative partnerships comprising the international community, nation states, smallholders, multinationals and fair trade assurance organisations. Irrigate large canal systems could be more profitably and efficiently with such an array of actors professionally focused towards this.

5.3 Environmental Issues

Irrigation has contributed significantly to poverty alleviation, food security, and improving the quality of life for rural populations. However, the sustainability of irrigated agriculture is being questioned, both economically and environmentally. The increased dependence on irrigation has not been without its negative environmental effects (FAO, 1997a).

The sustainability of irrigation projects depends on the taking into consideration of environmental effects as well as on the availability of funds for the maintenance of the implemented schemes. Negative environmental impacts could have a serious effect on the investments in the irrigation sector. Adequate maintenance funds should be provided to the implementing organizations to carry out both regular and emergency maintenance.

It is essential that irrigation projects be planned and managed in the context of overall river basin and regional development plans, including both the upland catchment areas and the catchment areas downstream.

Environmental impacts of irrigation are sometimes referred to as the changes in quantity and quality of soil and water as a result of irrigation and the ensuing effects on natural and social conditions at the tail-end and downstream of the irrigation scheme. An irrigation scheme often draws water from the river and distributes it over the irrigated area. The hydrological consequences can be summarized as:

- the downstream river discharge is reduced
- the evaporation in the scheme is increased
- the groundwater recharge in the scheme is increased
- the level of the water table rises
- the drainage flow is increased

These may be called direct effects. The effects thereof on soil and water quality are indirect and complex, waterlogging and soil salination are part of these, whereas the subsequent impacts on natural, ecological and socio-economy |socio-economic conditions is very intricate. Groundwater irrigation may result in the level of the groundwater descends. The effects may be water mining, land/soil subsidence, and, along the coast, saltwater intrusion.

FAO (1997) defined five major categories of potential environmental impacts of irrigation development:

- Waterlogging and salinization
- Water-borne and water-related diseases
- Potential environmental impacts of dams and reservoirs
- Socio-economic impacts irrigation schemes
- Alternatives to mitigate the negative impacts of irrigation projects

An important environmental issues related to irrigation is the so-called environmental flow requirements (World Bank, Hirji and Davis, 2009a). Environmental flows are really about the equitable distribution of and access to water and services provided by aquatic ecosystems. They refer to the quality, quantity, and timing of water flows required maintaining the components, functions, processes, and resilience of aquatic ecosystems that provide goods and services to people. Investments in water resources infrastructure, especially dams for storage, flood control, or regulation, have been essential for economic development (including hydropower generation, food security and irrigation, industrial and urban water supply, and flood and drought mitigation), but, when they are improperly planned, designed, or operated, they can cause problems for downstream ecosystems and communities because of their impact on the volume, pattern, and quality of flow. While aquatic life depends on both the quantity and quality of water, changes in flows are of particular concern because they govern so many ecosystem processes. Consequently, changes in flow have led to a diminution of the downstream ecosystem services that many of the poorest communities rely on for their livelihoods. In order to achieve sustainable development, downstream impacts will require more attention by all parties, as countries —through both public and private sector investments—expand their infrastructure in many sectors, especially dams for various purposes.

The provision of flows, including volumes and timings, to maintain downstream aquatic ecosystems and provide services to dependent communities has been recognized in developed countries for more than two decades and is increasingly being adopted in developing countries. These services include the following:

- Clean drinking water
- Groundwater recharge
- Food sources such as fish and invertebrates
- Opportunities for harvesting fuelwood, grazing, and cropping on riverine corridors and floodplains
- Biodiversity conservation (including protection of natural habitats, protected areas, and national parks)
- Flood protection
- Navigation routes
- Removal of wastes through biogeochemical processes
- Recreational opportunities
- Cultural, aesthetic, and religious benefits.

But the impacts of development on communities downstream are often diffuse, long term, poorly understood, and inadequately addressed.

In the developed world, there are now many more methods for estimating environmental flow requirements, and more information is available on the ecological response to different flow regimes. There is also growing experience in integrating information from across a range of physical, ecological, and socioeconomic disciplines. In addition, a wide variety of EFA (Environmental Flow Assessment) methods have been developed, backed by considerable field experience, to suit a variety of levels of environmental risk, time and budget constraints, and levels of data and skills. However, implementation in the developing world are still limited and often more driven by emotions and qualitative assumptions, rather than by proven science and technology.

6 Sub-basin results

6.1 General

Results of the analysis are also presented for the sub-basins in the Nile basin of the seven countries. The NEL area can be divided into seven sub-basins (Figure 45):

- Kagera
- Lake Victoria
- Victoria Nile
- Lake Albert
- Albert Nile
- Sudd
- Bahr el Ghazzal

Kagera is the furthest tributary of the Nile which drains the mountains of Burundi and Rwanda. It flows into **Lake Victoria** (about 1134 m in elevation) after meandering through a series of lakes and swamps adjoining the river channel. A number of tributaries drain the forested escarpment to the northeast of the Lake Victoria. Other less productive water courses drain the plains of the Serengeti to the southeast of the lake and the swamps of Uganda to the northwest. The outflow from Lake Victoria is confined to a single channel heading north towards Lake Kyoga, through several shallow falls and rapids. The outflow from the lake was controlled naturally by the geometry of the Ripon Falls. Since 1953, when the Owen Falls dam was constructed just downstream, the outflow has been controlled by international agreement according to the same relation between lake level and outflow. The **Victoria Nile** reaches Lake Kyoga (1031 m) some 100 km north of its outfall. This lake is essentially a grass-filled valley which used to drain to the west towards the DRC. In some periods the lake causes a net loss of river flow and in other periods provides a net gain. The Kyoga Nile flows west from the lake towards the western arm of the Rift Valley through level reaches with swamp vegetation, interrupted by rapids and falls culminating in the Murchison Falls. The river enters **Lake Albert** (Mobutu Sese Seko) (620 m) through a swamp near the northern end of the lake. The lake also receives the inflow of the river Semliki, draining Lake Edward (912 m) and the Ruwenzori and other mountains. The **Albert Nile** or Bahr el Jebel leaves Lake Albert at its northern end and flows northeast towards Nimule in a flat reach flanked by swamp vegetation. At Nimule the river crosses the Sudan border, turns abruptly to the northwest and flows in a steeper channel, with several rapids. Here the river enters the **Sudd** or Bahr el Jebel swamps. Within the Sudd the higher flows spill from the main channel into swamps and seasonally flooded areas. Evaporation from the flooded areas greatly exceeds rainfall, which itself is confined to a few months before the river rises. The effect of this spilling is that the outflow from the swamp is only about half the inflow and has little seasonal variation. At Lake No the Bahr el Jebel turns east and becomes the White Nile, and the **Bahr el Ghazal** flows into the lake from the west. The Bahr el Ghazal basin is relatively large and has the highest rainfall of any basin within the Sudan. However, the flows of the various tributaries of the Bahr el Ghazal are spilled into seasonal and permanent swamps, and virtually no flow reaches the White Nile. (Extracted from Sutcliff et al., 1999).

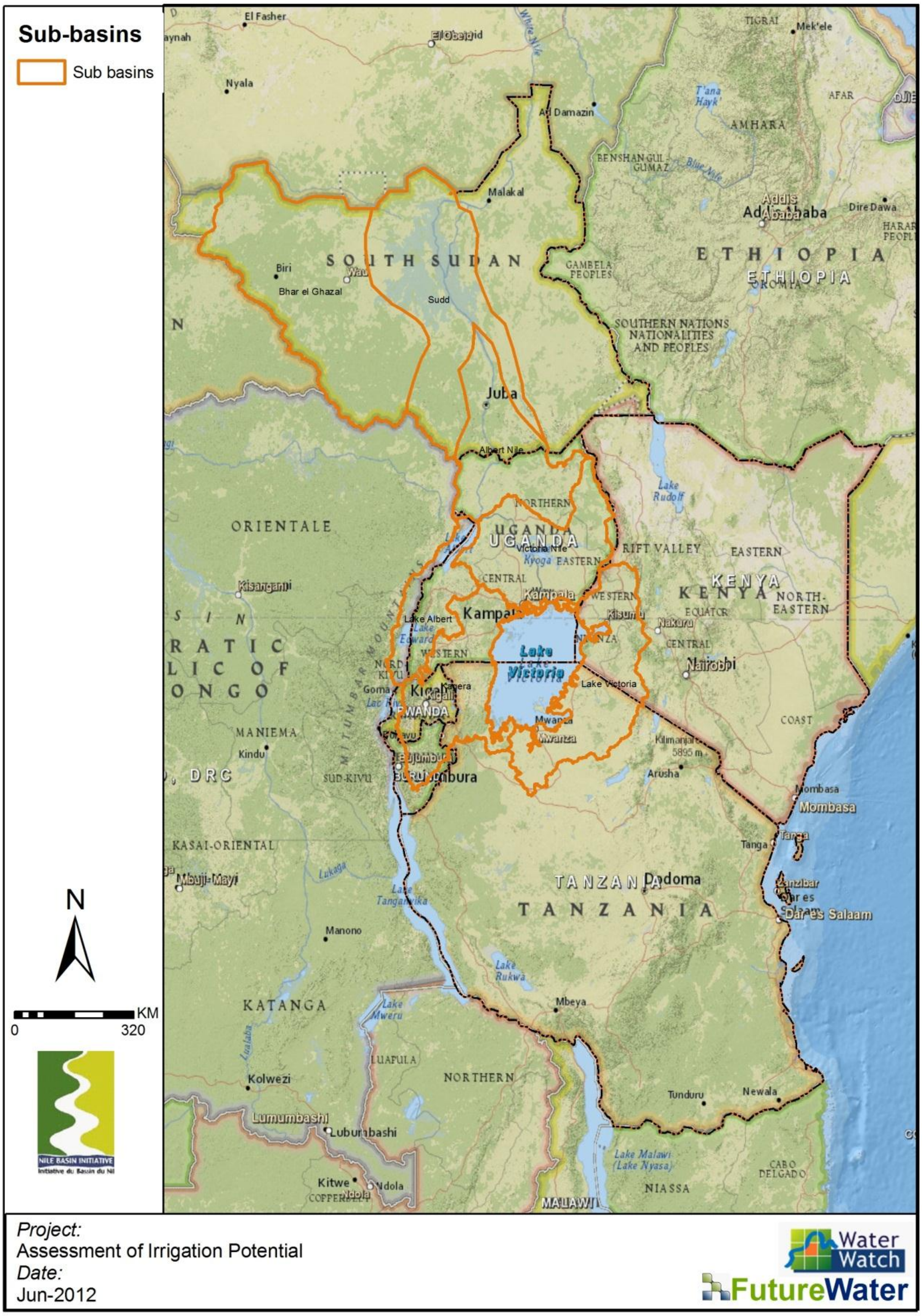

Figure 45: Sub-basins in NELarea (source: NBI – WRPM).

6.2 Kagera

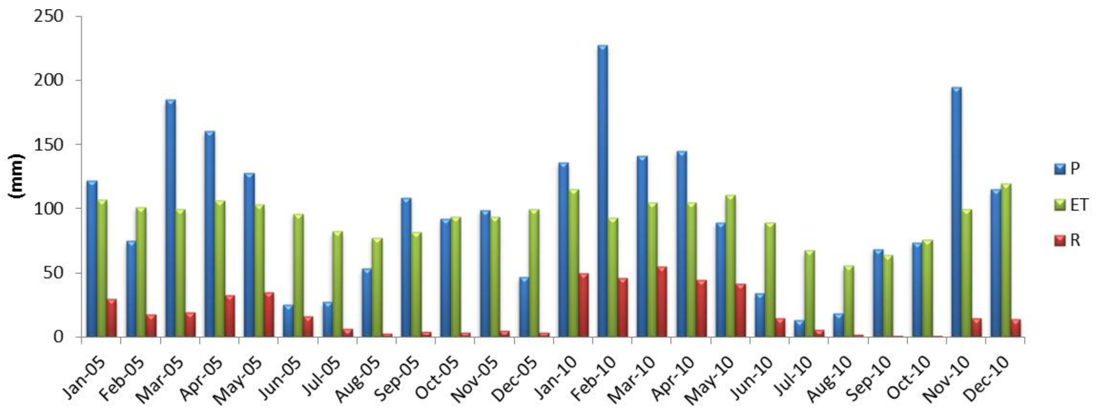

Figure 46. Main components of the water balance as assessed using NELmod. P is precipitation (mm/month), ET is actual evapotranspiration (mm/month), and R is runoff (mm/month).

Table 19. Suitability classes Kagera basin.

Suitability	Irrigation potential (ha)
0 - 10%	50
10 - 20%	9,250
20 - 30%	428,419
30 - 40%	5,135,506
40 - 50%	1,905,956
50 - 60%	803,663
60 - 70%	638,913
70 - 80%	203,413
80 - 90%	0
90 - 100%	0
Total >60%	842,325

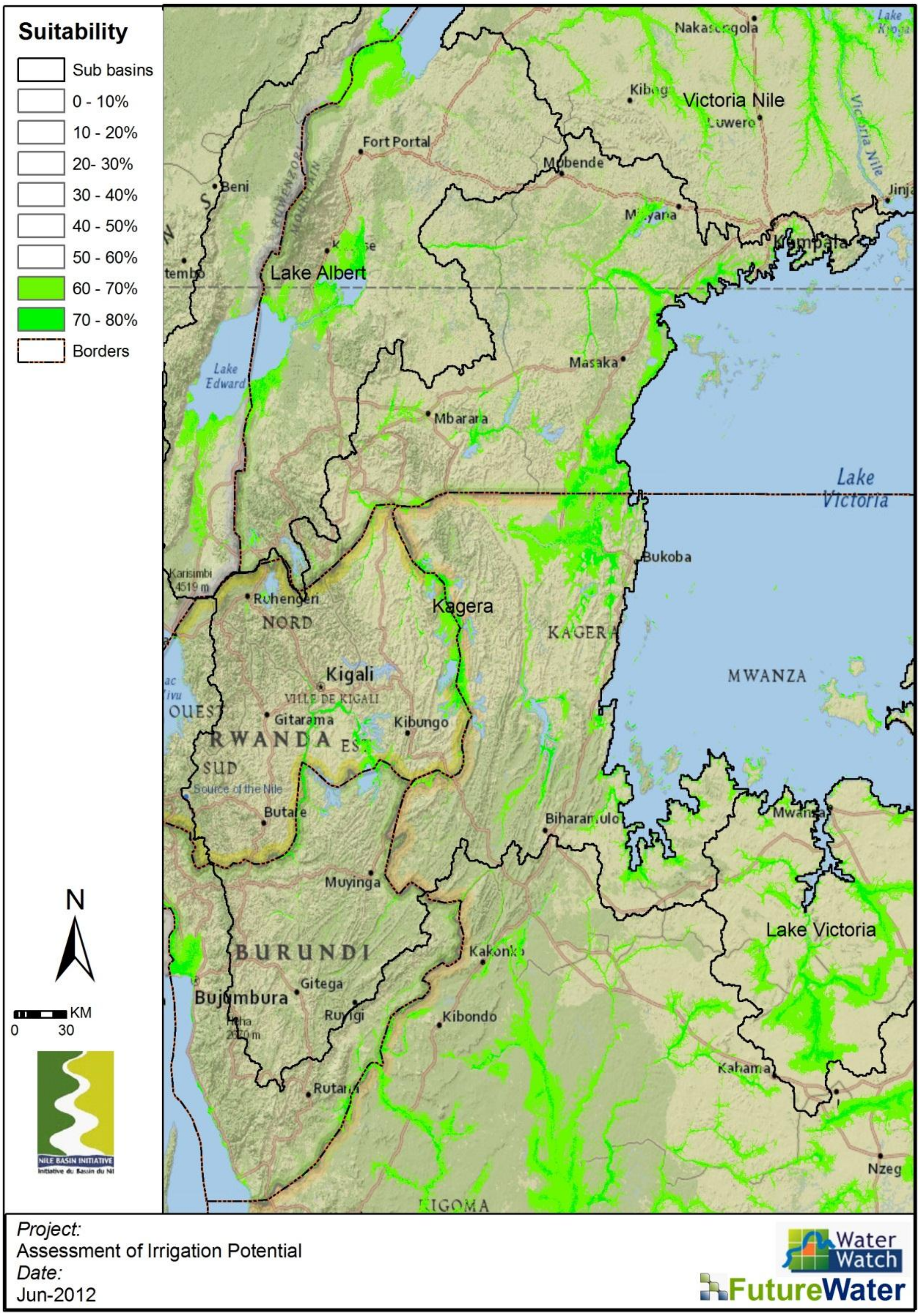

Figure 47. Areas suitable for irrigation Kagera basin.

6.3 Lake Victoria

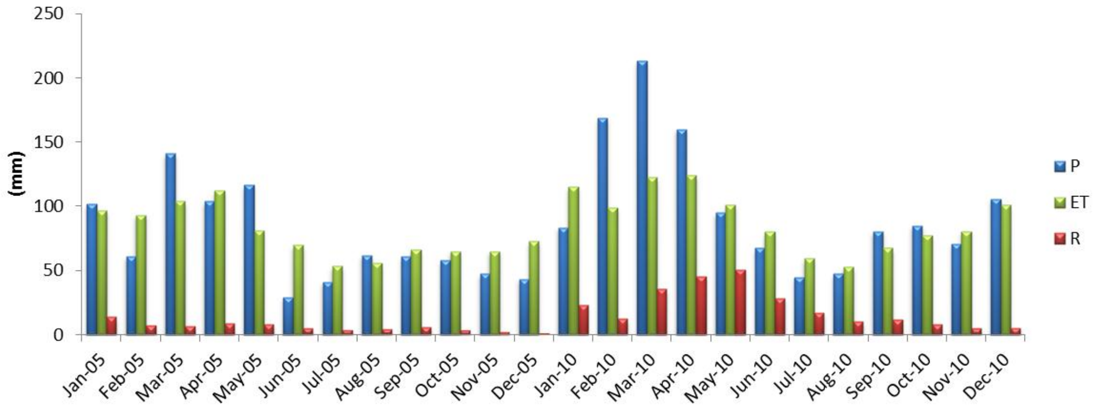

Figure 48. Main components of the water balance as assessed using NELmod. P is precipitation (mm/month), ET is actual evapotranspiration (mm/month), and R is runoff (mm/month).

Table 20. Suitability classes Lake Victoria Basin.

Suitability	Irrigation potential (ha)
0 - 10%	531
10 - 20%	107,713
20 - 30%	510,275
30 - 40%	3,815,981
40 - 50%	2,667,538
50 - 60%	1,845,225
60 - 70%	1,126,225
70 - 80%	182,206
80 - 90%	0
90 - 100%	0
Total >60%	1,308,431

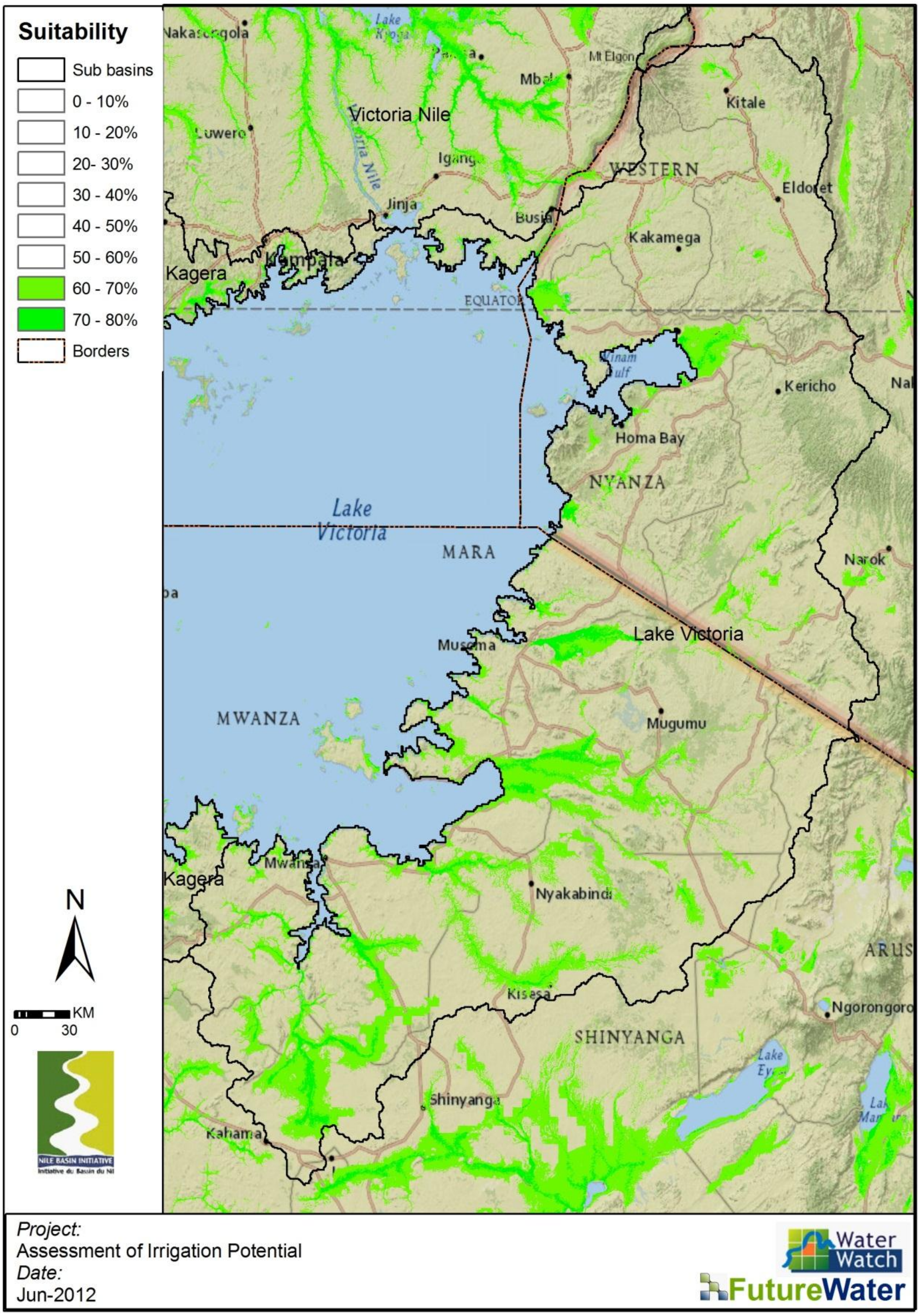

Figure 49. Areas suitable for irrigation Lake Victoria Basin.

6.4 Victoria Nile

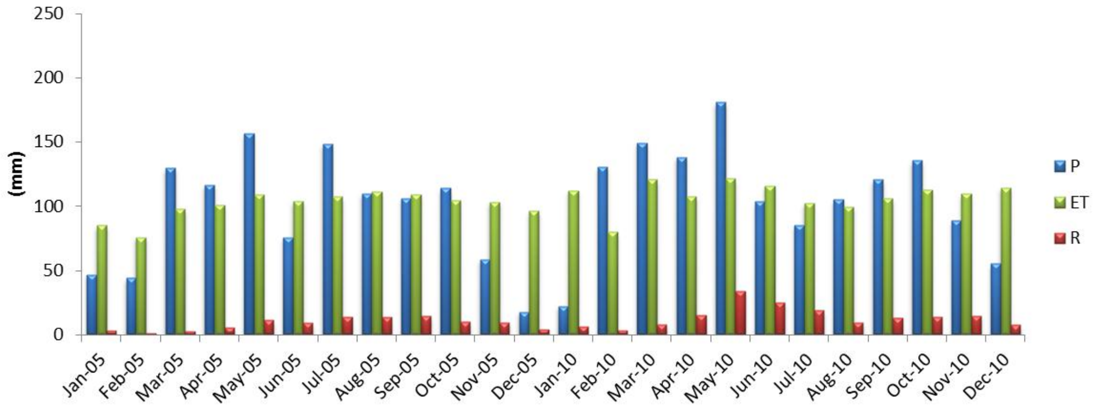

Figure 50. Main components of the water balance as assessed using NELmod. P is precipitation (mm/month), ET is actual evapotranspiration (mm/month), and R is runoff (mm/month).

Table 21. Suitability classes Victoria Nile Basin.

Suitability	Irrigation potential (ha)
0 - 10%	4,288
10 - 20%	164,594
20 - 30%	381,725
30 - 40%	1,850,706
40 - 50%	2,309,181
50 - 60%	2,232,894
60 - 70%	1,594,863
70 - 80%	393,963
80 - 90%	0
90 - 100%	0
Total >60%	1,988,825

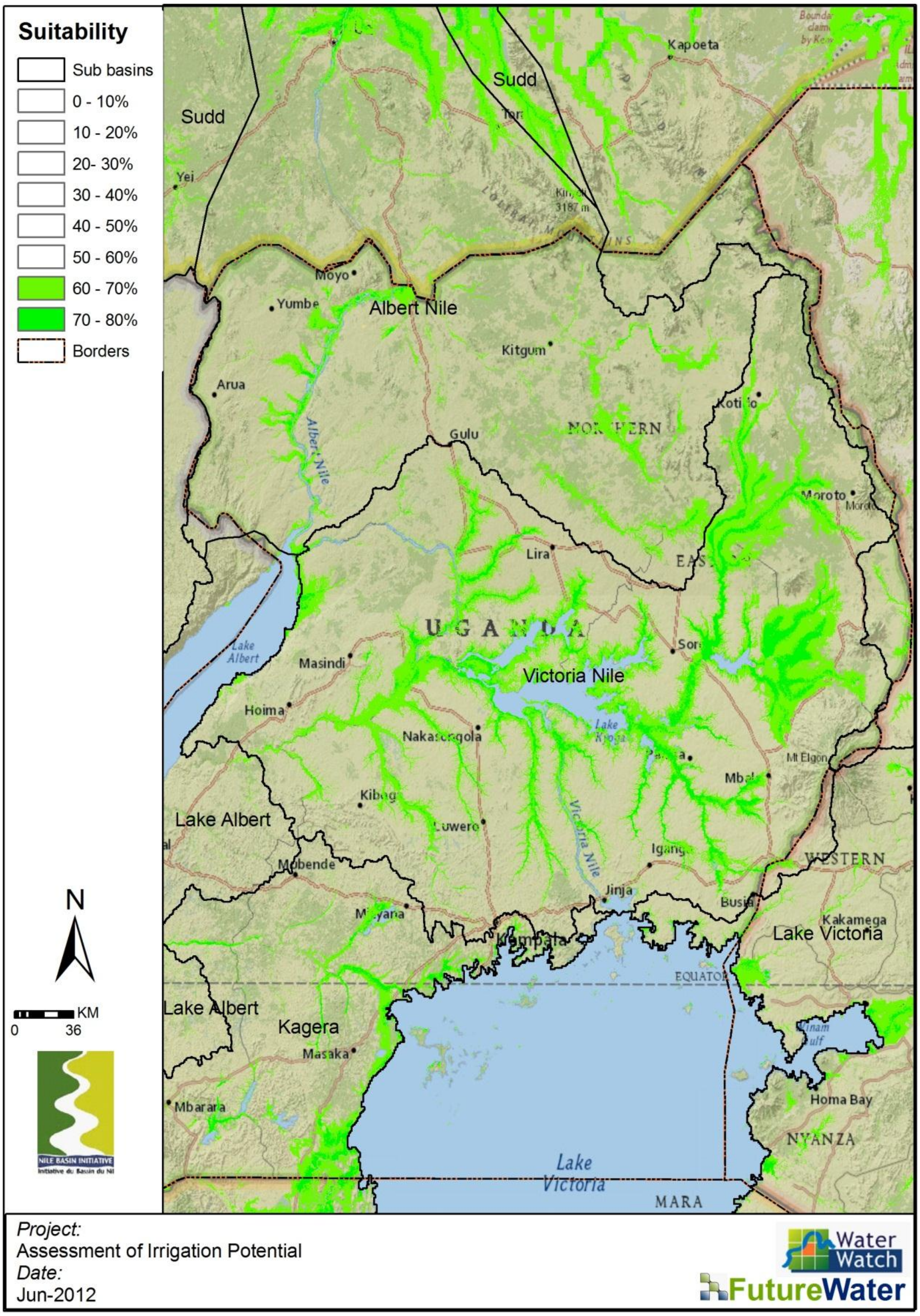

Figure 51. Areas suitable for irrigation Victoria Nile Basin.

6.5 Lake Albert

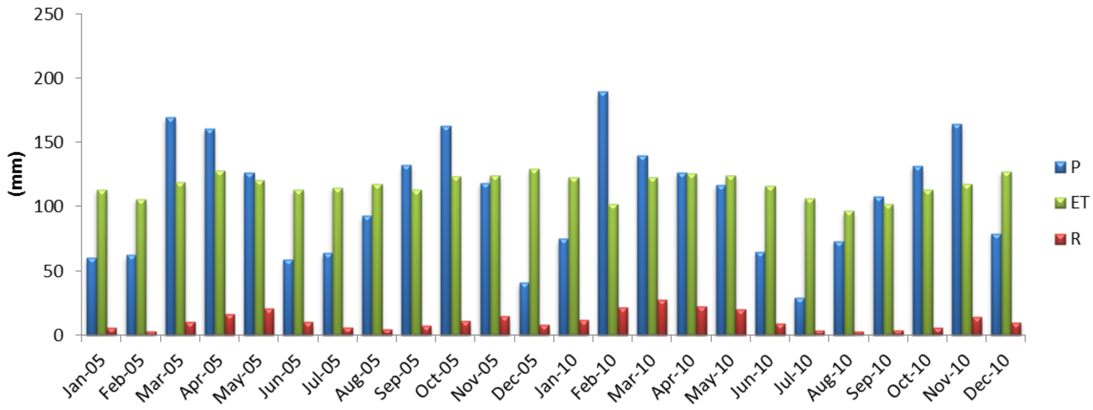

Figure 52. Main components of the water balance as assessed using NELmod. P is precipitation (mm/month), ET is actual evapotranspiration (mm/month), and R is runoff (mm/month).

Table 22. Suitability classes Lake Albert Basin.

Suitability	Irrigation potential (ha)
0 - 10%	51,850
10 - 20%	268,500
20 - 30%	352,181
30 - 40%	2,107,663
40 - 50%	746,781
50 - 60%	389,738
60 - 70%	331,594
70 - 80%	54,538
80 - 90%	0
90 - 100%	0
Total >60%	386,131

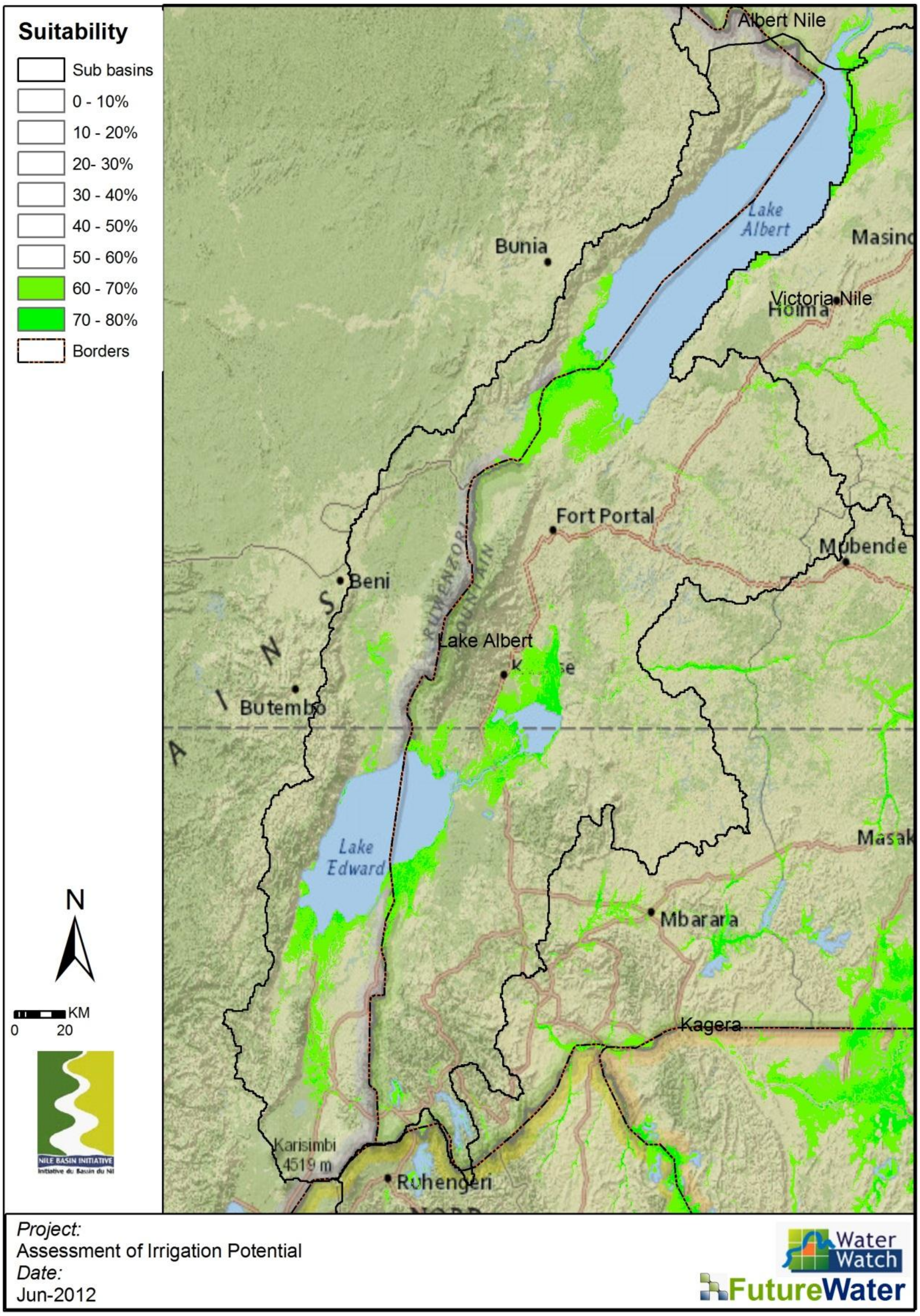

Figure 53. Areas suitable for irrigation Lake Albert Basin.

6.6 Albert Nile

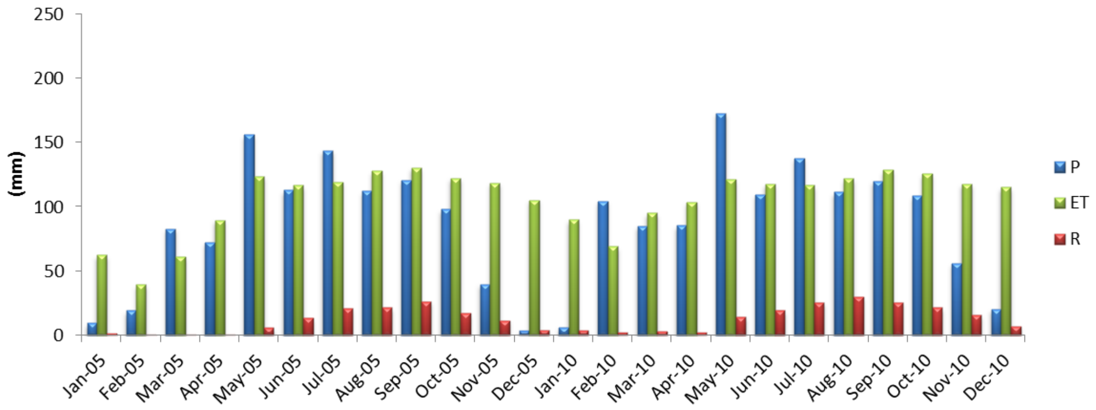

Figure 54. Main components of the water balance as assessed using NELmod. P is precipitation (mm/month), ET is actual evapotranspiration (mm/month), and R is runoff (mm/month).

Table 23. Suitability classes Albert Nile Basin.

Suitability	Irrigation potential (ha)
0 - 10%	45,088
10 - 20%	445,706
20 - 30%	932,225
30 - 40%	2,182,275
40 - 50%	2,255,913
50 - 60%	1,730,069
60 - 70%	1,390,663
70 - 80%	338,731
80 - 90%	0
90 - 100%	0
Total >60%	1,729,394

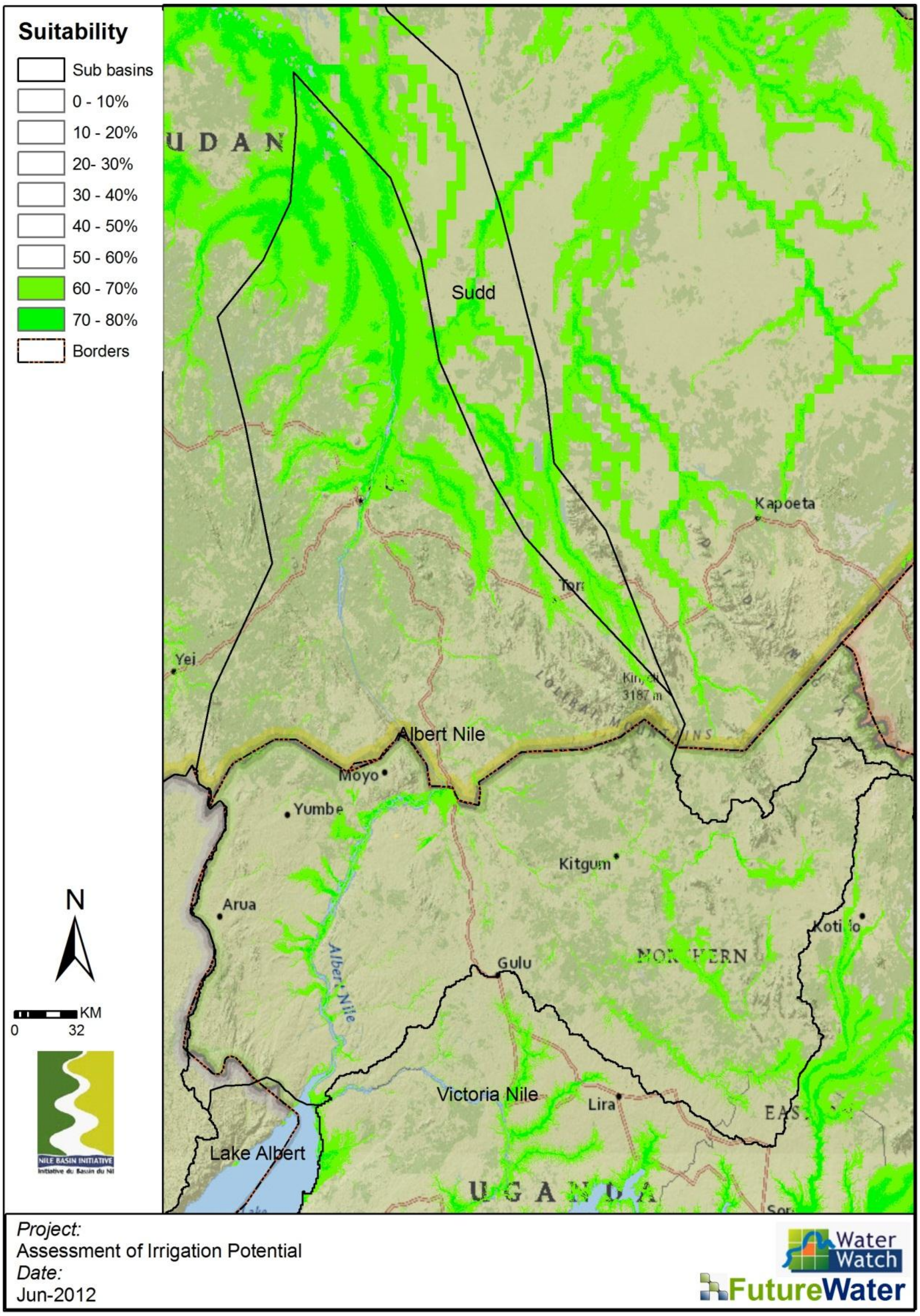

Figure 55. Areas suitable for irrigation Albert Nile Basin.

6.7 Sudd

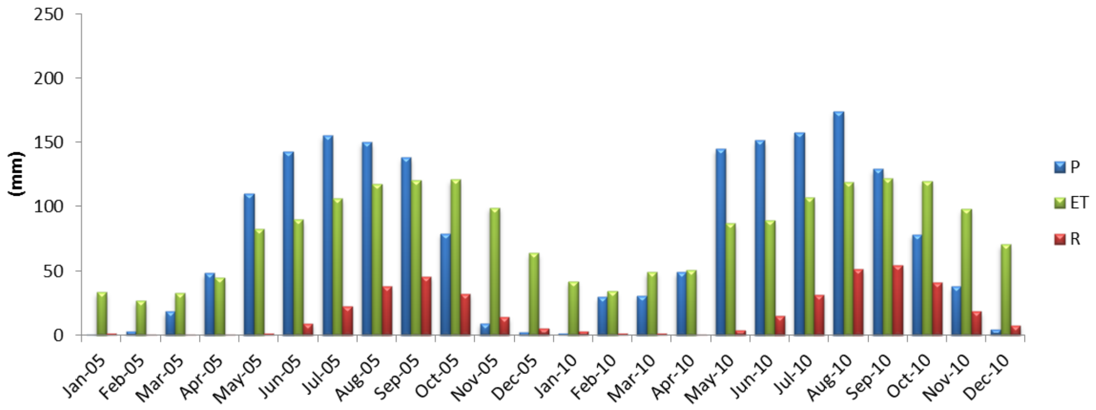

Figure 56. Main components of the water balance as assessed using NELmod. P is precipitation (mm/month), ET is actual evapotranspiration (mm/month), and R is runoff (mm/month).

Table 24. Suitability classes Sudd Basin.

Suitability	Irrigation potential (ha)
0 - 10%	0
10 - 20%	17,588
20 - 30%	201,444
30 - 40%	844,019
40 - 50%	2,179,781
50 - 60%	3,386,831
60 - 70%	6,931,675
70 - 80%	2,164,044
80 - 90%	0
90 - 100%	0
Total >60%	9,095,719

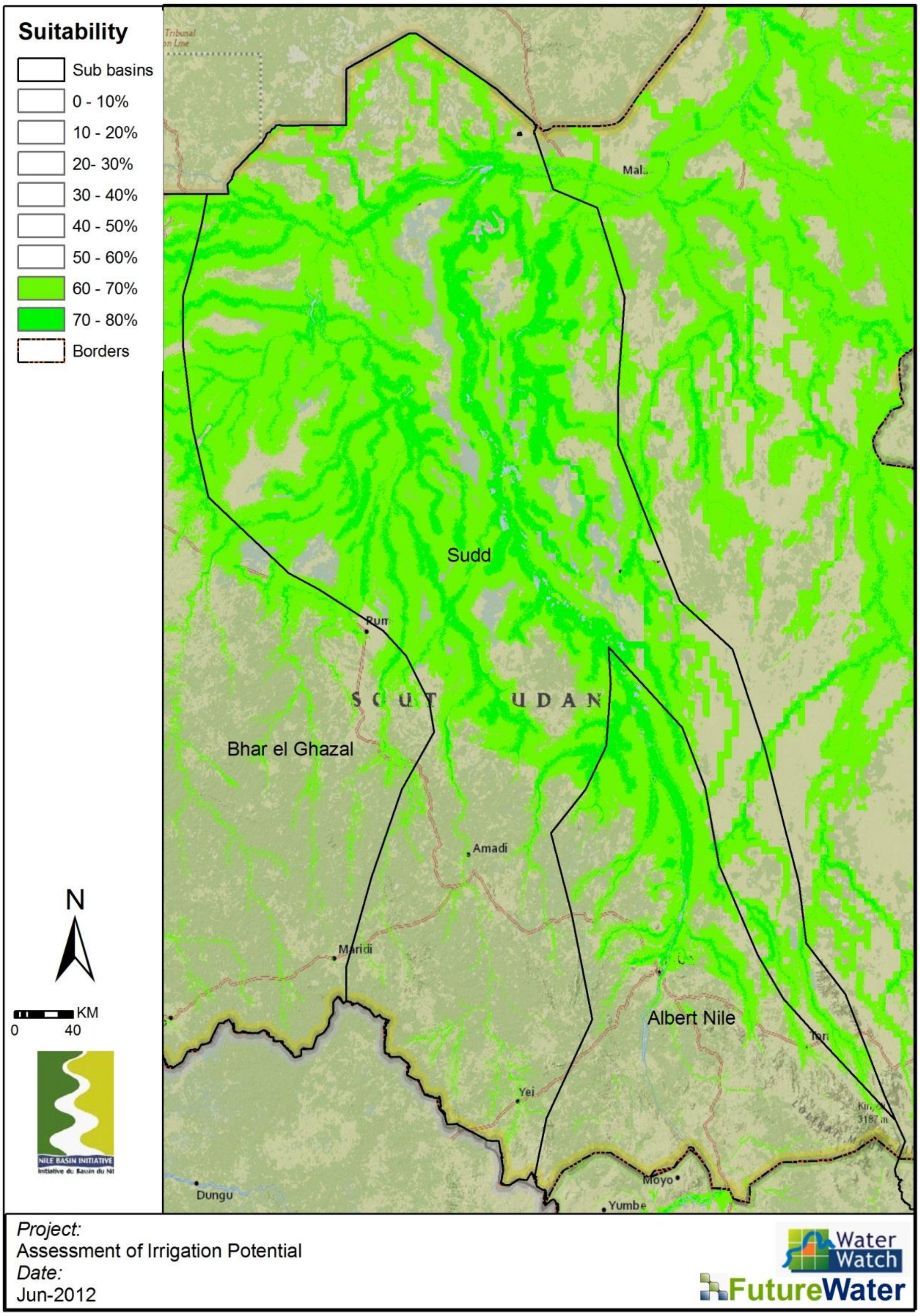

Figure 57. Areas suitable for irrigation Sudd Basin.

6.8 Bahr el Ghazal

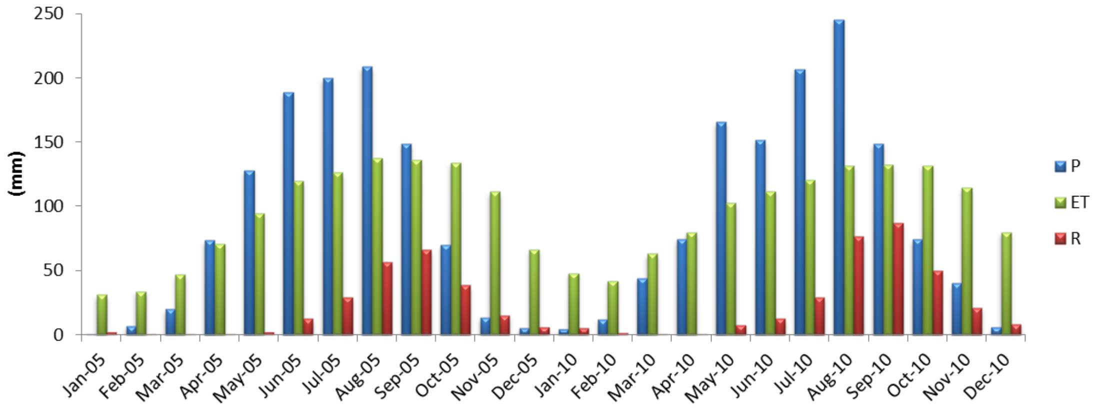

Figure 58. Main components of the water balance as assessed using NELmod. P is precipitation (mm/month), ET is actual evapotranspiration (mm/month), and R is runoff (mm/month).

Table 25. Suitability classes Bahr el Ghazzal Basin.

Suitability	Irrigation potential (ha)
0 - 10%	0
10 - 20%	20,138
20 - 30%	505,975
30 - 40%	3,218,244
40 - 50%	6,771,913
50 - 60%	6,433,275
60 - 70%	4,080,013
70 - 80%	590,106
80 - 90%	0
90 - 100%	0
Total >60%	4,670,119

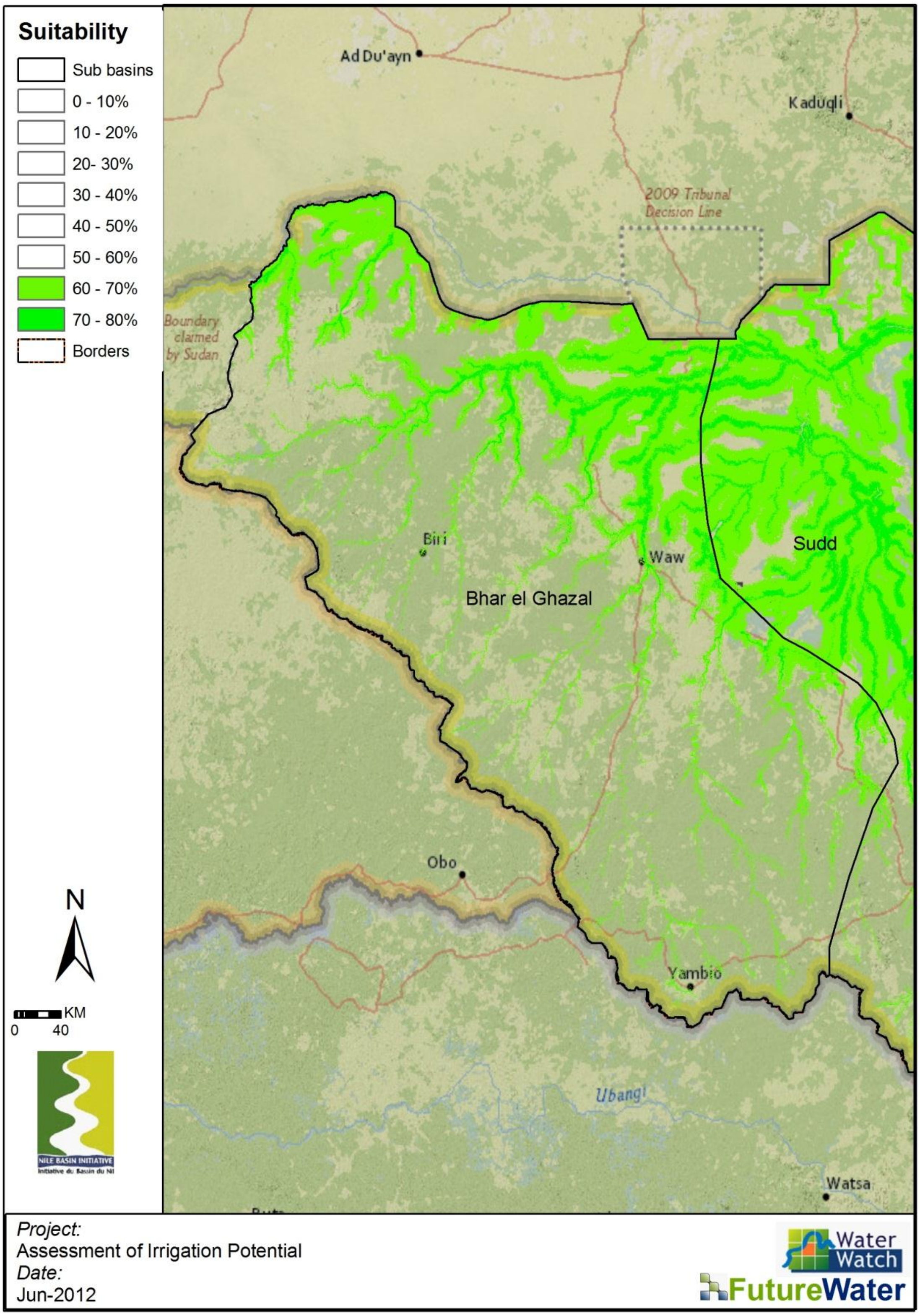

Figure 59. Areas suitable for irrigation Bahr el Ghazzal Basin.

7 Conclusions and Recommendations

7.1 Approach and Methodology

This report presents the results of the study “Assessment of the Irrigation Potential in Burundi, Eastern DR Congo, Kenya, Rwanda, South Sudan, Tanzania and Uganda”. The study can be categorized as preparation for a development program (pre-feasibility) and the objective is to support policy/decision making. The unique features of this study, compared to previous irrigation potential studies, can be summarized as: (i) similar methodology applied to all countries, (ii) combining quantitative and qualitative information, (iii) high spatial resolution, (iv) daily-monthly approach, (v) use of innovative and advanced analysis tools, and (vi) downscaling to small scale areas.

Using a similar methodology is essential to support policy/decision making. Especially decision making at country or multi-country level should trust that results can be inter-compared and are not biased by differences in methods and data use. Obviously, minor local specifics can be somewhat less captured on these large scales but this is outweighed by the advantage of having results that are intercomparable.

Combining quantitative and qualitative approaches in this study was materialized by using on the one hand remote sensing, models at various scales and advanced data exploration techniques. On the other hand local experts have visited the, so-called, 34 focal areas and information from multiple other studies were included. Also institutional, economic and sociological information was included by using expert knowledge from the seven countries involved.

Although the study was not a hydrological one, the highest resolution hydrological model ever built for the seven countries was setup to support the determination of the irrigation potential. This was only possible by developments in remote sensing, data bases and computer technologies over the last few years. A clear demonstration of these new opportunities in terms of spatial resolution is that one of the reference studies on irrigation potential (FAO, 1997) was based on 136 units for the whole of Africa, which translate to a resolution of about 200,000 km^2 (~ 450 x 450 km). Also, the recently completed IFPRI study for Sub-Saharan Africa (You et al., 2007) was based on a resolution of 5 arc-min (~ 10 x 10 km). The study as presented in this report uses a resolution of 250 x 250 meter for the seven countries and for the focal areas 30 x 30 meters.

The approached followed here is based on a monthly assessment, while most previous approaches considered annual water availability and water requirements. The monthly approach ensures that seasonal water shortages are not compensated during wet seasons in the analysis. Moreover, the monthly water demand, supply and shortages are generated by the models that run on daily time steps to ensure that stormflow events are well captured. Obviously, some of the most extreme short-duration storm events might be not probably represented in the model, but time and space resolution is the optimum tradeoff between required detail for processes, data availability, calculation times and study objectives (Droogers et al., 2012).

Innovative and advanced analysis tools have provided the opportunity to undertake the analysis at a much more reliable and unbiased level compared to a few years back. Typical examples from the current study are: remotely sensed based rainfall, crop water consumption, land cover and DEMS; modeling tools such as NELmod and AquaCrop; advanced spatial GIS analysis and stake-holder data/results distribution tools.

Finally, the study uses the large scale results (countries) to downscale to relatively small areas of a few thousands hectares. By combining these two scales using the quantitative and qualitative analyses, the study can be seen as a benchmark to be used by decision makers to develop further policies.

The above should be considered in the context of the objectives of the study: “preparation for a development program” and “pre-feasibility”, and has therefore a strategic perspective

7.2 Basin and Sub-Basins

The overall irrigation potential for the entire study area (six entire countries and for DR Congo only areas located within the Nile Basin) is about 51 million ha. In Figure 60 suitability classes can be seen where a threshold value of > 60% is defined as suitable. Note that given the vast extent of the study area, small details are not visible in this Figure, but can be found in the Annexes and the digital database attached to the report. Some typical examples are shown in Figure 64.

Interesting is that suitable areas are quite well distributed over the entire study area (Figure 63). One of the main features of the current study is that the suitability is expressed between 0% and 100%, where 0% reflects a location with major restrictions in all factors included and 100% indicates no restriction at all (Figure 60 and Figure 63). The study provides for each suitable area a clear indication whether limitations are in terrain, soils, water availability, socio-economics and/or accessibility. Though, the overall strength of the current study in the context of strategic planning is that a uniform methodology has been used over the entire area and that all relevant determining factors for irrigation potential have been integrated, while maintaining the information on the individual limiting factors.

Within the seven sub-basins of the Nile Equatorial Lake a total area of about 20 million hectares can be considered as suitable to develop irrigation (suitability score > 60%) and an area of almost 4 million hectare is very suitable (suitability score > 70%). For the seven sub-basins suitability classes are also shown as percentage of total area in Figure 61. Overall, the Bhar el Ghazal and Sudd sub-basins offer the best opportunities to develop irrigation, although in the other sub-basins also very suitably areas can be found (Figure 63).

7.3 Countries

Detailed results per country can be found in the seven Appendixes for each country, while totals are shown in Table 26. Overall, the potential to develop irrigation are sufficient and the high-resolution maps (e.g. Figure 64) have been proven very useful to select detailed areas to focus on. The current study has the advantage that not only suitability or non-suitability is determined, but also suitability classes are produced (Figure 61). Even more important is that the detailed maps provide limitations for each location in terms of physical restrictions to develop irrigation.

The results for the individual countries indicate that in each country suitable (classes >60%) and very suitable (classes >70%) areas can be found (Figure 61). Obviously, for the more mountainous countries the total suitable area is somewhat lower and suitability includes also small-scale hill-side irrigation. For other countries options for larger scale irrigation exists, although the selection of the focal areas in this study was limited to a few thousands hectare.

The country analysis includes also semi-quantitative and qualitative aspects such as: Millennium Development Goals, poverty reduction strategies, legal aspects (land ownership), socio-economic contexts, institutional settings, yield gap analysis and potential cropping patterns, environmental aspects (protected areas), socio considerations (population displacements), and upstream-downstream impacts (water treaty agreements). Obviously, a study encompasses such a large area and many topics, cannot cover all minor details and aspects. Therefore, based on the country results 34 so-called focal areas were selected and more detailed analyses were undertaken.

7.4 Focal Areas

Based on the countries results and interactions with many experts from the countries and from NBI a selection of the most promising irrigation areas has been made. A total of 34 so-called focal-areas was selected and detailed data collection, including field-visits, were made. It has to be realized that the current project has a strategic perspective (pre-feasibility), with very limited time/resources per area (about three days). Details about these focal areas can be found in the seven Appendixes. The overall results of these focal areas shows that for most of the areas opportunities for a following-up study (feasibility) are justified.

The overall result is that all focal areas have a clear scope to develop irrigation. Initial investments range from about 5 million US$ up to 60 million US$, while Internal Rate of Returns vary quite substantial with averages between 10% and 25% (although also some negative as well as some very high IRRs can be found) . Important to note is that the IRRs depend very much on the expected crop choice, crop yields and prices which are very local specific and have large uncertainties. Equally important is the relevance for people living in the area if irrigation would be developed. The details for each focal area provide full insight in the physical, economic, and social dimensions of the specific focal area and its potential to develop irrigation.

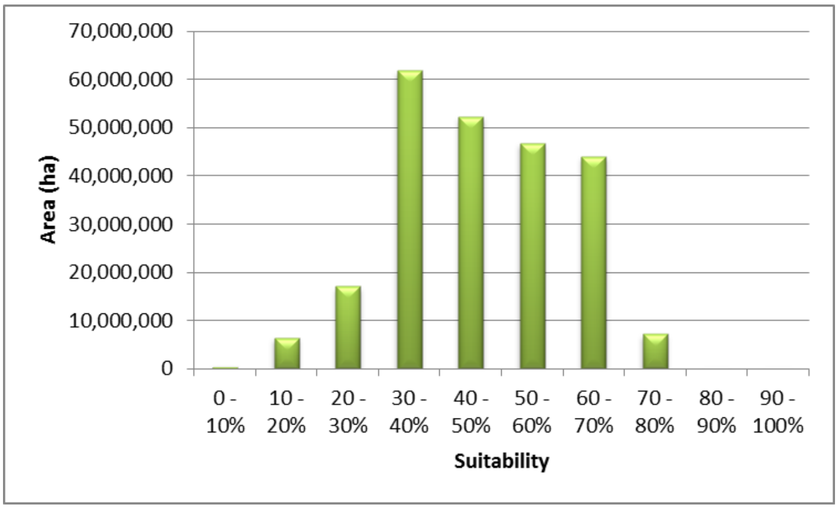

Figure 60. Suitability classes for the entire study area. Values >60% can be considered as suitable to develop irrigation.

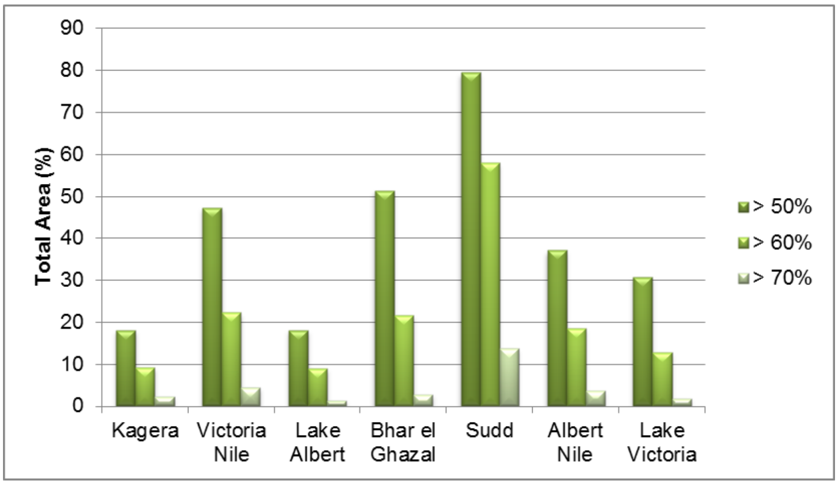

Figure 61. Suitability classes for irrigation expressed as percentage of total area of each sub-basin. Values >60% can be considered as suitable to develop irrigation.

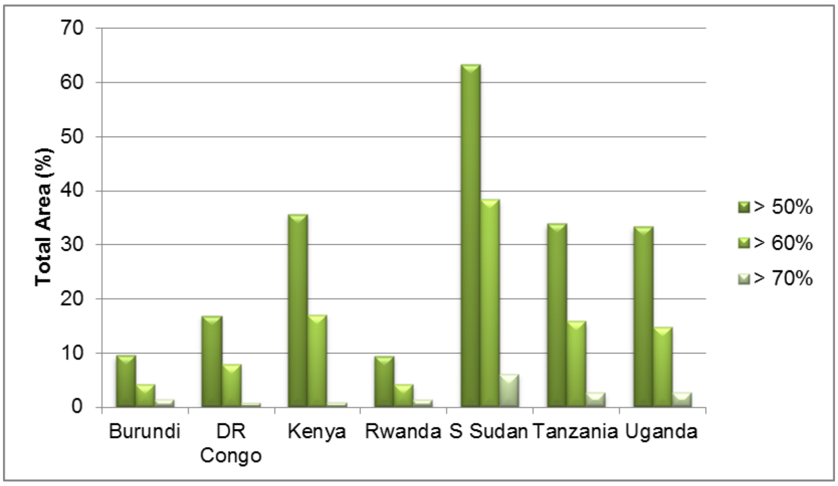

Figure 62. Suitability classes for irrigation expressed as percentage of total area of each country. Values >60% can be considered as suitable to develop irrigation.

7.5 Recommendations and Following Up

Interesting is to compare in Table 26 the results from this study with some earlier assessments. The deviation between these various studies in terms of irrigation potential can be attributed to the difference approaches as stated by FAO's AquaStat "*Country/regional studies assess this value according to different methods. For example, some consider only land resources, others consider land resources plus water availability, others include economic aspects in their assessments (such as distance and/or difference in elevation between the suitable land and the available water) or environmental aspects, etc.*" The current study is a typical example of progress in analysis techniques and combining quantitative and qualitative aspects at a high spatial resolution.

Comparing the results of the current study with the ones from various previous studies shows that the potential areas from this study differs as well (Table 26). There are various reasons for this difference. The most important one is that the current study includes all factors important for irrigation potential not taken into account in previous studies. Typical examples are studies focusing mainly on soils and land (e.g. FAO, 1997a) or economics (You et al., 2007). In the current study an integration of soils, land use, water availability and socio-economics was considered. Moreover, the current study uses a combined daily/monthly approach rather than the commonly applied annual approach. This was all possible since more advanced tools and data are available because of developments in public domain datasets, fast computers, and remote sensing. The presented results can therefore be considered to be more accurate than any previous study. However, rather than concentrating on comparing the actual numbers from various studies, it is more important to focus on the usefulness of the results. The current study opens the opportunity to decision makers to assess what the limitations for an area are and to make justified assessments for further development.

The impact of development of irrigation on downstream water availability depends, obviously, completely on the size of the areas developed and on the selected crops. A rough assessment shows that for every 1000 ha irrigation development about 5 MCM per year reduction in downstream flows can be expected (assuming an increase of evapotranspiration of 500 mm per year). If we take roughly a current downstream flow of 50 BCM, development of 10,000 ha irrigated land would lead to a reduction of 0.1% in downstream annual flows. The total area of the 34 focal areas is about 215 thousands ha of which about 120 thousand ha are actually irrigable fields. If even all those focal areas will be brought under irrigation, an annual flow reduction of about 0.6 BCM per year can be expected; this means an annual flow reduction of about 1% of the river Nile.

The current study is a solid base for further investigations that will lead to actual development of irrigation in the countries. The current study is scoping from nature and can be categorized as pre-feasibility. Based on these results, potential investors (either private, governments or donors) might select some of the focal areas for a feasibility study. By using results from the current study such a feasibility study might be undertaken relatively quickly. If outcome of such feasibility study are positive one can move to a detailed design phase and implementation if resources can be secured.

Table 26. Irrigation potential of the seven countries included in the study. Note that also areas outside Nile Basin are include, while for DR Congo only the area within the Nile Basin is considered.

Description	Total area suitable for surface irrigation (ha)	Irrigation potential (ha)	Area equipped for full control irrigation (ha)	Irrigation potential (ha)	Irrigation potential (% of total area)
Source	FAO, 1997	AquaStat, 2009	You et al., 2010	This study	This study
Burundi	588,800	215,000	42,000	105,400	4%
DRC	9,303,200	7,000,000	579,000		
Nile-DRC[20]				124,400	8%
Kenya	17,384,700	539,000	338,000	9,683,400	17%
Rwanda	300,900	165,000	N/A	99,900	4%
Sudan[21]	68,769,200	2,784,000	628,000		
South-Sudan				24,145,300	39%
Tanzania	24,253,400	2,132,000	1,012,000	13,975,100	15%
Uganda	7,675,700	90,000	1,151,000	3,027,800	13%

[20] This study considered only DRC part in the Nile Basin.
[21] Figures for Sudan reflect the country before the split between Sudan and South Sudan

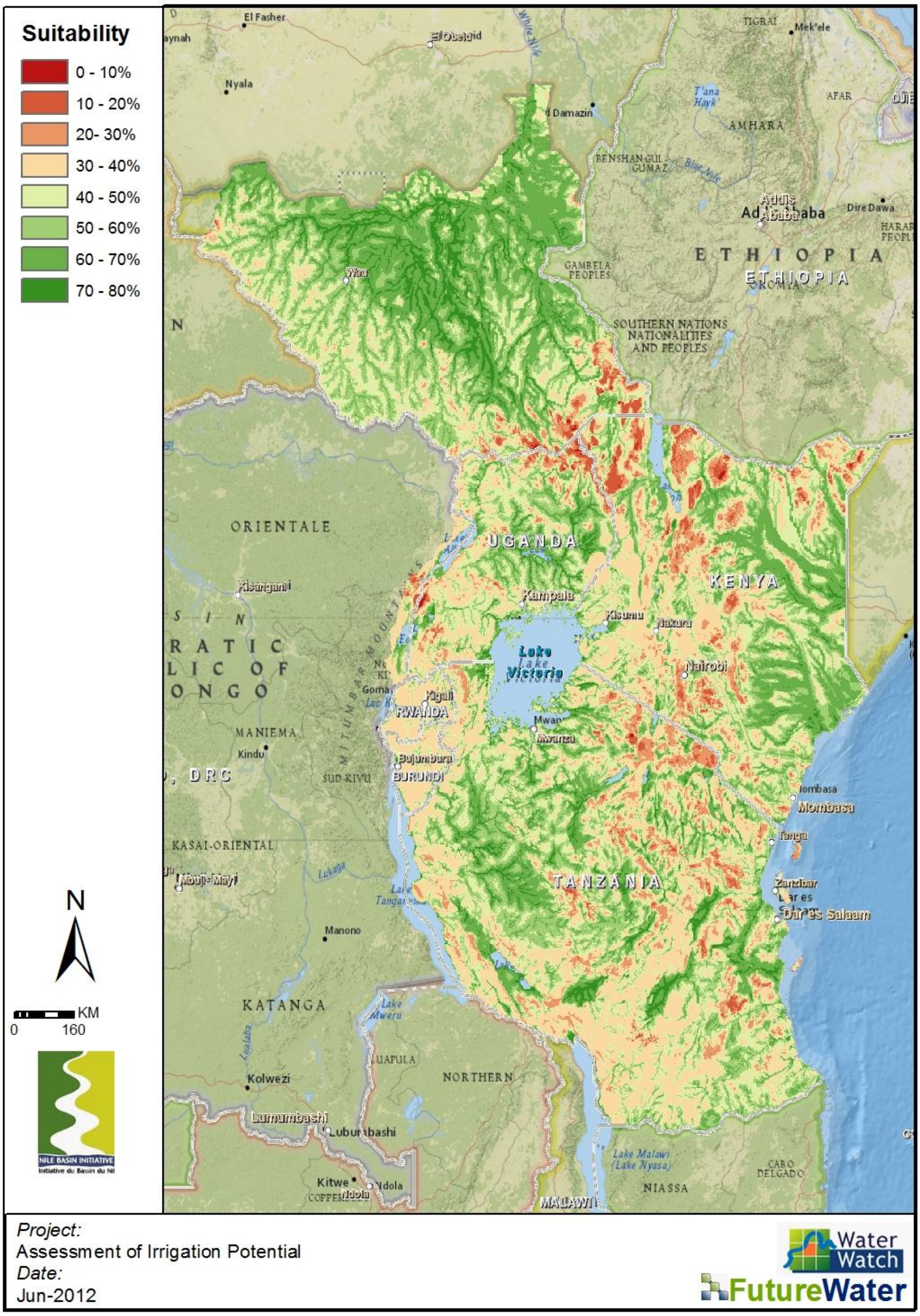

Figure 63. Suitability classes for irrigation based on soils, water availability, water requirements, socio-economics, and accessibility. Values >60% can be considered as suitable to develop irrigation.

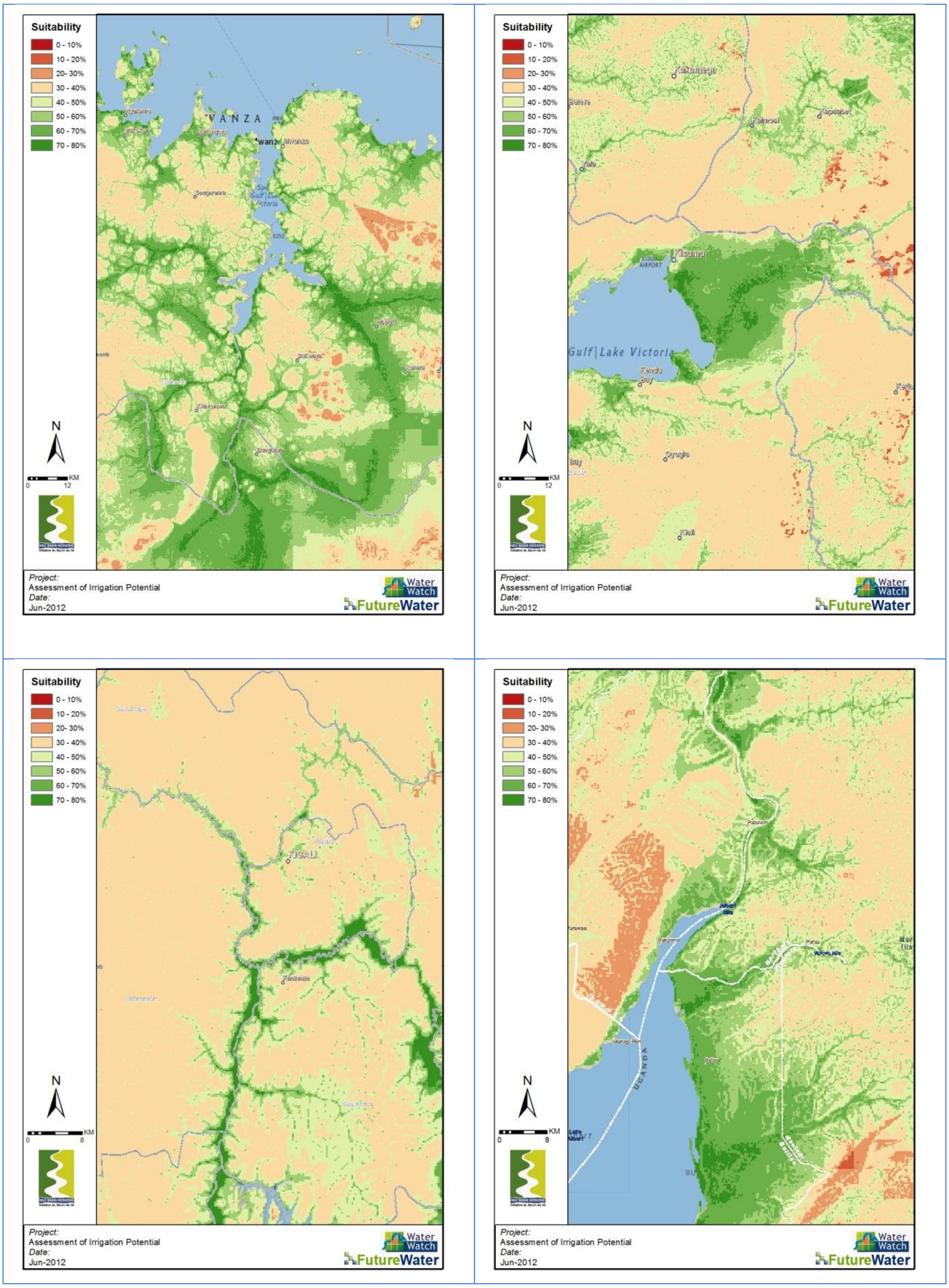

Figure 64. Some typical examples showing the level of detail included in the study (top-left Tanzania, top-right Kenya, bottom-left Rwanda, bottom-right Uganda.

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APPENDIX: Burundi
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