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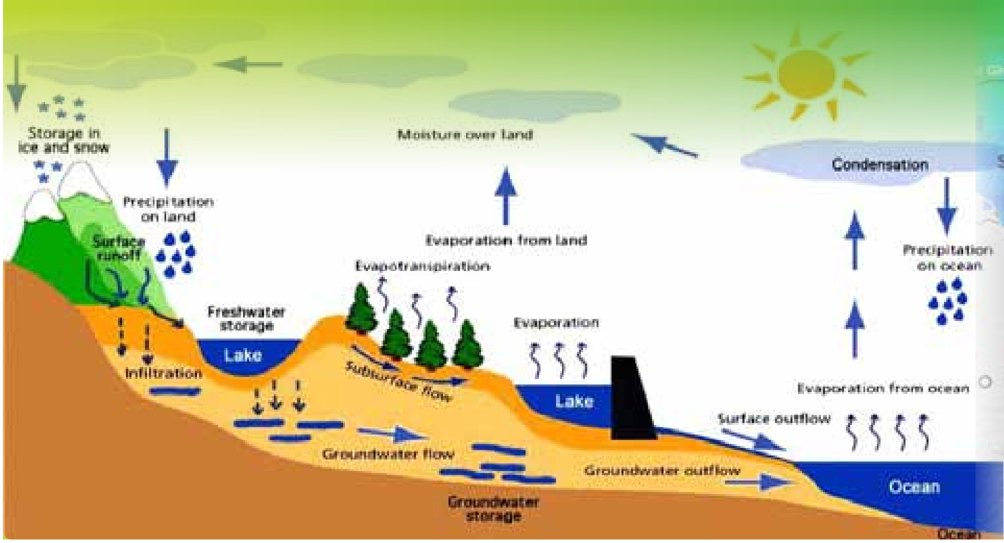
NILE BASIN INITIATIVE
Initiative du Bassin du Nil

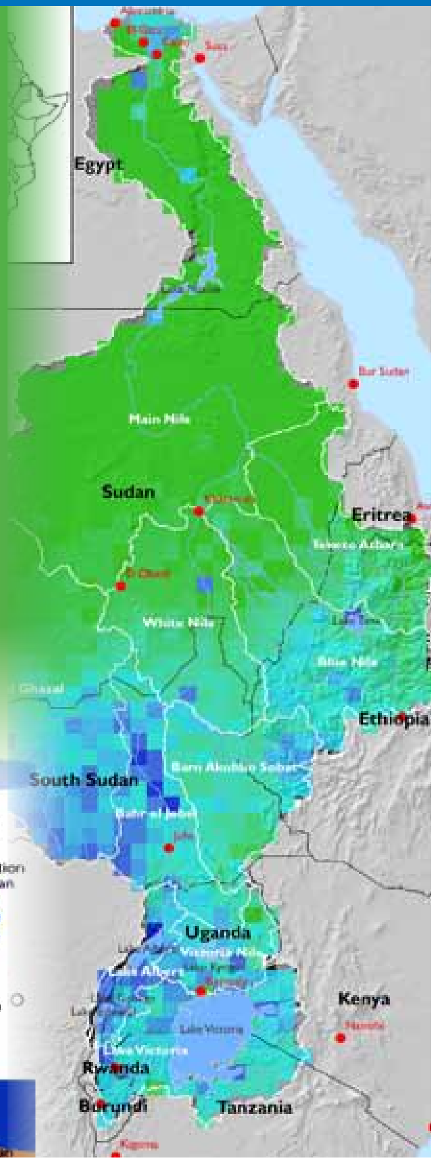
Nile Waters

TECHNICAL BULLETIN FROM THE NILE BASIN INITIATIVE SECRETARIAT

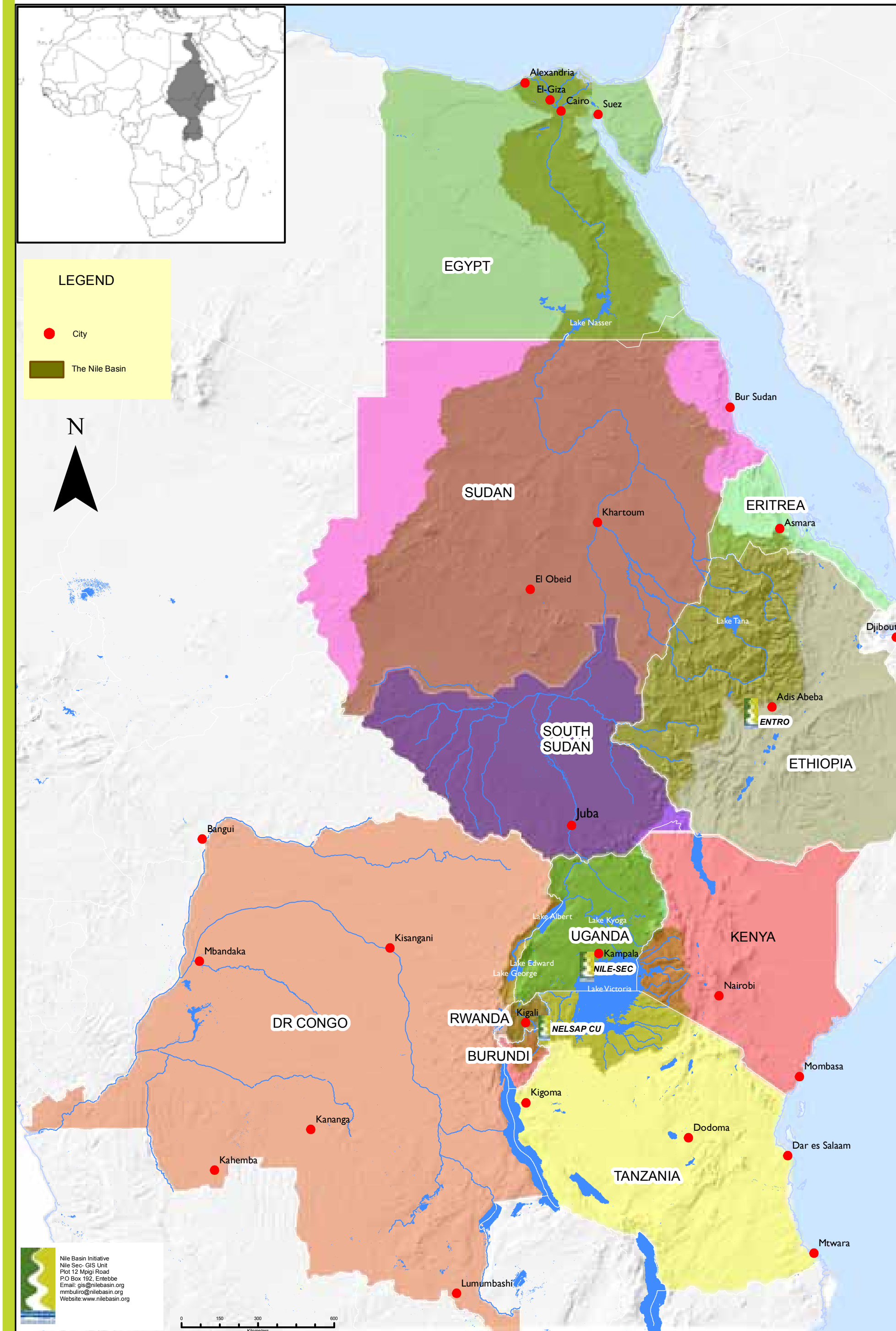
UNDERSTANDING NILE BASIN HYDROLOGY

Mapping Actual Evapotranspiration over the Nile Basin





THE NILE BASIN COUNTRIES



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ABBREVIATIONS AND ACRONYMS

CRU	Climatic Research Unit
ET	Evapotranspiration
ETo	Reference Crop Potential Evapotranspiration
LAI	Leaf Area Index
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NBI	Nile Basin Initiative
PET	Potential Evapotranspiration
RFE	RainFall Estimates
TRMM	Tropical Rainfall Measuring Mission

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SUMMARY

Evapotranspiration (ET) is one of the major components of the water balance over the Nile Basin and its sub-basins. It accounts for about 87% of the basin's rainfall but this value varies from a sub-basin to another Based on land use/cover and prevailing climatic conditions. It is difficult to measure evapotranspiration but recent advances in satellite observations have enabled its estimation over large areas such as the Nile basin. The Nile Basin Initiative (NBI) has utilized such advances and generated a dataset of ET estimates over the Nile Basin spanning the period 2000 to date. Analyzing this dataset revealed some interesting insights for water management. Lake Albert basin seems to have the highest evapotranspiration to rainfall ratio (almost 90%) of all water generating sub-basins. This ratio is around 100% for Bahr El-Ghazal which confirms that this basin does not contribute to the Nile flow while it is around 108% for Bahr El-Jebel indicating excessive water losses in the Sudd swamps. Although all these conclusions are already known, the difference that the ET dataset made is allowing the quantification of the figures. The following sections discuss the concepts and methods for providing such quantifications, examples for use, and displays some of the challenges that are yet to be addressed.

INTRODUCTION

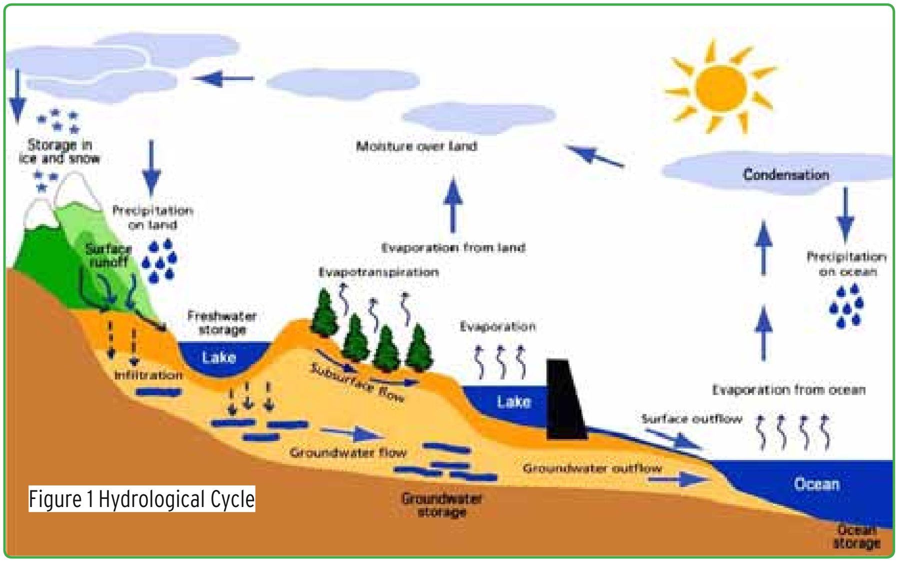


Figure 1 Hydrological Cycle

Evapotranspiration (Evaporation + Transpiration) is a natural process through which water moves from land and water surfaces back to the atmosphere. It is one of the largest components of the water balance of the Nile Basin. It accounts for more than 70% of the water balance in the wettest areas of the Nile Basin like the Blue Nile and the Equatorial Lakes sub-basins and even a higher percentage in drier areas. Evapotranspiration is the combined process of evaporation from wet surfaces (soil, water, and vegetation) and transpiration from the vegetation cover whether natural or made-made (e.g. irrigated land). The two processes occur simultaneously and are difficult to separate. They form an integral part of the hydrological cycle (Figure 1).

TYPES OF EVAPOTRANSPIRATION

Distinction should be made between potential and actual evapotranspiration.

Potential Evapotranspiration

Potential evapotranspiration (PET) is the amount of water that would leave the surface (land or water) if water was abundant. It depends only on the atmospheric conditions (temperature, wind speed, humidity, radiation, etc.) and vegetation characteristics (coverage, growth stage, height, etc.) and therefore termed the evaporative demand. It is a reflection of the energy available to evaporate water, and of the wind available to transport the water vapour from the ground up into the lower atmosphere. Normally, potential evapotranspiration is calculated for a specific "reference" crop, and therefore, is referred to as reference crop potential evapotranspiration (ETo). The "reference crop" is normally a clipped grass-surface having 0.12m height and bulk surface resistance equal to 70 sm^{-1}, an assumed surface albedo of 0.23 (Allen et al., 1998). Values for other types of crops/vegetation are estimated from ETo using crop coefficients.

Actual Evapotranspiration

Actual Evapotranspiration (ET), however, is the amount of the evaporative demand satisfied according to the availability of moisture in the soil and vegetation. When water is in shortage, soil is generally dry (i.e. less evaporation) and plants raise their stomatal resistance to release water to the atmosphere reducing transpiration. For open water surfaces, the actual and potential values are thus identical.

ESTIMATING ET: METHODS AND TECHNIQUES

Evapotranspiration is not easy to measure. Specific devices and accurate measurements of various physical parameters (e.g. the soil water balance in lysimeters, or evaporation pans) are required to determine ET. The methods are often expensive, demanding in terms of accuracy of measurement and can only be fully exploited by well-trained research personnel. Additionally, they are meant to measure actual ET only from a limited area. Although the methods are inappropriate for routine or large scale measurements, they remain important for the evaluation of ET estimates obtained by more indirect methods (Allen et al., 1998).

Traditional Methods Versus Remote Sensing

Measurements of the net change in the vapour content of the air over large areas using balloons can provide estimates of the regional ET rate but this method is not widely used (Shuttleworth, 1993). Moisture flux from land surface is measured using Eddy Covariance Techniques (Aubinet et al., 2012) and they are gaining more and more use specially to collect data that would be used for calibration of ET algorithms and thereby refine indirect estimation of actual ET.

Previously, water balance models were used to estimate ET as the remainder after determining all other balance components (rainfall, river flow, storage changes). Then surface energy balance techniques emerged (SEBAL, Bastiaanssen et al., 1998) utilizing available satellite information and avoiding the error in estimating other water balance components from propagating into the ET estimate.

Remote Sensing

Therefore, remote sensing has long been recognized as the most feasible means to provide spatially distributed regional ET information on land surfaces. Remotely sensed data, especially those from polar-orbiting satellites, provide temporally and spatially continuous information over vegetated surfaces useful for regional measurement and monitoring of surface biophysical variables affecting ET, including albedo (surface reflectance), biome type and leaf area index (LAI) (Los et al., 2000). The Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA's Terra and Aqua satellites, provide unprecedented global information on vegetation dynamics and surface energy variations (Justice et al., 2002), which can be used for regional and global scale ET estimation in near real-time.

NBI SATELLITE BASED ET ESTIMATES

Realizing the importance of ET to the water balance of the Nile Basin, and utilizing the available satellite information and advanced algorithms, the NBI has produced estimates of actual ET over the whole of the Nile Basin at a resolution of 1 km^2 at 8-day time step. This dataset starts from January 2000 to date and can help in establishing more accurate water balances for the various Nile sub-basins especially those with large swamps (e.g. the Sudd) and those with inaccessible river gauges. ET can also provide estimates of the consumptive use for cropped areas. Having time series estimates for ET can also help in detecting changes in land use/cover and in studying climatic trends in the various regions of the basin. Figure 2 shows the mean annual and monthly patterns of ET over the whole of the Nile Basin. It is clear that open water surfaces (lakes and rivers) have the highest annual ET values followed by wetland areas (e.g. the Sudd). The intensively irrigated areas in the Nile Delta and along the Nile in Egypt are also clear and crop consumption can be quantified using the dataset. Other areas of high annual ET values are in Bahr El-Ghazal basin and the Equatorial lakes (especially around Lakes Albert and Kyoga). Further analysis is presented in subsequent sections.

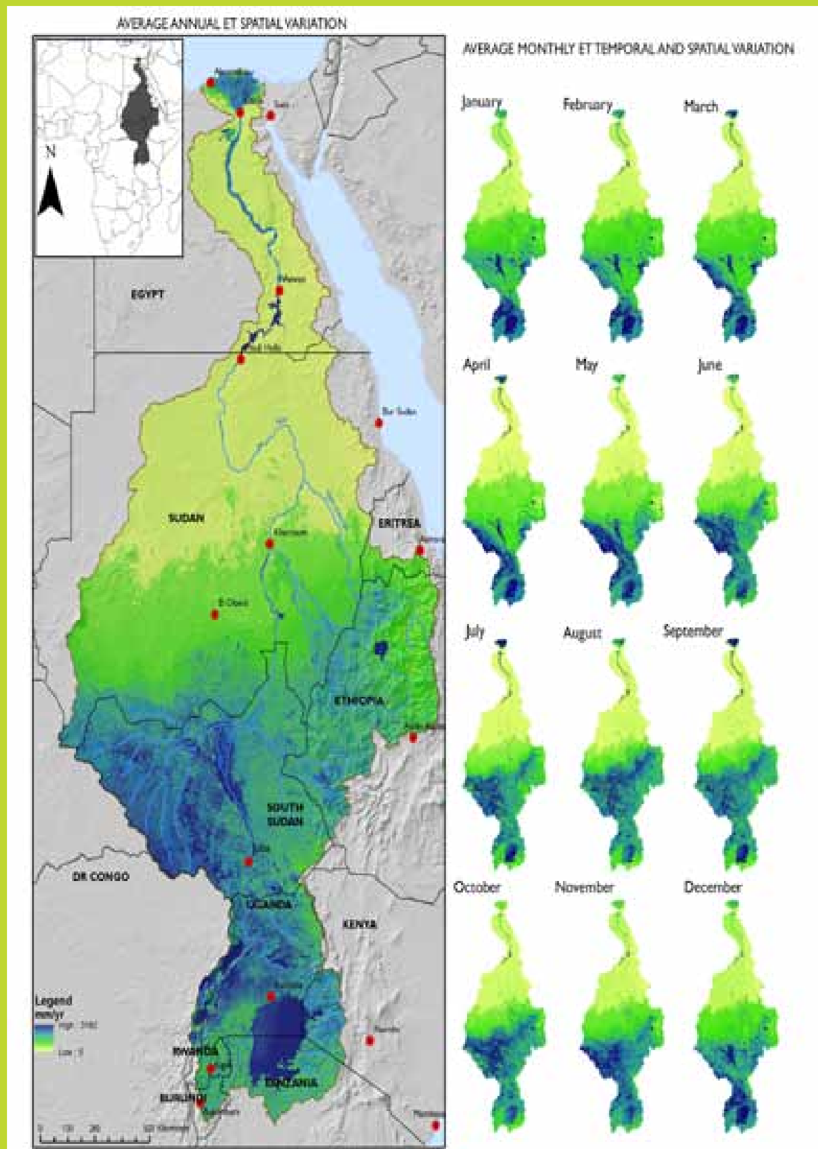


Figure 2 Temporal and Spatial Patterns of ET over the Nile Basin (2000-2012 Average Values)

ANALYSIS OF ET ESTIMATES OVER THE NILE BASIN

Here the satellite ET estimates are compared to estimates of ETo and rainfall over the basin and at sub-basin scale. ETo and rainfall are obtained from the CRU TS 3.21 dataset (Harris et al., 2013) except for Lake Victoria where TRMM rainfall was used because CRU data underestimate the lake rainfall as it is based on gauge data (with no gauges within the area covered by the vast lake). CRU TS 3.21 is the most recent update of the CRU comprehensive gridded gauge-only dataset of basic surface climate variables (precipitation, temperature, humidity – expressed as vapour pressure, cloudiness – as a surrogate for radiation, diurnal temperature range – from which maximum and minimum temperatures are derived, and frequencies of wet days and frost days) covering all land areas for the period 1901-2012 at 0.5° x 0.5° spatial resolution with a monthly time step. CRU rainfall was selected after comparing to other satellite products (RFE 2.0 and TRMM 3B43); however, it still needs verification against gauge dataset and is used indicatively in this analysis. ETo is a derived variable calculated using the standard modified Penman-Monteith procedure (Allen et al., 1998) using temperature, humidity, and wind speed, and cloudiness data. As the CRU TS does not contain wind speed data series, the wind speed climatology of 1961-1990 (New et al., 1999) is used. Harris et al. (2013) report that the impact of using the average wind patterns (climatology) rather than a time series is generally small and mainly affects the variability of ETo. It should be noted that the dataset does not reflect the vegetation types and, therefore, the ET/ETo and ET/P ratios are only indicative.

ANNUAL PATTERNS

Figure 3 shows the spatial distributions of annual ET/ETo and ET/P ratios based on averages over the 2000-2012 period. It is clear that ratios of ET/ETo are high up to a division line in Sudan which shows a clear divide between humid and sub-humid conditions on one side where there is enough water to satisfy most of the evaporative demand (ETo), and the arid and semi-arid zones of Sudan and Egypt on the other side where there is very low moisture except where irrigation is provided in the Nile Delta and along the river. The ET/P shows an interesting pattern because there are high ratios in the dry areas of northern Sudan and Egypt reflecting the fact that any moisture available evaporates and some of this moisture comes along the river. In wetter basins (e.g. Ethiopian Plateau, Eastern Equatorial Lakes), ratios are around 0.5-0.6 allowing for some runoff to be generated. In the vast plains of South Sudan and around Lake Albert, ratios near to 1.0 are observed meaning that almost all rainfall, which is relatively high in these regions, is lost to evaporation. Table 1 quantifies these ratios for 10 sub-basins which are shown on the maps of Figure 3.

Table 1 shows the highest ET/ETo ratio for a sub-basin occurs for the Lake Albert basin (87%) due to the existence of forests followed by Bahr El-Jebel (73%) which includes the largest swamps while the lowest occur for the dry Main Nile sub-basin (4%) followed by the Tekeze-Atbara (16%) which is also mostly dry. The ratios are indicative of moisture availability (mostly through rainfall but through the river and irrigation canals in some areas) and of the land cover type because ETo does not consider the type of vegetation. For lakes, the ratios should be all close to 1.0, however, this is not always the case raising alarms regarding the quality of the data used to estimate either ET or ETo. A note on this is given below.

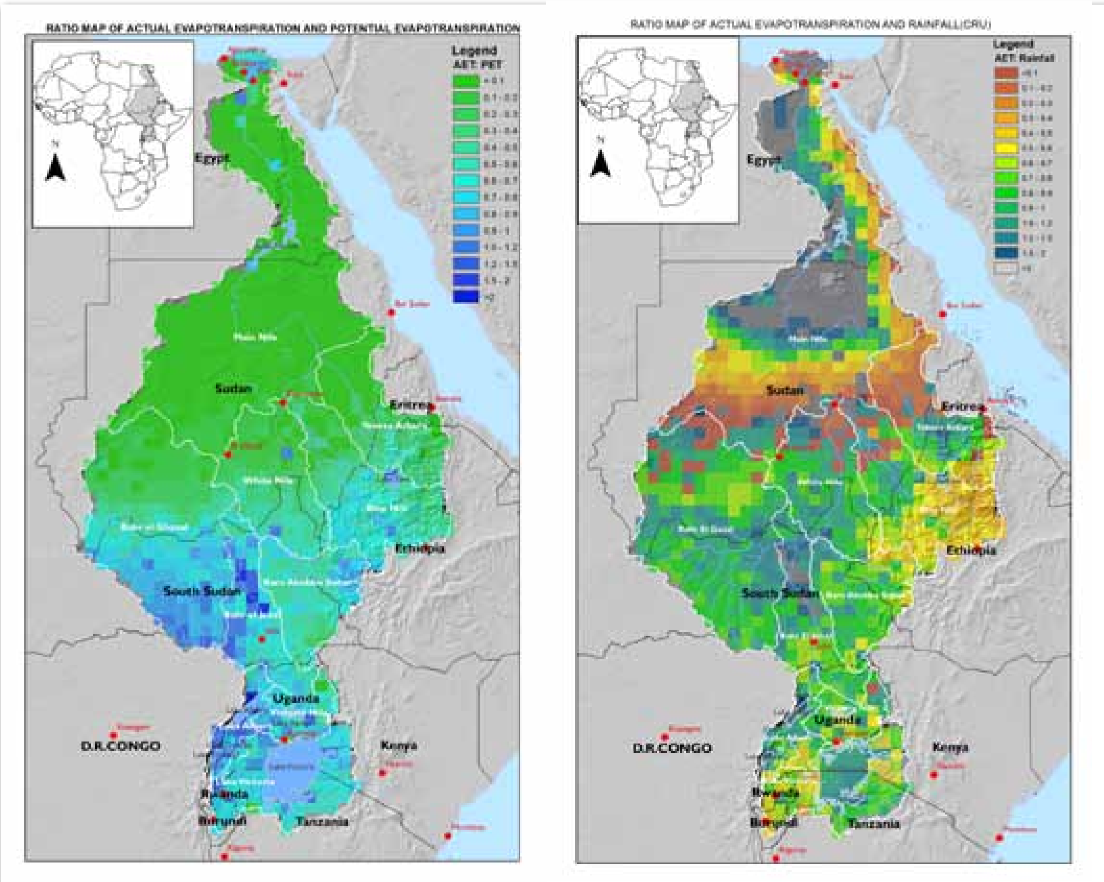


Figure 3 Temporal and Spatial Patterns of ET over the Nile Basin (2000-2012 Average Values)

The ratio of ET/P shows the conversion rate of available moisture to evapotranspiration. When this ratio is less than one (in the sub-basins of Lake Victoria, Lake Kyoga, and the Ethiopian Plateau), there is room to generate runoff and/or charge groundwater from the excess rainfall. When this ratio is more than 1.0 (Bahr El-Jebel and the Main Nile sub-basins), this means that all locally generated and some of the transported water into the basin is lost and therefore those basins are a source of loss. The difference of P-ET indicates the amount of such water losses. Whether it is a beneficial or a non-beneficial loss depends on the nature of land use/cover through which water evaporates (whether to maintain agricultural or natural systems). Looking at all major lakes within the system, they all lose water to evaporation more than they gain via direct rainfall except Lake Victoria. The excess moisture is supplied via river flow generated from the lakes' respective or upstream catchments. Lake Nasser is a special example where almost all of the evaporated water is not supplied via rainfall but via the river itself. It should be noted that the ratios are indicative because the quality of global scale rainfall datasets (CRU TS 3.21 and TRMM 3B43 used for this analysis) still need to be verified against local and regional scale observations.

Table 1 Evapotranspiration over Nile Sub-basins and Lakes in Comparison to Potential Values and Rainfall

Sub-basin[1]/Lake	Area (km2)	ETo/Eo[2] (mm/yr)	ET (mm/yr)	ET (BCM/yr)	ET:ETo[2] (%)	ET:P[3] (%)
Lake Victoria Basin	108,412	1,248	794	86.09	64%	68%
Lake Kyoga Basin	82,764	1,552	992	82.12	64%	79%
Lake Albert Basin	88,712	1,221	1,058	93.89	87%	87%
White Nile Basin	258,864	1,810	525	135.93	29%	96%
Baro-Akobo Sobat	204,336	1,502	809	165.37	54%	80%
Blue Nile	300,719	1,507	589	177.07	39%	58%
Tekeze Atbara	231,465	1,810	295	68.18	16%	70%
Bahr El-Ghazal	598,867	1,628	774	463.67	48%	97%
Bahr El-Jebel	185,319	1,452	1,063	197.00	73%	105%
Main Nile	951,994	2,314	85	81.22	4%	157%
Sub-Total/Average	3,011,451	1,815	515	1,550.54	28%	86%
Lake Victoria	6,712	1,821	1,522	101.56	84%	89%[4]
Lake Kyoga	2,801	2,115	1,896	5.31	90%	135%
Lake Albert	5,502	1,845	1,795	9.87	97%	150%
Lake Edward	2,232	1,622	1,500	3.35	92%	137%
Lake George	269	1,636	1,558	0.42	95%	148%
Lake Tana	3,047	2,048	1,722	5.25	84%	138%
Lake Nasser	5,370	3,222	2,220	11.92	69%	25653%
Sub-Total/Average	85,934	1,922	1,602	137.68	83%	105%
Basin-wide Average/Total	3,097,385	1,818	545	1,688.22	30%	87%

[1] Major lakes mentioned in the Table are excluded from sub-basin calculations as they are considered separately as shown

[2] For basins, ETo is taken from CRU TS 321 as described in the text; For Lakes, Eo is open water evaporation calculated using spatially averaged time series of temperature, humidity (vapor pressure) and cloudiness from the CRU TS 3.21 dataset, in addition to wind speed climatology only (from the CRU CL 2.0 - 1961-1990 mean); CRU Wind speed climatology has limited spatial coverage over Lake Victoria

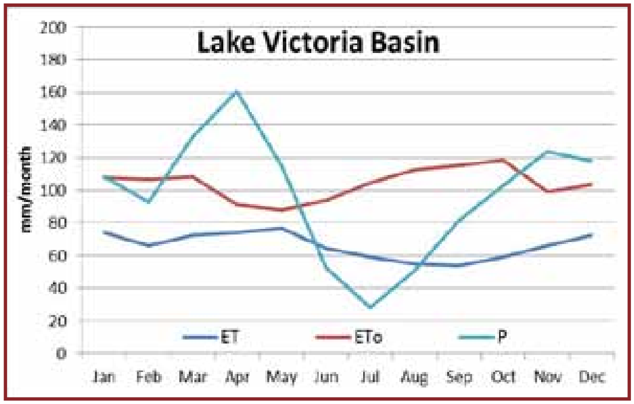
[3] CRU TS 3.21 rainfall except for Lake Victoria – see ([4]) below – Ratios are indicative and as rainfall need verification versus raingauges

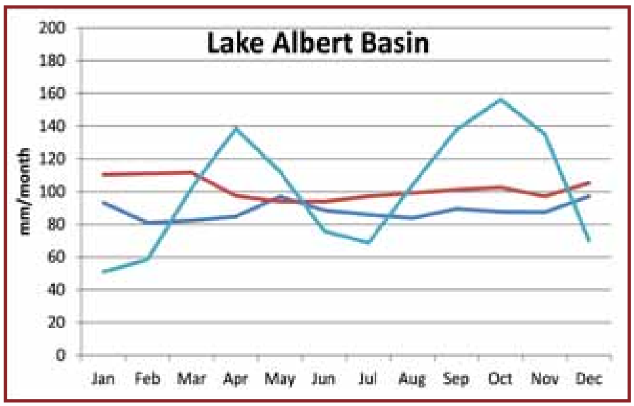
[4] For Lake Victoria, Rainfall used to calculate the ration is based on TRMM 3B43 Rainfall data – CRU value is underestimated because it is based on gauges around the lake in absence of gauges inside the lake; it is often reported that rainfall rate inside the lake is much higher than its shores

SEASONAL PATTERNS

Analyzing seasonal patterns (Figure 4) reveals contrasting patterns between the different sub-basins but there are some common features as well. The Equatorial Lakes catchments are all known to have bi-modal rainfall regimes and this is reflected to some extent in ETo distribution which are mostly bi-modal with peaks in the drier seasons and minimal in the wet seasons (due to the effect of cloudiness associated with rainfall which reduces ETo) but the seasonality is less pronounced than that of the rainfall. ET approaches ETo when moisture (mostly rainfall) is available and peaks about one month after the rainfall peak. For the three equatorial lakes' basins, ET reaches ETo only for the Lake Albert basin in May and stays close to ETo for most of the year. The South Sudan basins are characterized by uni-modal rainfall with considerable amounts of rainfall over several months (compared to the Blue Nile and the Atbara where rainfall is more concentrated in fewer months). Again, ETo shows some inverted distribution to rainfall with less pronounced seasonality while ET peaks one month after the rainfall peak except for Bahr El-Jebel because the source of moisture here is partly from the river flow coming from the equatorial lakes upstream. The Sudd is located mostly within Bahr El-Jebel basin and during the summer months, all the evaporative demand is satisfied through rainfall and river flow so that ET/ETo ratios are around 1.0 on average.

The White Nile, Blue Nile and Tekeze Atbara catchments are all characterized by a uni-modal rainfall pattern with a shorter rainy season. ETo patterns for the three basins are similar in shape and inverted with respect to rainfall, reflecting the same phenomena. Here ET patterns also peak one month later than the rainfall peak which is a common feature of almost all basins. However, the evaporative demand is under-satisfied in all basins with the Blue Nile having the highest satisfaction rate (Annual ET/ETo of about 39%) due to higher rainfall volume over the basin. Finally, the main Nile is the driest basin which has the highest evaporative demand but the lowest rainfall and therefore ET almost diminishes.





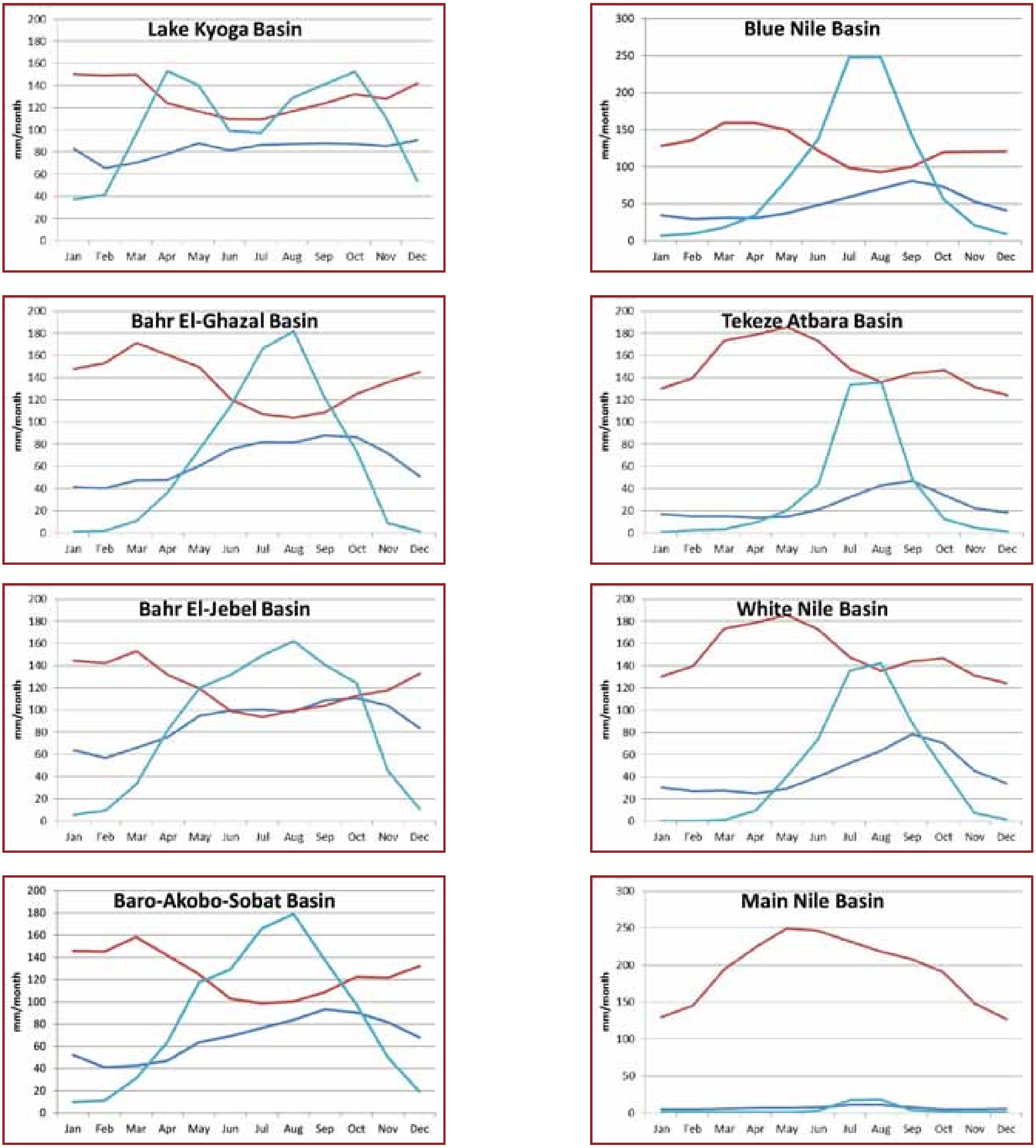


Figure 4 Mean Monthly Distributions for Evapotranspiration (ET), ETo, and Rainfall for various sub-basins of the Nile over the 2000-2012 period

APPLICATION 1: WATER BALANCE OF THE LAKE ALBERT BASIN

The water balance any sub-basin is described by the equation of mass conservation:

$$\Delta S=P-ET+Q\_in-Q\_out$$

For the Lake Albert basin (Figure 5), river inflows (Q_{in}) and outflows (Q_{out}) from the basin are available at Paraa and Laropi respectively for the period Jan 2000 to Oct 2010 with some gaps. Average monthly flow volumes for both stations are calculated (from the available data) and the total annual flow volumes are 32.91 and 37.60 BCM/yr respectively. P-ET is termed the net rainfall and distinction is made here between lakes and their catchments in calculating this quantity as in Table 2. Putting the elements together, ΔS = 8.39 + 32.91 - 37.60 = 3.70 BCM/yr. This water could be stored in the lakes in the basin (Albert, Edward, and George which represent around 8% of the total basin area), in small wetlands within the basin or recharge the groundwater. Water levels for the three lakes within the same period are not available to assess whether this water has been stored in the lakes. Given the lakes' areas (total of about 8000 km^2), a level rise of 0.46m/yr over the three lakes could explain the difference. However, this means a steady rise each year (i.e. around 5m rise over the whole period) which is unreasonable. Assuming that small wetlands can store such amount annually does not seem reasonable either. Given the lack of any information about groundwater recharge or wetland sizes, this amount remains unexplained. It could also result from errors in estimating any of the quantities especially rainfall and evapotranspiration which are estimated indirectly from satellite/gauge data.

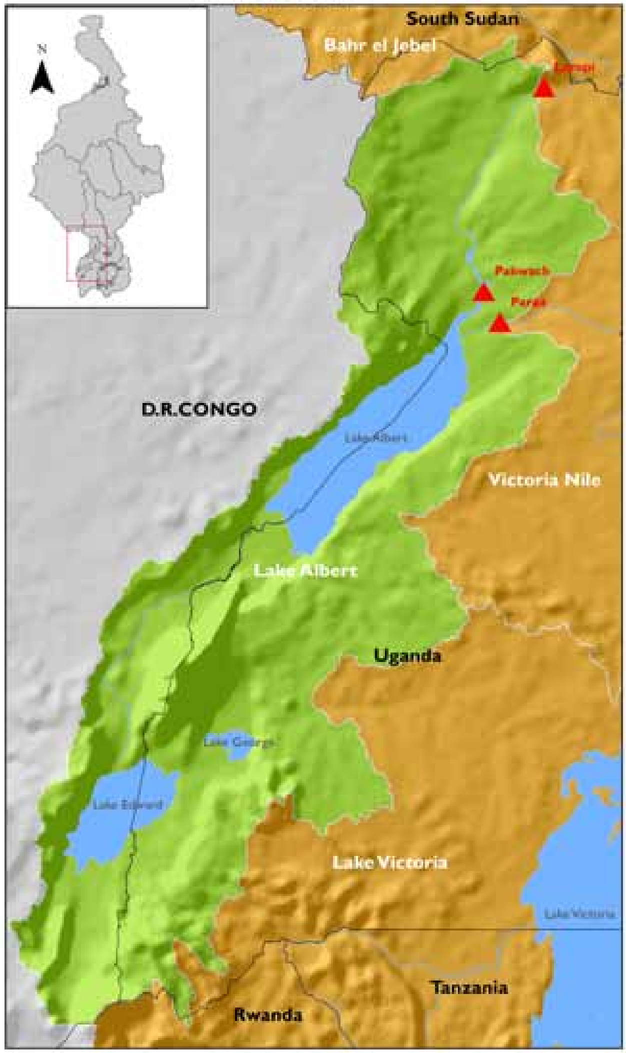


Figure 5 Lake Albert Catchment

Table 2 Net Rainfall over Lake Albert Basin (BCM/yr)

Lake/Sub-basin	P	ET	P-ET
Lake Albert	6.53	9.80	-3.27
Lake Edward	2.42	3.31	-0.89
Lake George	0.29	0.42	-0.13
Lake Albert Basin	106.66	93.98	12.67
Total	115.90	107.51	8.39

APPLICATION 2: DETECTING TRENDS IN ET

Analysis of annual series can provide evidence of any trends regarding P, ET, or ETo. As shown in Figure 6, there seems to be a downward trend over Bahr El-Jebel basin in terms of ET while ETo seems to be constant and P to be highly variable. The significance of such trend needs to be tested especially on a longer period. This should also be verified against the area of the Sudd swamps which is the major contributor to ET in this basin.

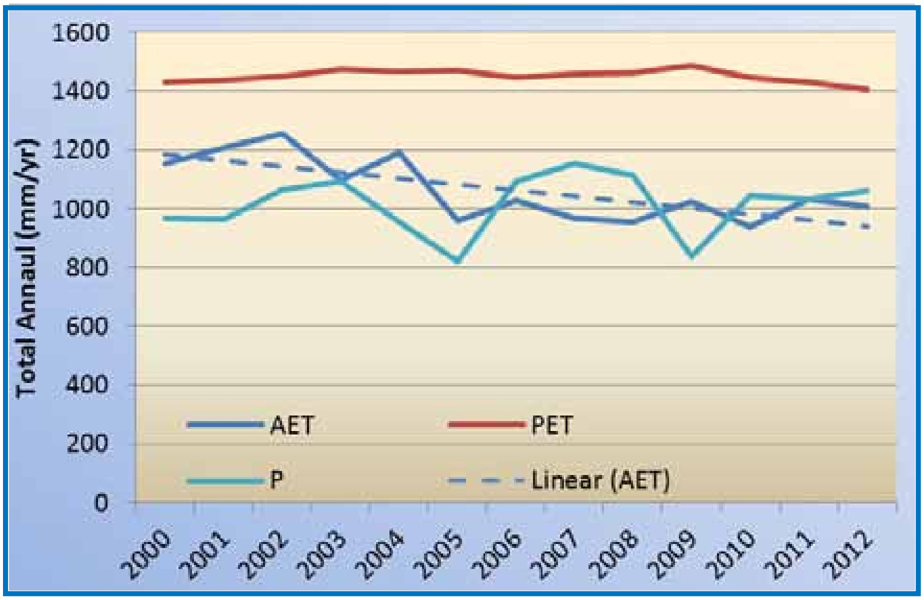


Figure 6 Annual Series for Bahr El-Jebel Basin

IMPLICATIONS FOR WATER MANAGEMENT

From the different analyses presented, mapping ET for the basin and at smaller sub-basin scale can play a role in the water management through the identification of areas where the ET rates are high to propose water conservation projects or to put the water to a more beneficial use. It helps in better understanding the basin, verifying water models, and detecting trends.

CHALLENGES

In order to realize the full value of the satellite-based ET estimates, data about other water balance component have to be available including rainfall, river flow, and lake level data. Satellite observations provide a lot of potential in estimating rainfall, ET, and even lake levels (through satellite altimetry). The accuracy of each element needs to be verified independently using ground observations and this calls for a regional data collection and exchange effort. Inter-comparison of the different available estimates for ET, ETo, and rainfall is another key process to validate the estimates in order to reach the best approach.

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