CUBANGO-OKAVANGO RIVER BASIN WATER AUDIT (CORBWA) PROJECT

Water Accounting Plus (WA+)

Cubango-Okavango River Basin

REPORT INFORMATIONS

Title	Water Accounting Plus (WA+)
Date	August 2011
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Water Accounting Plus (WA+) in the Okavango River Basin

Coping with Water Scarcity – Developing National Water Audits Africa

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Client:

FAO, Land and Water Division

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1 Background

The Land and Water Division (NRL) of FAO is currently executing the project "Coping with water scarcity – the role of agriculture". One component of the project is "Developing National Water Audits in Africa". The main outputs and activities of the project are the following:

Output 1: Develop a general methodology for a Water Audit to be applied in African countries or river basins.

Activities:

1.1 Developing general guidelines to perform Water Audits

1.2 Selecting three pilot countries or river basins willing to test guidelines

1.3 Developing an information and communications package to present the results of the project

Output 2: Three studies leading to a comprehensive report that forms the basis for future water management and water policy on country or river basin level, and a summary report with a compilation of key options for decision makers (Figure 1**).**

Activities:

2.1. Information protocols - Developing of a land and water resources database.

2.2. Water supply - Assessing trends of meteorological and runoff records and effectiveness of monitoring networks.

2.3. Water demand - Performing a water use assessment with emphasise on water use for agriculture.

2.4. Institutional mapping - Reviewing social, political and institutional factors that influence access to water and water services for men and women of different social groups.

2.5. Water accounting tool - Developing and parameterising of a spatially distributed water accounting tool.

2.6. Report Compilation and Presentation - A comprehensive report with recommendations for the monitoring of fresh water resources availability and use to improve future water management and water policy.

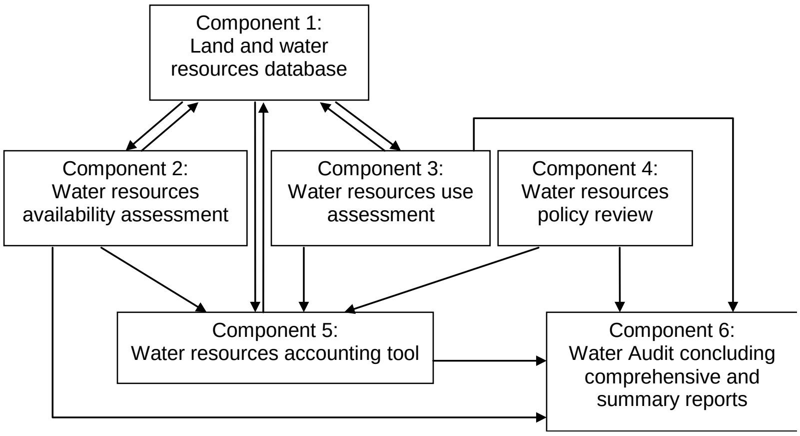


Figure 1. FAO-Water Audit project.

One of the Water Audit case studies will be implemented in the Okavago river basin. Parts of the activities 2.2, 2.3 and 2.5 of the Water Audit, will be carried out through on a rapid Remote Sensing based assessment.

Activity 2.2, the water supply study for the river basin, should provide insight in the extent to which water resources availability depends of variations in climate. The study includes also an assessment of the performance and effectiveness of the existing water monitoring networks with a view to possible network improvement and rationalization.

Activity 2.3, the water use study, will include all water use sectors including the environment, but the major effort will address agricultural water use assessment. The agricultural water use assessment will involve analyses of the water supply and demand on different spatial scales, taking into account both rainfed and irrigated agriculture and livestock production systems. In this component an assessment will be made of the dynamics of water productivity (including yield gap analyses for both irrigated and rainfed agriculture) and water use efficiency at different segments of the agricultural production process.

Activity 2.5, the water resources accounting tool, will provide the information needed to evaluate the implications of changes in boundary conditions (population, climate and trade) for the performance of the existing and projected future water management infrastructure.

In summary, the combined activities relevant to the rapid remote sensing components of 2.2, 2.3 and 2.5 encompass:

- Prepare, on the basis of satellite images, a water balance of the Okavango River basin for a three year period and a spatially differentiated resolution of one kilometre;
- Estimate, on the basis of the spatial water balance, water use and consumption for different types of land cover and land use;
- Assess, on the basis of satellite images, water productivity in terms of biomass per volume of water used for the different types of land cover and land use;
- Compare results against data collected by the Transboundary Diagnostic Assessment of the Okavango basin, and existing national water accounts.

The outputs of these activities are:

- Prepare data products to present assessment results in tabular, graphical, and geo-referenced form to be compared and validated with statistics and otherwise published material;
- Prepare a detailed technical documentation of the applied methodology, and a synthesis report with the results of the water accounting.

This report describes the development of the so-called Water Accounting Plus (WA+) framework that is based on remote sensing analysis and can be considered as a first demonstration that Water Accounting can be mainstreamed within, what should be, regular accountable water management practice.

2 Water Accounting Background

2.1 Introduction

Over the last two decades various initiatives have been started to develop a system of water accounting to support water managers and decision makers. However, up to now a well-accepted standard widely used by water managers and policy makers has not emerged despite the fact that quite a diverse set of frameworks have been proposed. The most relevant water accounting frameworks that have been developed so-far includes:

- International Water Management Institute water accounting framework (Molden and Sakthivadivel, 1999)
- United Nations Statistics Division has developed recently the System of Environmental-Economic Accounting for Water (SEEAW, 2009)
- Australian Water Accounting Conceptual Framework (Water Accounting Standards Board, SKM, 2006).
- UNEP's Water Footprint, Neutrality, and Efficiency (WaFNE) (Morrison and Schulte, 2009)
- "Water-use accounts" framework of the Challenge Program on Water and Food (CPWF) (Kriby, et al., 2010).

These water accounting frameworks have been proven to be useful to convince policy makers that water should be considered as an important resource and should be quantified in terms of supply, demand and value. There is a growing group of policymakers, water managers and donors who realize that, like financial accountable of organizations, water accounting is essential to ensure sustainable use of the resource. However, none of the frameworks have been adopted as a general accepted standard. Various reasons for this lack of uptake are:

- Results of some of these frameworks are too complex to be used as supporting tool for decision making.
- Input requirements are often not available or are based on long-term expensive monitoring activities.
- In many frameworks only abstracted water is considered. In many areas only a small fraction of the entire water resources and water use is actually abstracted.
- Most frameworks are location specific rather than universal applicable.
- Limited focus on intervention options by decision makers. Most frameworks present results without a differentiation between managed, manageable and non-manageable water flows.

In particular this last point is one of the reasons that the existing water accounting frameworks have not been adopted. A framework providing numbers where it is unclear how and where interventions are possible, remain to a large extent a more academic exercise rather than a solid base to explore options to improve water resources management.

2.2 Water Accounting Plus – Remote Sensing

Based on the previous section it is clear that there is a need to develop an integrated water accounting framework addressing shortcomings of existing water accounting systems. The developed Water Accounting Plus (WA+) framework builds on a combination of systems and approaches as developed in the past, and in particular the work from IWMI (Molden, 1997) and from WaterWatch (Bastiaanssen, 2009).

WA+ is based on Remote Sensing and will therefore be easily applicable worldwide without the need of extensive field monitoring and data collection.

Since WA+ is focussed on supporting stakeholders in evaluating water accountability a straight-forward division in four main land and water groups is used:

- **Conserved Land Use**: areas where no changes in land and/or water management are possible. Typical examples include tropical rainforests, wetlands, and mountainous vegetation.
- **Utilized Land Use**: land where vegetation is not managed on a regular base; typical examples include forests, natural pastures, and savannas.
- **Modified Land Use**: areas where vegetation and/or soils are managed, but all water supply is natural (rainfall); typical examples include rainfed agriculture.
- **Managed Water Use**: all sectors that abstract water from surface water and/or groundwater; typical examples include irrigated agriculture, urban water supply, and industrial extractions.

Results of WA+ will be presented in three so-called accounting sheets: (i) Resource Base Sheet (Figure 2), (ii) Consumptive Use Sheet (Figure 3), and (iii) Productivity Sheet (Figure 4). Moreover, some key summarizing indicators will be calculated to support water managers, policy makers and donors in their task to ensure accountable water resources management. These indicators will be discussed in the following paragraph.

The basis of the Water Accounting Plus (WA+) is the standard water balance approach with specific emphasis on the various water users (Figure 5).

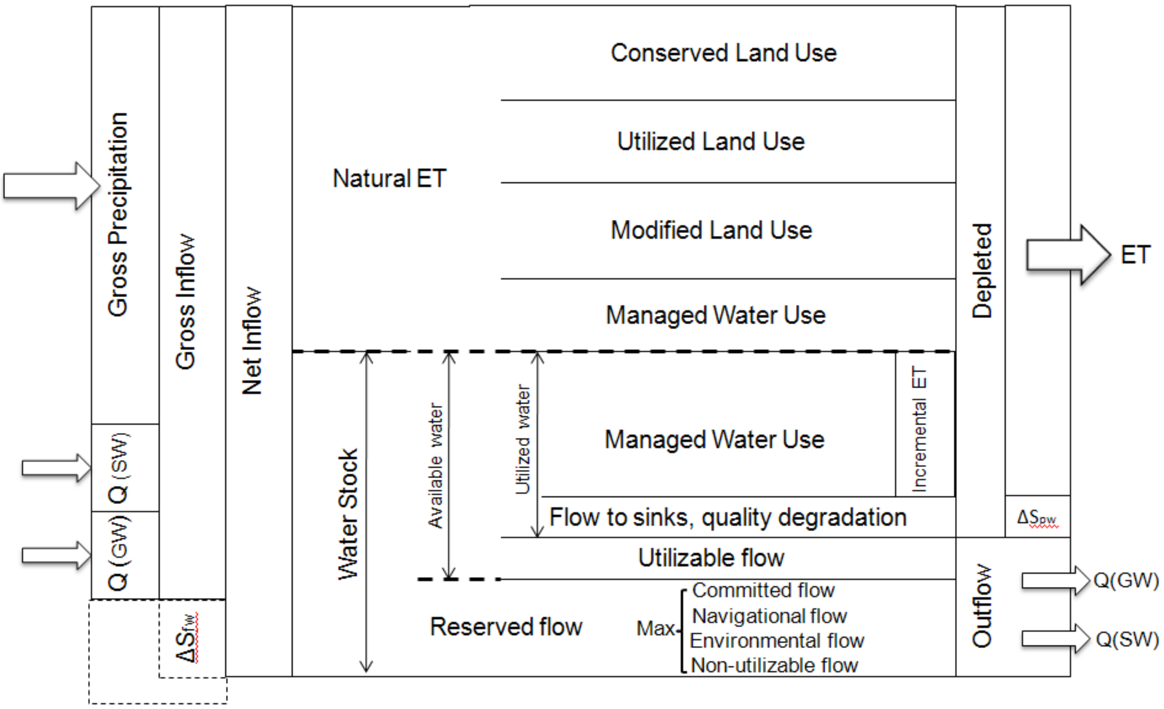


Figure 2: Water Accounting Plus: Resource Base Sheet (sw = surface water, gw = groundwater, dSfw = storage of fresh water, dSpw = storage of polluted water).

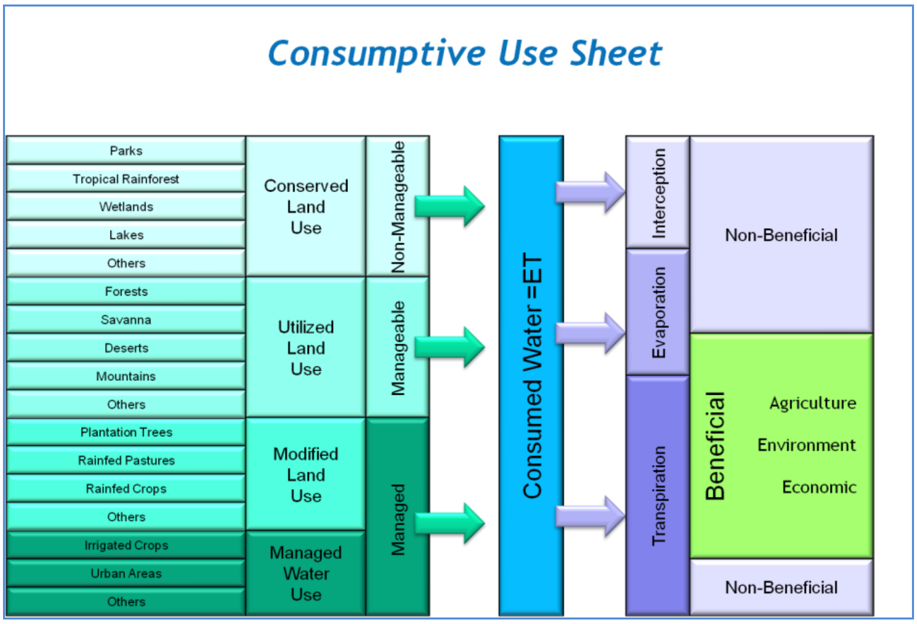
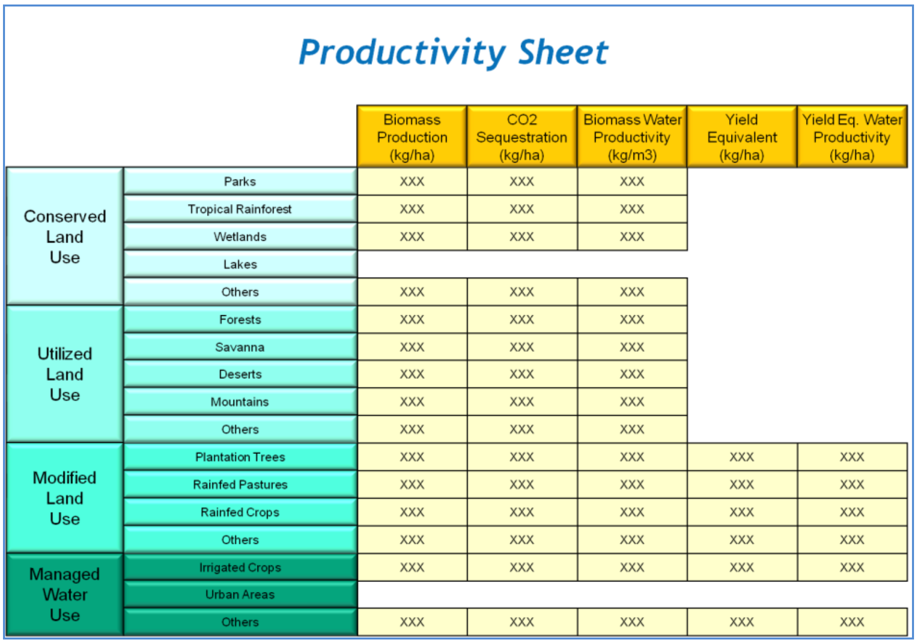


Figure 3: Water Accounting Plus: Consumptive Use Sheet.



Productivity Sheet

		Biomass Production (kg/ha)	CO2 Sequestration (kg/ha)	Biomass Water Productivity (kg/m3)	Yield Equivalent (kg/ha)	Yield Eq. Water Productivity (kg/ha)
Conserved Land Use	Parks	XXX	XXX	XXX		
	Tropical Rainforest	XXX	XXX	XXX		
	Wetlands	XXX	XXX	XXX		
	Lakes					
	Others	XXX	XXX	XXX		
Utilized Land Use	Forests	XXX	XXX	XXX		
	Savanna	XXX	XXX	XXX		
	Deserts	XXX	XXX	XXX		
	Mountains	XXX	XXX	XXX		
	Others	XXX	XXX	XXX		
Modified Land Use	Plantation Trees	XXX	XXX	XXX	XXX	XXX
	Rainfed Pastures	XXX	XXX	XXX	XXX	XXX
	Rainfed Crops	XXX	XXX	XXX	XXX	XXX
	Others	XXX	XXX	XXX	XXX	XXX
Managed Water Use	Irrigated Crops	XXX	XXX	XXX	XXX	XXX
	Urban Areas					
	Others	XXX	XXX	XXX	XXX	XXX

Figure 4: Water Accounting Plus: Productivity Sheet.

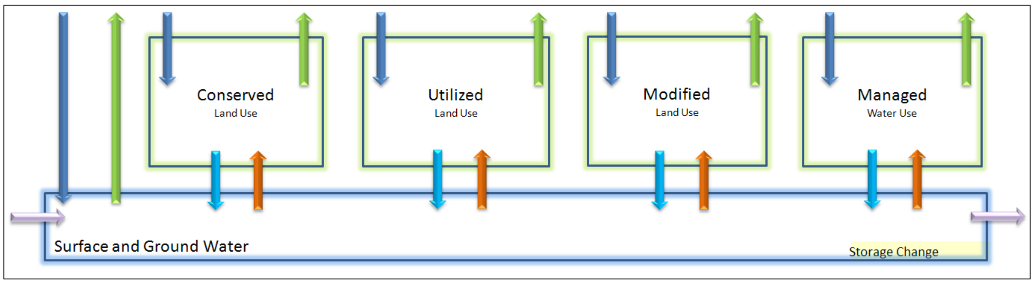


Figure 5: Resource Base calculation framework.

2.3 Key Indicators

An important aspect of financial accounting is to deliver key indicators in order to express performances in summarizing numbers. A set of key indicators have been defined along the same lines for Water Accounting Plus (WA+), that will provide a quick and clear overview of water resources issues in the area under consideration. Four WA+ sets of indicators are used and are summarized below.

The first set of indicators can be considered as key parameters to characterize the area under consideration.

- ET Fraction = ET_{tot} / (P + Q_{in}) (%)
    - ET fraction indicates which portion of the total inflow of water is consumed and which part is converted into renewable resources. A value higher than 100% indicates over-exploitation or a dependency on external resources.
- Stationarity Index = ΔStorage / ET_{tot} (%)
    - Stationarity Index is an indication of the depletion of water resources. Positive values indicate that water is added to the groundwater and/or surface water storage. Negative values indicate a depletion of the storage.
- Basin Closure = 1 - Outflow / (P + Q_{in}) (%)
    - Basin Closure defines the percentage of total available water resources (= precipitation + basin inflow) that is consumed and/or stored within the basin. A value of 100% indicates that all available water is consumed and/or stored in the basin.

The second set of indicators focuses on the actual amount of water that is currently managed, or is available to be managed.

- Available Water (AW) = Water Stock – Reserved Flow - ΔS (MCM)
    - Total amount of water that is available to be managed.
- Managed Water (MW) = Withdrawals by Managed Water Use (MCM)
    - Total amount of water that is abstracted for Managed Water Use.
- Managed Fraction = Managed Water / Available Water (%)
    - Percentage of water that is actually managed from the total amount of water that is available.

The third set of indicators shows for which purpose water is used in area under consideration. This set of indicators is closely related to the Consumption Sheet.

- Beneficial Consumption (%) = ET_{ben} / ET_{tot}

  - Percentage of water that is actually consumed beneficially. The portion of ET that is assumed beneficial to either agriculture, economy or environment for a certain land cover type is a flexible decision by the policy maker.
- Agricultural Consumption (%) = ET_{agr} / ET_{ben}
  - Percentage of beneficial water consumption attributed to agriculture.
- Environmental Consumption (%) = ET_{env} / ET_{ben}
  - Percentage of beneficial water consumption attributed to the environment.
- Economic Consumption (%) = ET_{econ} / ET_{ben}
  - Percentage of beneficial water consumption attributed to the economy.

The last set of WA+ indicators compares the current year with the long-term averages.

- Deviation Beneficial Consumption = $-(1 - ET_{ben,\ current} / ET_{ben,\ long\ term})$
- Deviation Agricultural Consumption = $-(1 - ET_{agr,\ current} / ET_{agr,\ long\ term})$
- Deviation Environmental Consumption = $-(1 - ET_{env,\ current} / ET_{env,\ long\ term})$
- Deviation Economic Consumption = $-(1 - ET_{econ,\ current} / ET_{econ,\ long\ term})$

3 Okavango Basin

Summarized from "The Permanent Okavango River Basin Water Commission"

The Okavango River Basin remains one of the watersheds least affected by human impacts on the African continent. In its present near-pristine status, the river provides significant ecosystem benefits and can continue to do so if managed appropriately. However, mounting socio-economic pressures on the basin in the riparian countries, Angola, Botswana and Namibia, could change its present character. Maintaining the river's benefits requires agreement over the sharing of both the benefits and associated liabilities through joint management of the basin's natural resources.

The river rises in the headwaters of the Cuito and Cubango Rivers in the highland plateau of Angola. It derives its principal flow from 120,000 km3 of sub-humid and semi-arid rangeland in the Cuando-Cubango Province of Angola before concentrating its flow along the margins of Namibia and Angola and finally spilling into the Okavango fan or 'Delta' in Botswana. Geological controls on the margins of the fan determine the eventual flow of remaining water into a set of evaporation pans in the Kalahari Desert.

The Okavango Basin could also be delineated to include a substantial area of fossil rivers which are not hydrologically active, and other rivers that have headwater flows but do not contribute to flows in the Okavango River but are nevertheless a part of the topographic basin. In this study, the entire topographic basin is taken into account (Figure 6). Figure 7 presents the different subbasins that are distinguished within the area.

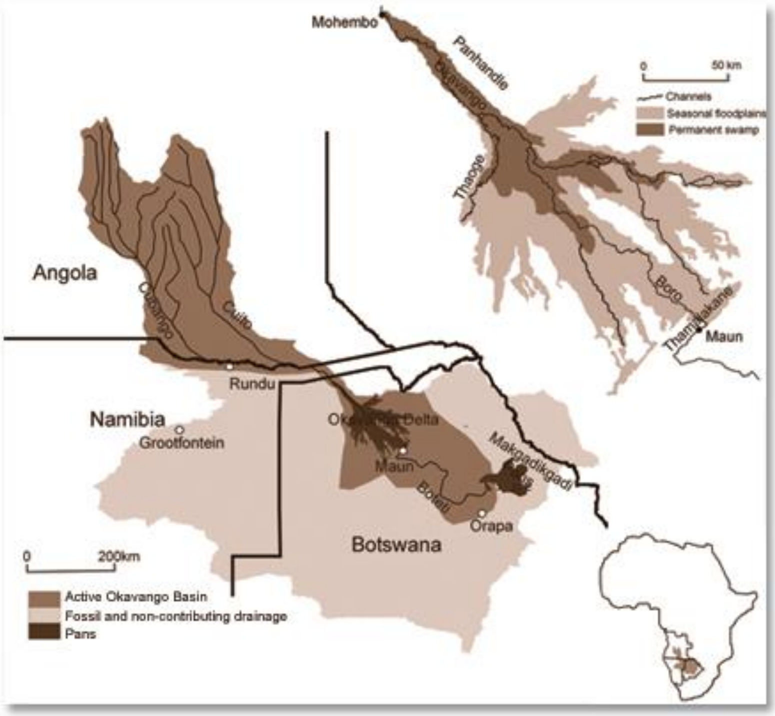


Figure 6. Okavango Basin.

The Okavango waters are relatively clear with few dissolved chemicals, solutes or pollutants. The riparian landscapes along many of the waterways are largely unchanged with natural plant and aquatic life remaining healthy. The river supports people, their livestock and a myriad of livelihoods ranging from artisanal fisheries to small scale agriculture, as well as diverse wildlife. Population density in the basin is quite low, with an average density of just 1.1 persons / km^2 in the Botswanan part of the basin (OKACOM). Consequently, human land use in most parts of the basin is quite extensive.

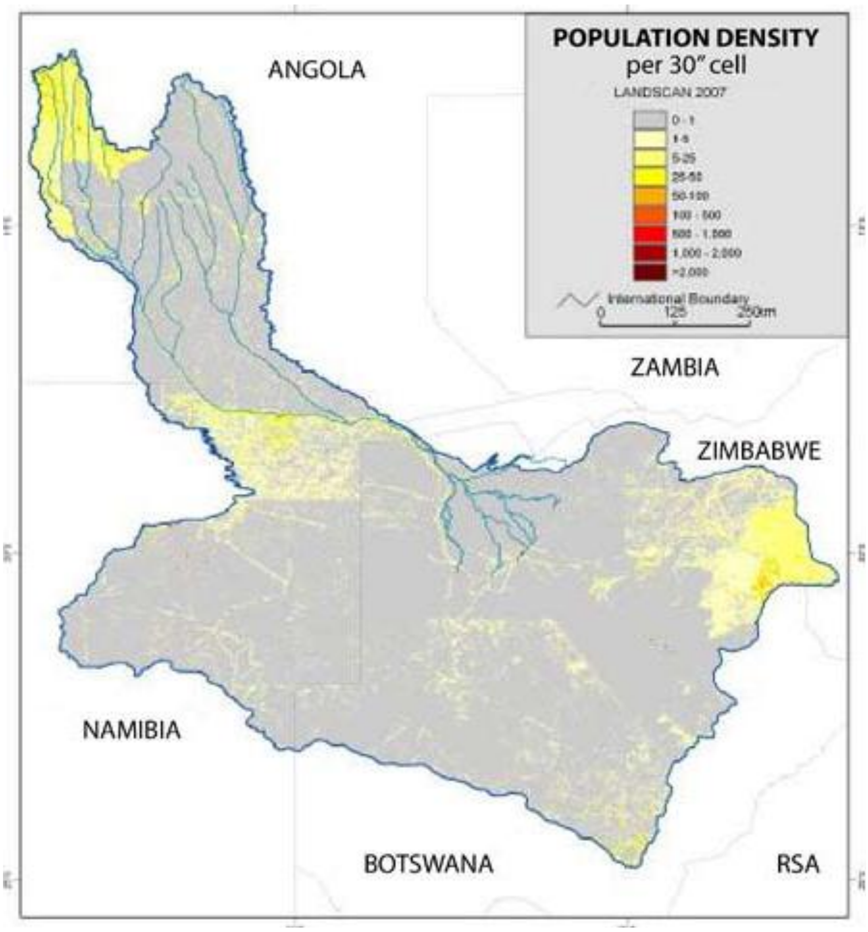


Figure 7. Population density in the Okavango Basin (source: OKACOM).

The Okavango Delta, a unique ecosystem, is a significant source of tourism income and cultural value to the people of Botswana. The generally low level of economic development associated with the Okavango is a by-product of history and geopolitics. Nevertheless the current situation offers the riparian countries of the Okavango an opportunity to choose a development pathway for the basin without compromising the set of environmental goods and services, including global benefits, distributed across the whole basin.

Further background information on the Okavango is beyond the scope of this document but can be found in various literature (see List of references).

Figure 8. Delineation of the subbasins within the Okavango River macrobasin.

4 Data

4.1 Land cover and land use information

An accurate Land Use and Land Cover (LULC) classification is necessary for applying the WA+ framework, which is based to create the four groups of Land/Water Uses: (i) Conserved Land Use, (ii) Utilized Land Use, (iii) Modified Land Use and (iv) Managed Water Use. Use has been made as much as possible of existing data, but, as explained further in this section, some additional tailor-made activities were essential.

4.1.1 Available regional data

In the frame of the EPSMO-BIOKAVANGO project, a GIS database was constructed containing a land cover map based on MODIS imagery (Verissimo 2009, Figure 9). This map has a spatial resolution of 250 meters and distinguishes 10 different land cover classes in the basin. Other GIS layers in the database contain basic land use information for parts of the basin, such as a low-detail delineation of Namibian farms and a land use map taken from the National Atlas of Botswana. Overall, however, a combination of the land use and land cover data in the EPSMO GIS database does not provide sufficient basis for the application of WA+ for the entire basin. The OKACOM map server provides also a land use map, but this map covers only the Okavango Delta and classes are defined but legends are not available (Figure 10).

Personal communication with Susan Ringrose and Masego Dhliwayo from OKACOM revealed also that no land cover / land use information was available at a level of detail required to perform WA+. It is therefore required to produce a land cover / land use map including all relevant information needed to undertake water accounting. Basis will be still other available LULC datasets and satellite imagery to construct a new LULC database.

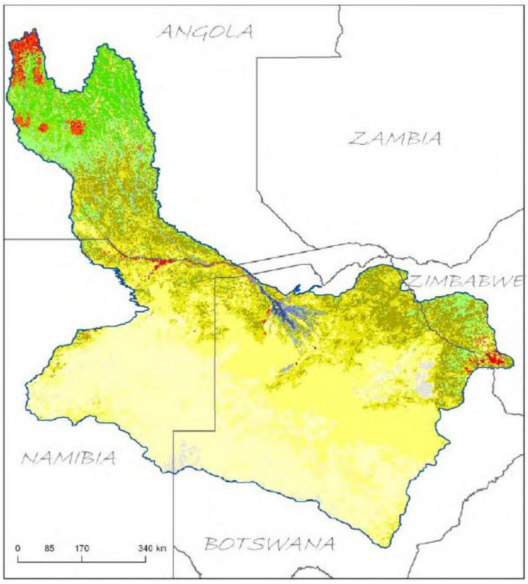


Figure 9. The land cover map used in the GIS database of the EPSMO project (Verissimo, 2009).

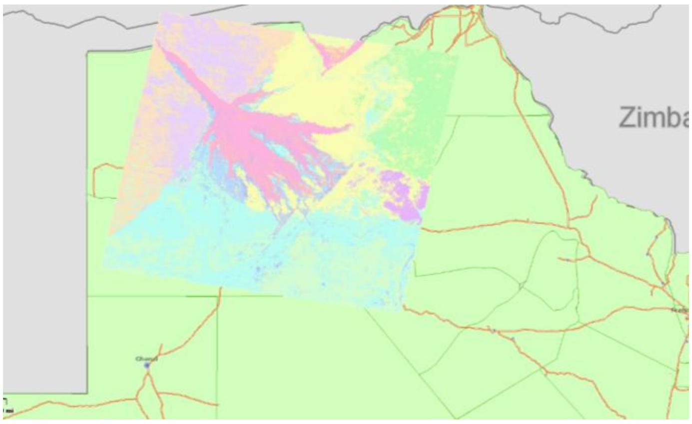


Figure 10. Landcover OKACOM (source: http://odis.orc.ub.bw/odis/)

4.1.2 GlobCover

The GlobCover land cover product is the highest resolution (300 meters) global land cover product ever produced and independently validated. It is derived from an automatic and regionally-tuned classification of a time series of MERIS satellite images, covering the period December 2004 until June 2006. MERIS is a wide field-of-view pushbroom imaging spectrometer measuring the solar radiation reflected by the Earth in 15 spectral bands from about 412.5 nm to 900 nm (the visible and near-infrared portions of the electromagnetic spectrum). The sensor is designed to acquire data over the Earth whenever illumination conditions are suitable. MERIS is on board the ENVISAT satellite and was launched in 2002.

The GlobCover classification has both a global and a regional character. The global land cover product has the property to be consistent. It is described by a legend counting 22 land cover types that are well documented and comparable all over the world. Regional GlobCover maps may show more detailed legends, depending on the reference land cover maps available to discriminate them. For the Okavango basin, the regional product does not provide additional detail relevant for the application of Water Accounting.

For the Okavango river basin, an excerpt of the GlobCover global land cover map is presented in Figure 11. A total of 14 GlobCover classes are present in the basin. The map shows the wooded highlands in central Angola in the northwest, with a transition through open forest and shrubland to mostly grassland (savanna) in the south of the image. The delta in the center and the Makgadikgadi salt pans to the east are clearly visible, the latter being referred to as *water bodies*. Since the GlobCover dataset does not contain any data of irrigated or rainfed croplands for the basin, it is concluded that all agricultural activity is classified as *mosaic vegetation/cropland*. This is supported by the spatial distribution of this class, which is roughly consistent with the known primary locations of agricultural activity (AQUASTAT (FAO), EPSMO-BIOKAVANGO technical documentation).

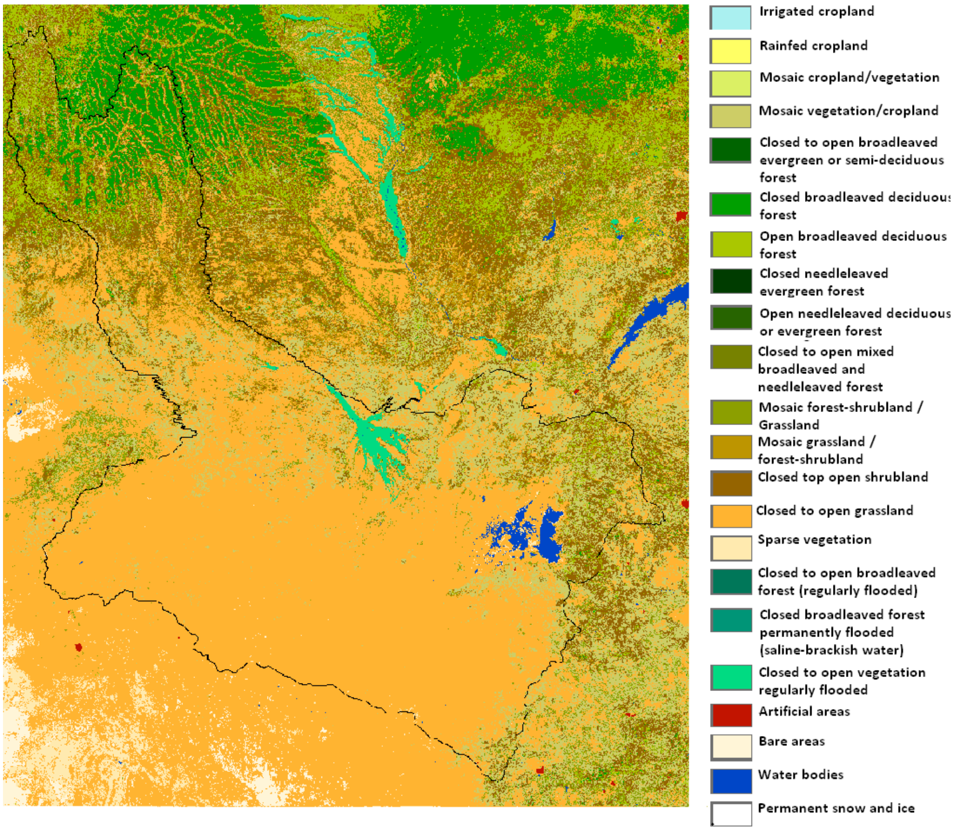


Figure 11. GlobCover land cover map of the Okavango basin.

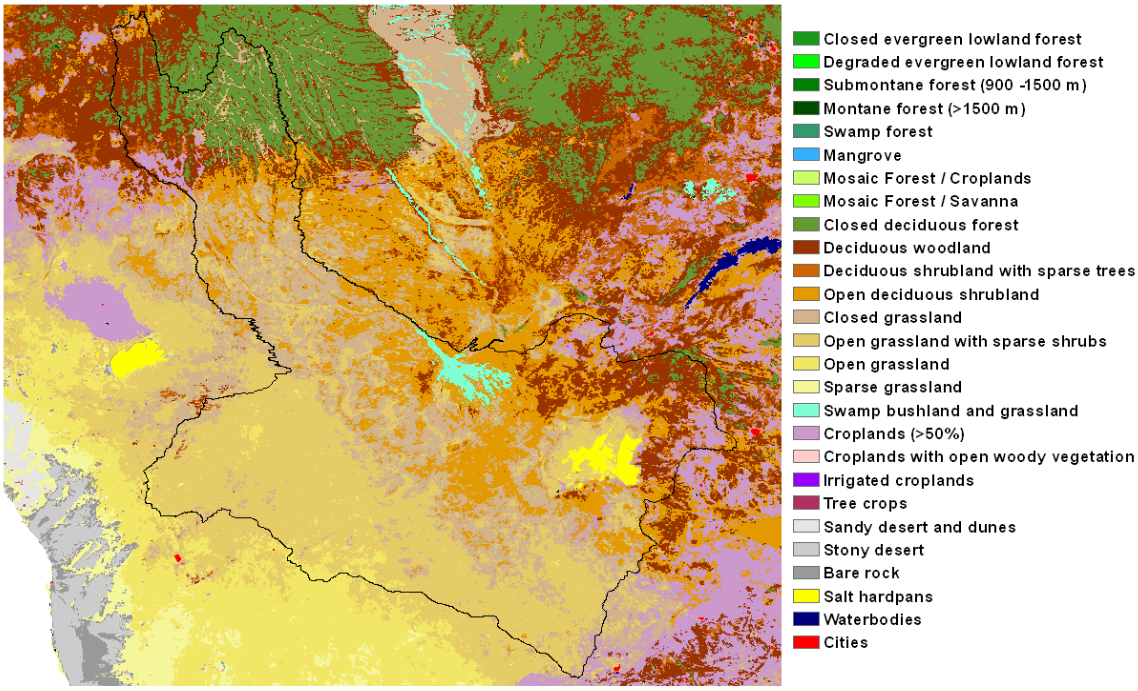


Figure 12. GLC2000 land cover map of the Okavango basin.

4.1.3 GLC2000

The GLC2000 land cover dataset was developed by the Joint Research Center of the European Commission (JRC). It integrates multiple regional land cover studies making use of SPOT-4 VEGA2000 and following the FAO land cover classification system. With a spatial resolution of 30 arc seconds (± 1 km) it is less detailed than the GlobCover product, but it is still of value to this project due to its different grouping of land cover classes. Figure 8 presents GLC2000 land cover for the Okavango basin. As opposed to the GlobCover product, it contains multiple grassland and shrubland classes distinguished based on vegetation cover.

4.1.4 MIRCA

The Institute of Physical Geography of the Goethe University of Frankfurt developed the MIRCA data set, containing monthly growing areas and crop calendars of 26 irrigated and rainfed crops (documented at http://www.geo.uni-frankfurt.de/ipg/ag/dl/forschung/MIRCA/index.html). The data set includes 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). MIRCA contains data from the 1998-2002 period and has a spatial resolution of 5 arc minutes. The data set is consistent to the irrigated area statistics of the FAO AQUASTAT programme and to version 4.0.1 of the Global Map of Irrigation Areas (GMIA). At the pixel scale, these data were combined with the total cropland extent and harvested crop areas provided by the Center for Sustainability and the Global Environment (SAGE) of the University of Wisconsin at Madison.

Figure 13 and Figure 14 display an excerpt of the global MIRCA maximum cropped area dataset for Sub-Saharan Africa. The maximum cropped area is defined as the sum of the maximum monthly growing areas for all rainfed (Figure 13) or irrigated (Figure 14) crops. Since the MIRCA pixel size varies with latitude, cropped areas are expressed in percentages of the entire pixel. The figures show that there is relatively little agricultural activity in the Okavango river basin. Most rainfed agriculture is present in the Angolan highlands in the northwest of the basin and the Botswana-Zimbabwe border area in the east. Patches of irrigated farming are located in the vicinity of the Okavango River.

Table 1 presents a selection of the crops being grown in the Okavango basin, according to MIRCA data. It shows that maize is the most abundant crop, followed by cassava and millet. An impression of the spatial distribution of these crops is provided in Figure 15. Agriculture fed by irrigation is largely absent in the area, with the main irrigated crops being sugar cane, maize and other annual and perennial crops. Overall, MIRCA data indicate that only 0,4 % (300775 ha) and 0,005 % (3716 ha) of the land surface of the basin is dedicated to rainfed agriculture and irrigated agriculture respectively. The latter number is roughly in agreement with the technical documentation of the EPSMO-BIOKAVANGO project (Beuster, 2009), quantifying the main present day water resource demand for irrigation at 2700 ha, all in the Namibian portion of the basin. Other, small-scale irrigation development projects are present in Angola and Botswana, such as described by Masamba (2009).

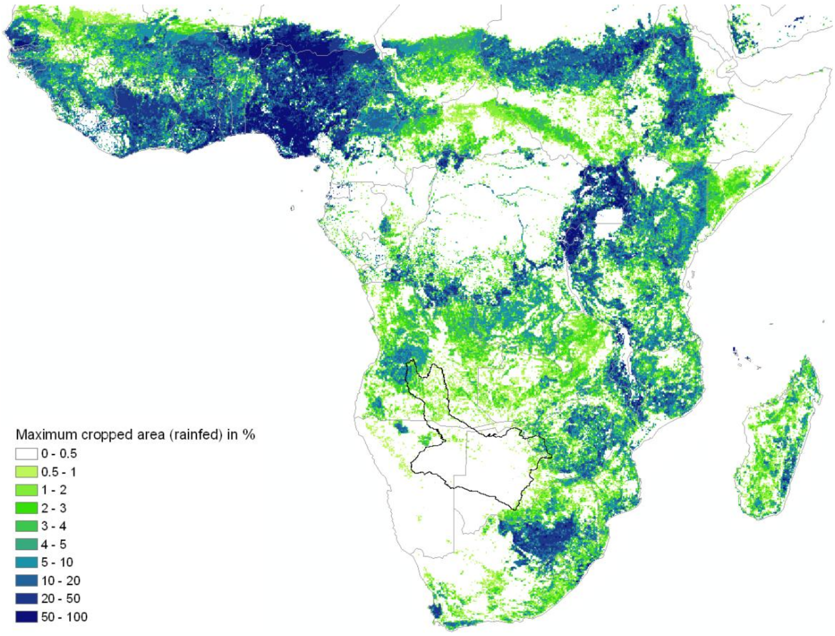


Figure 13. MIRCA maximum cropped area of rainfed crops for Sub-Saharan Africa.

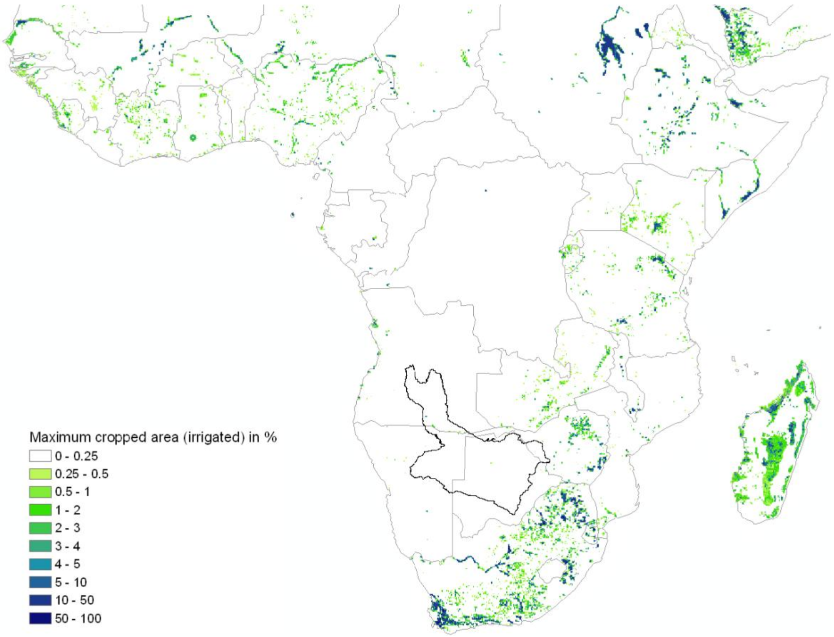


Figure 14. MIRCA maximum cropped area of irrigated crops for Sub-Saharan Africa.

Table 1. Main crops grown in the Okavango river basin, derived from the MIRCA dataset.

Crop	Rainfed area (ha)	Irrigated area (ha)	% of total rainfed area	% of total irrigated area	% of total agriculture
Maize	115535	550	36.9	13.1	36.6
Cassava	63288	-	20.2	-	19.9
Millet	35105	-	11.2	-	11.1
Pulses	28622	-	9.1	-	9.0
Sorghum	18948	-	6.1	-	6.0
Groundnuts/peanuts	7940	-	2.5	-	2.5
Coffee	6871	-	2.1	-	2.1
Fodder grasses	-	563	-	13.4	0.2
Sugar cane	462	418	0.1	10.0	0.3
Others(annual)	20504	1080	6.5	25.6	6.8
Others (perennial)	5197	455	1.7	10.8	1.8

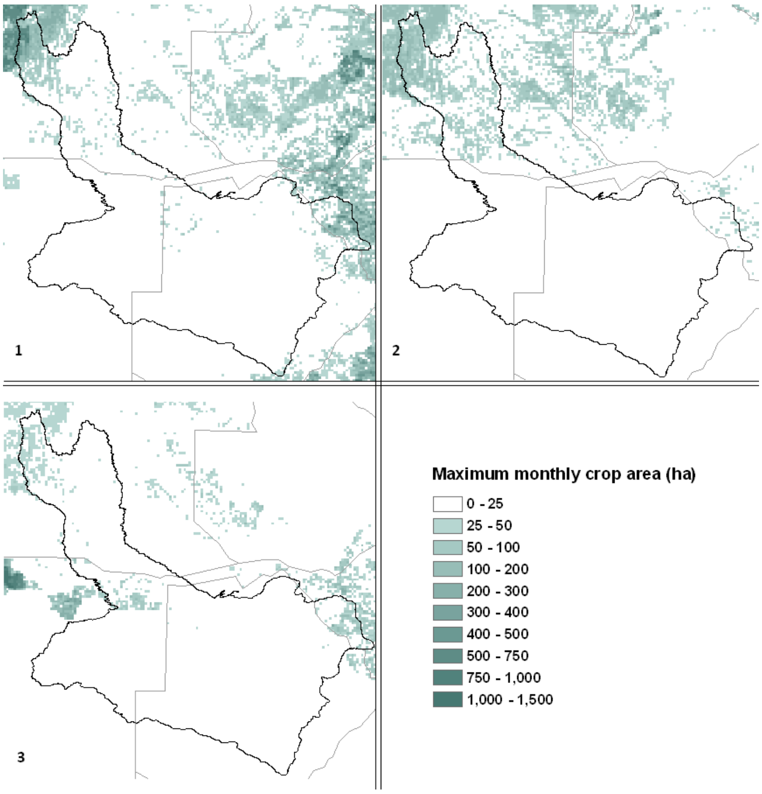


Figure 15. Maximum monthly crop area for the main crops in the Okavango basin: 1) maize, 2) cassava and 3) millet.

4.1.5 Combined land use / land cover product

A new LULC product, customized for applying the Water Accounting concept in the Okavango basin. was created by integrating data from GlobCover, MIRCA. GLC2000, source data from the FAO Global Map of Irrigated Areas (GMIA) and observations from satellite imagery. As the GlobCover product contains the most recent data as well as having the highest level of spatial detail, it was used as the basis for the new integrated LULC product.

For successfully performing Water Accounting, it is essential to make the distinction between rainfed and irrigated agriculture. It was assumed that the GlobCover *mosaic vegetation/cropland* class contains both the rainfed and irrigated croplands in the Okavango basin, as well as some additional grass- or shrubland. The MIRCA maximum cropped area values were used to identify the areas of rainfed agriculture. For the MIRCA pixels with a percentage of cropped area higher than a certain threshold value, GlobCover *mosaic vegetation/cropland* pixels were accepted as rainfed cropland. This threshold value was determined by evaluating the resulting total area of rainfed agriculture, and comparing this to the corresponding area according to the MIRCA dataset. A check of the obtained locations of agricultural activity was performed by means of satellite imagery derived from the ESRI World Imagery GIS layer. For the Okavango basin, this dataset is made up of NASA Blue Marble 500 m resolution images on small scales and i-cubed 15m eSAT imagery at larger scales. Using the method described above, a threshold value of 3.5 % is obtained for rainfed agriculture. This corresponds with a total area of approximately 315,000 ha of rainfed cropland.

Source data from the FAO GMIA was available for identifying the locations of irrigated agriculture in the Okavango basin. With a spatial resolution of approximately 1 km, this data was preferred over the MIRCA database in order to construct a LULC map correctly representing the small patches of irrigated cropland along the river. GlobCover pixels were accepted as irrigated agriculture when the GMIA source data exceeds a threshold value of 25 %. This corresponds with a total area of approximately 4500 ha of irrigated cropland in the Okavango River basin. The obtained locations of irrigated schemes show a pattern similar to the overview of irrigation water demands in Namibia provided by OKACOM (2010, Figure 16).

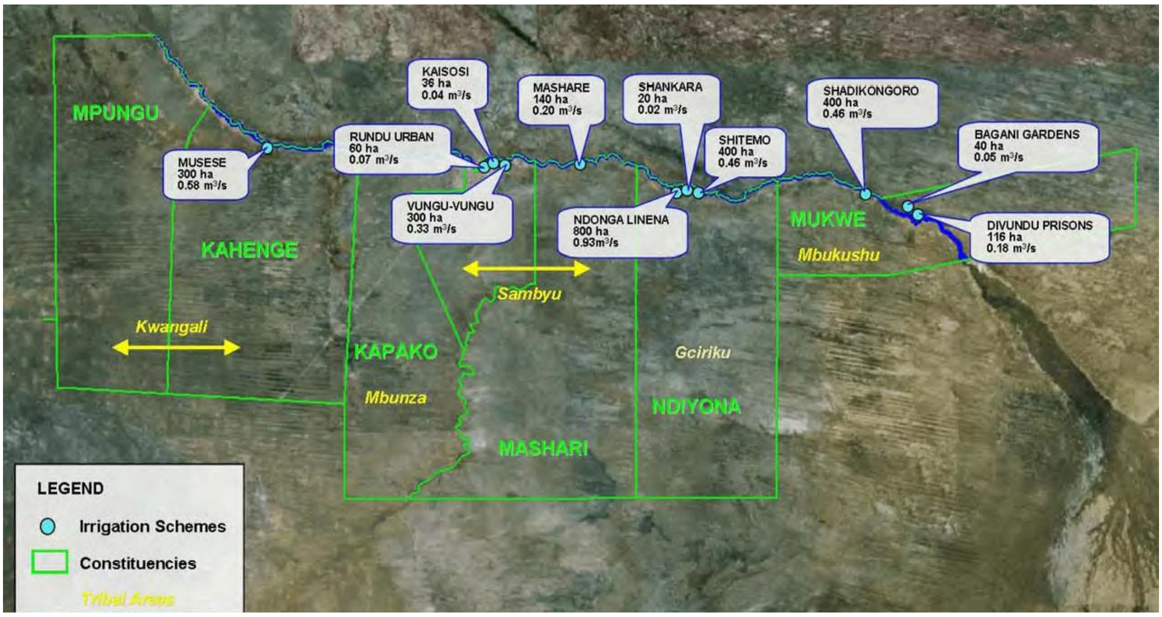


Figure 16. Present irrigation water demands on the Namibian side of the Okavango River (Liebenberg, 2009).

Figure 17 shows the resulting locations of rainfed and irrigated agriculture in the Okavango basin, projected against satellite imagery. Again, the earlier identified areas with the highest concentration of agriculture (in the northwest and east of the basin) are visible. Although the total areas of rainfed and irrigated agriculture approach FAO data, there are still agricultural fields visible on the satellite imagery that are not included in the newly defined classification. This is due to the assumption that all of the cells in the GlobCover *mosaic vegetation/cropland* class within certain MIRCA / GMIA pixels are dedicated to agriculture. This results in concentrated patches of cropland, while fields may be more distributed in reality. Another reason for the absence of visible agricultural fields from the classification may be that they are not utilized at present. This is illustrated by Masamba (2009), who states that only 17% of the land allocated for irrigated agriculture in the Okavango Delta is used as such.

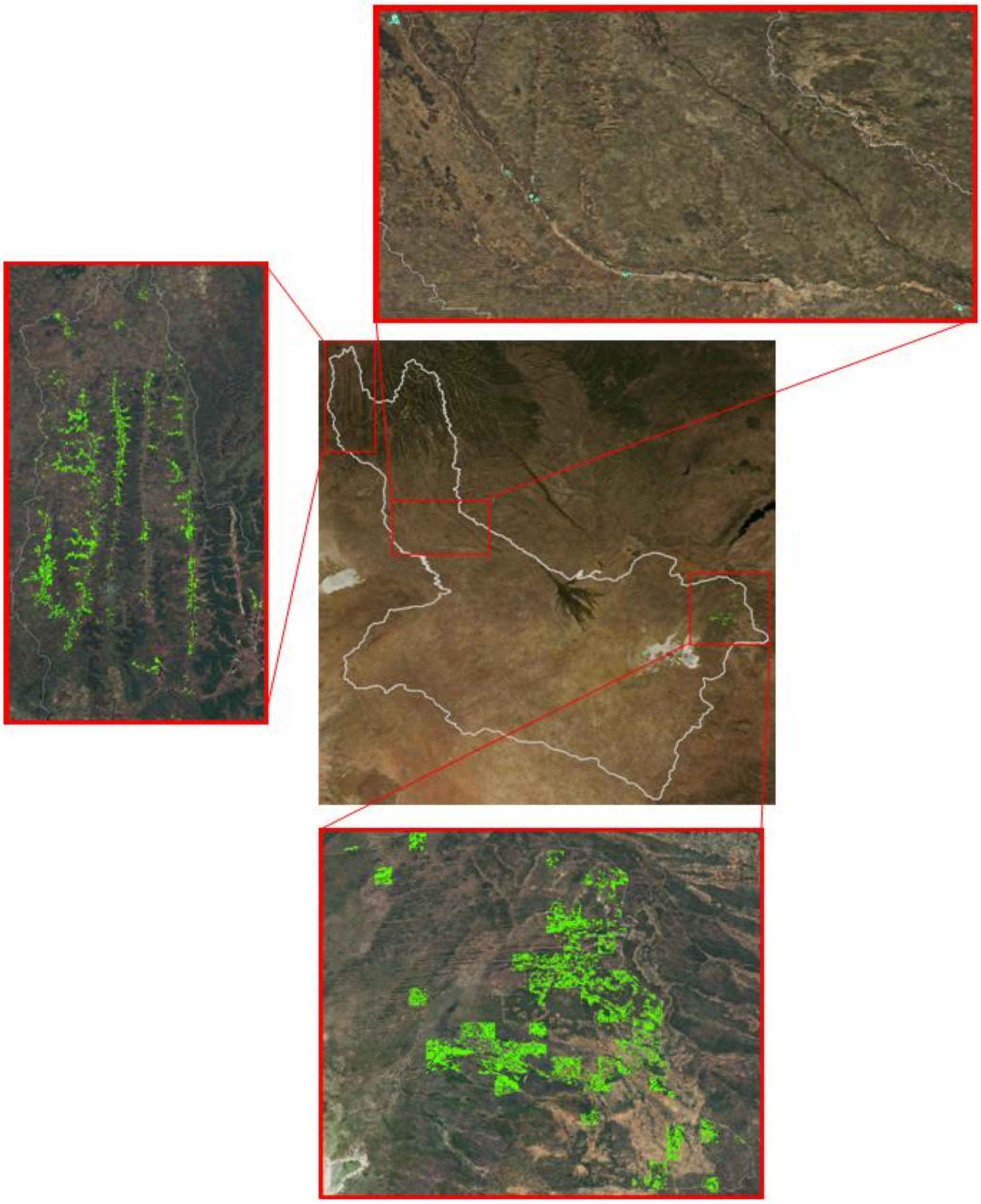


Figure 17. Locations of rainfed (green) and irrigated (blue) croplands in the Okavango basin.

A major part of the Okavango basin surface area (over 60%) is classified as *closed to open grassland* in the GlobCover database. Based on the GLC2000 land database, the pixels in this class were distributed over four different classes based on their vegetation cover. A check of this classification was performed using satellite NDVI data (see par. 3.5), which indeed showed an NDVI increasing with the vegetation cover as indicated by the GLC2000 land cover map.

Other adjustments to the original GlobCover database include the merging of irrelevant forest classes, removal of absent classes and the renaming of some of the original classes based on specific knowledge of the regional land cover. The remaining vegetation from the *mosaic vegetation/cropland* was grouped under o*pen deciduous shrubland*. The final LULC product is presented in Figure 18.

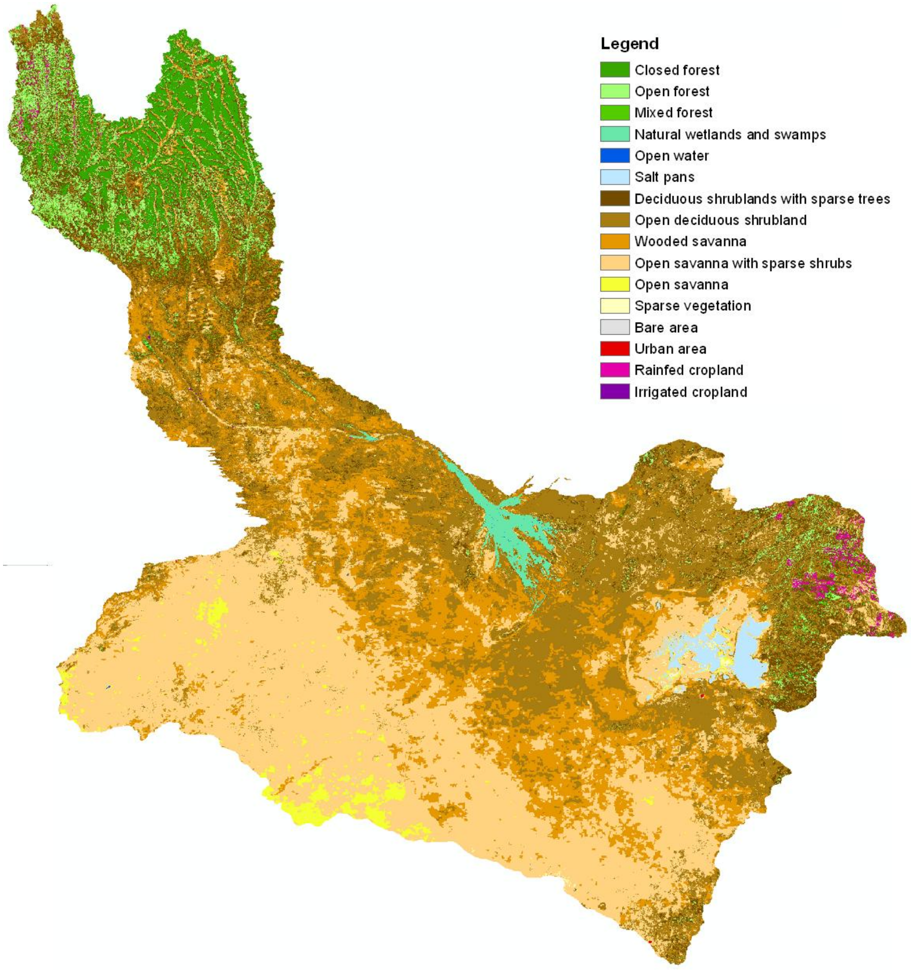


Figure 18. The combined land use / land cover classification used for WA+ in the Okavango basin.

4.2 Precipitation

Since the Okavango basin is composed of regions differing highly in terms of climate, annual precipitation values depend greatly on location in the basin. On average, a north-south gradient in rainfall is observed, ranging from the tropical northern part in Angola to the semi-arid southern part in Botswana (Wilk *et al.*, 2006). In terms of rainfall distribution through the year, there is a clear distinction between the wet and dry season. Rains typically start in October or November and persist until March or April.

Daily rainfall data were obtained from the U.S. Agency for International Development (USAID) Famine Early Warning Systems Network (FEWS NET). This is an information system designed to identify problems in the food supply system that potentially lead to famine or other food-insecure conditions in sub-Saharan Africa, Afghanistan, Central America, and Haiti. FEWS NET is a multi-disciplinary project that collects, analyzes, and distributes regional, national, and sub-national information to decision makers about potential or current famine or other climate hazard-, or socio-economic-related situations, allowing them to authorize timely measures to prevent food-insecure conditions in these nations. One of the inputs into the FEWS NET information system is an estimate of daily rainfall, with a spatial resolution of 8 x 8 km. The FEWS RFE 2.0 algorithm has been implemented by NOAA's Climate Prediction Center and uses an interpolation method to combine Meteosat and Global Telecommunication System (GTS) data.

Figure 20 shows FEWS daily rainfall values for a wet day (17/01/2008) in the Okavango basin.

Table 2. Annual precipitation in the Okavango basin according to FEWS rainfall data.

Year	Precipitation (mm)
2005(1)	768
2006	493
2007	647
2008	631

(1) *2005 refers to the hydrological year (1-Jul-2005 to 30-Jun-2006)*

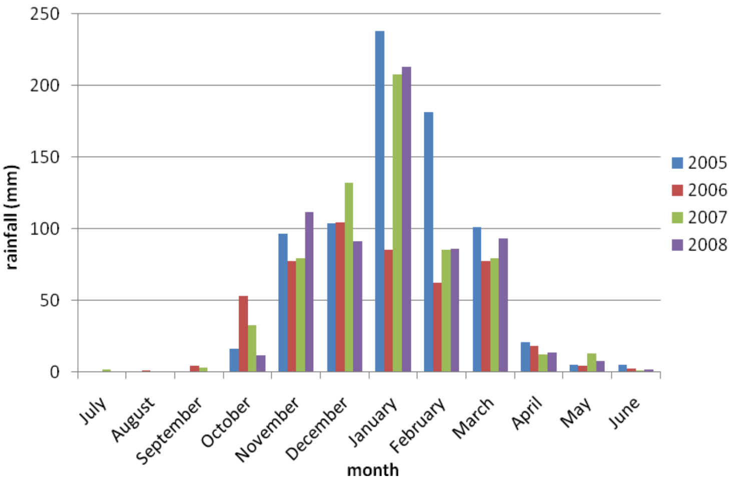


Figure 19. Monthly precipitation in the Okavango basin.

A comparison with historical rainfall records is required to put the FEWS annual rainfall data into perspective. However, reliable long-term rain gauge measurements are scarce for the Okavango basin, especially for the wet Angolan highlands. For this reason, efforts have been made to extend the existing precipitation time series by means of satellite derived rainfall products (Wilk *et al*. 2006). Mean annual rainfall has been estimated at 680 mm (FAO, 1997) and 837 mm (EPSMO-BIOkavango, 2009) for different delineations of the Okavango basin, both lacking the semi-arid south-eastern part that is included in the present study. These figures were therefore assumed to be overestimations for the current basin definition. Based on this assumption and the annual rainfall amounts obtained from FEWS estimates (table 1), the hydrological 2005, 2006 and 2007 were identified as wet, dry and average years respectively.

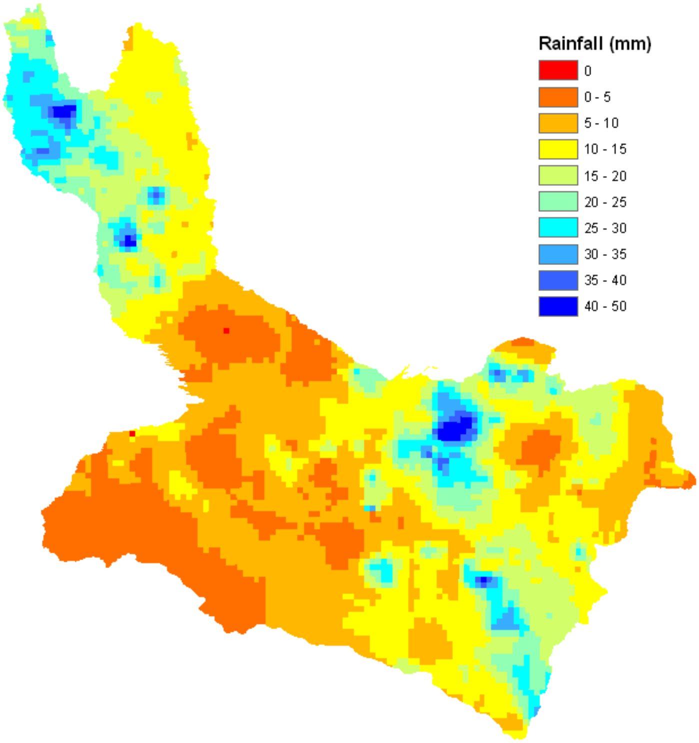


Figure 20a. FEWS daily rainfall in the Okavango basin on January 17th, 2008.

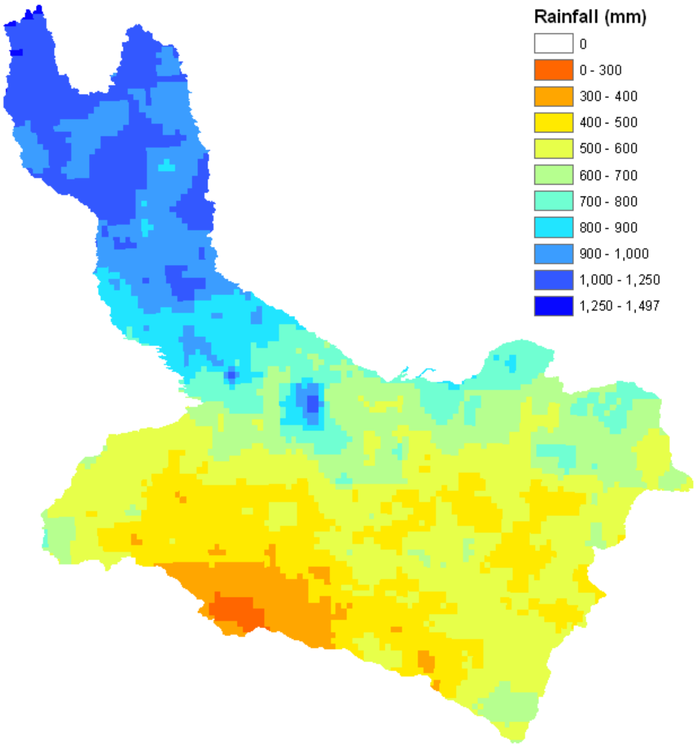


Figure 21b. FEWS annual rainfall in the Okavango basin (July 1, 2007 - June 30, 2008).

4.3 Air temperature, wind speed and relative humidity

The input parameters air temperature, wind speed and relative humidity were based on measurements conducted at 55 metereological stations in and around the Okavango river basin. These data were obtained from the NOAA database and interpolated for the entire basin, accounting for differences in elevation. Figure 22 displays the gridded average air temperature in the Okavango basin for the entire modeling period and the locations of the metereological stations.

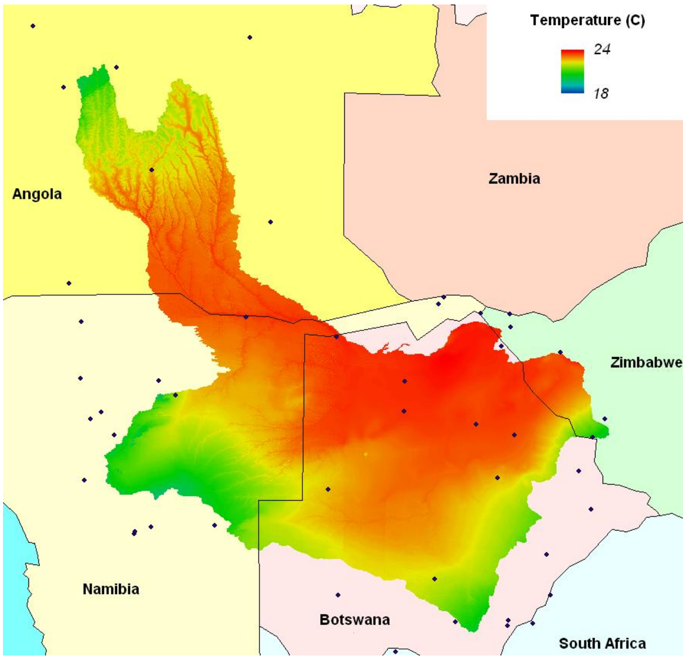


Figure 22. Average air temperature in the Okavango river basin over the period 01/07/2006 - 30/06/2008. Dark blue dots indicate locations of measurement stations.

4.4 Transmissivity

Daily atmospheric transmissivity were calculated from the Meteosat Second Generation (MSG) 30-minute interval incoming short wave radiation product, provided by the Land Surface Analysis Satellite Applications Facility (LSA SAF). MSG transmissivity data is available starting May 2005, on a spatial resolution of 1 x 1 km.

4.5 Albedo and NDVI

Values for surface albedo and NDVI were derived from the Filled NDVI Product and the Filled Land Surface Albedo Product, which are provided by NASA based on Moderate Resolution Imaging Spectroradiometer (MODIS) data. Measurements are conducted with a temporal resolution of 16 days by MODIS instruments on board of the Aqua and Terra platforms. Combined, 8-daily albedo and NDVI products are available on a spatial resolution of 1 x 1 km.

4.6 Soil moisture

Actual soil moisture data are collected by the Advanced Microwave Scanning Radiometer - Earth Observing System (**AMSR-E**) on NASA's Aqua satellite, measured at two instances per day along an ascending and descending path. AMSR-E soil moisture data were averaged to obtain 8-daily values. AMSR-E data are available on a spatial resolution of 25 x 25 km. Soil moisture information is a necessary input of ETLook and is not listed separately in the WA+ results.

5 Satellite Derived Actual Evapotranspiration

5.1 ETlook

ETLook is an algorithm developed by WaterWatch (Pelgrum et al., 2010) 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, it relies on thermal infrared sensors that are sensitive to cloud cover.

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 (transpiration T) and soil (evaporation E):

$$E = \frac{\Delta\left(Q^*_{soil} - G\right) + \rho c_p \frac{\Delta_e}{r_{a,soil}}}{\Delta + \gamma\left(1 + \frac{r_{soil}}{r_{a,soil}}\right)} \qquad T = \frac{\Delta\left(Q^*_{canopy}\right) + \rho c_p \frac{\Delta_e}{r_{a,canopy}}}{\Delta + \gamma\left(1 + \frac{r_{canopy}}{r_{a,canopy}}\right)}$$

where Δ [mbar/K] is the slope of saturation vapor pressure curve, Q_{soil} [W/m^2] is the net radiation for soil, G is the soil heat flux [W/m^2], ρ [kg/m^3] is the air density, c_p is the specific heat for dry air = 1004 J/kg/K, Δe is the vapor pressure deficit [mbar], r_a is the aerodynamic resistance for soil and canopy respectively [s/m], γ is the psychrometric constant [mbar/K] and *r* is the soil and canopy resistance respectively [s/m].

Figure 23 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 Ta, wind speed u_{obs}, relative humidity RH and atmospheric transmissivity. The soil is divided into two sections, the top soil and sub soil. On the basis of AMSR-E measurements and knowledge on soil types (FAO soil map) it is possible to calculate the effective saturation for both top soil Se_{top} and sub soil Se_{sub}. The transmissivity parameter is used to determine the actual amount of incoming solar radiation Q* that reaches the surface. The leaf area index LAI is used to separate the net radiation Q* into a soil and canopy part, energy dissipation (heat production) by the interception process is taken into account. The two resistance types in the Penman-Monteith equation: surface *r* and aerodynamical r_a are solved separately for soil and canopy. This approach enables ETLook to calculate the transpiration T for the canopy part and evaporation E for the soil part.

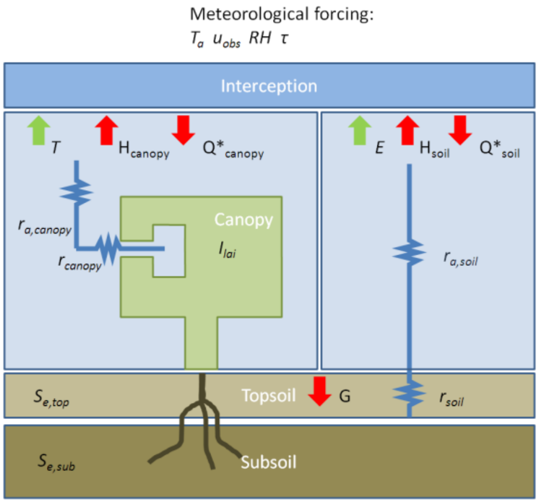


Figure 23. Overview ETLook algorithm.

The outputs of ETLook consist of reference evapotranspiration ET0, actual and potential transpiration Tact and Tpot, actual evaporation Eact for soil, water and wet leaves. Interception is computed as a function of the Leaf Area Index (LAI) and rainfall. ETLook is also capable of calculating the potential and actual biomass production, based on the photosynthetically active radiation (PAR) and various stress functions.

The model 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.

Details on ETLook including references to other literature and validations are summarized in Appendix B and are based on an IAHS (International Association of Hydrological Sciences) publication.

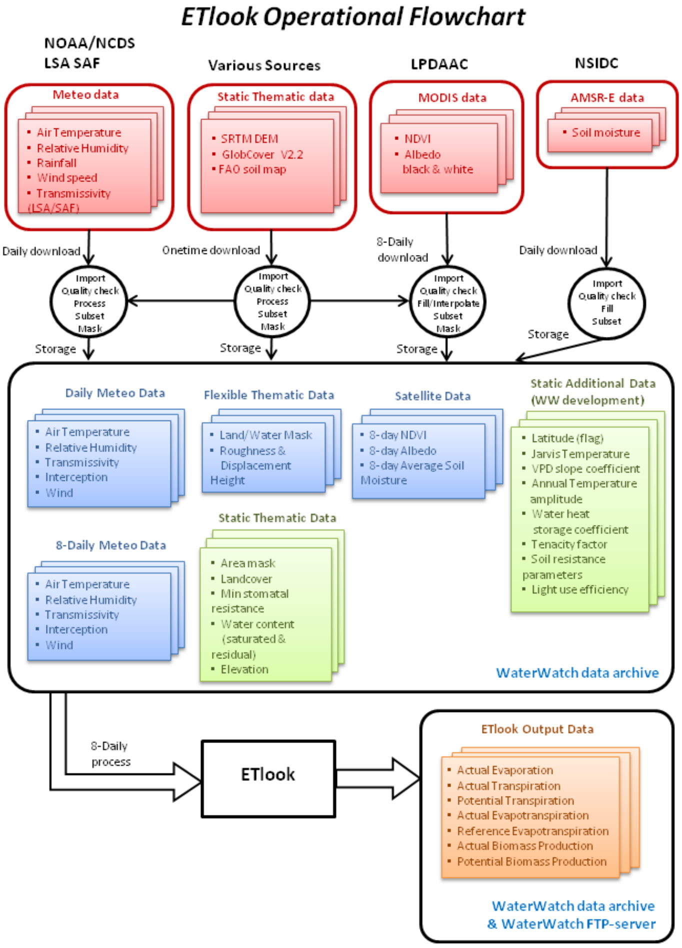
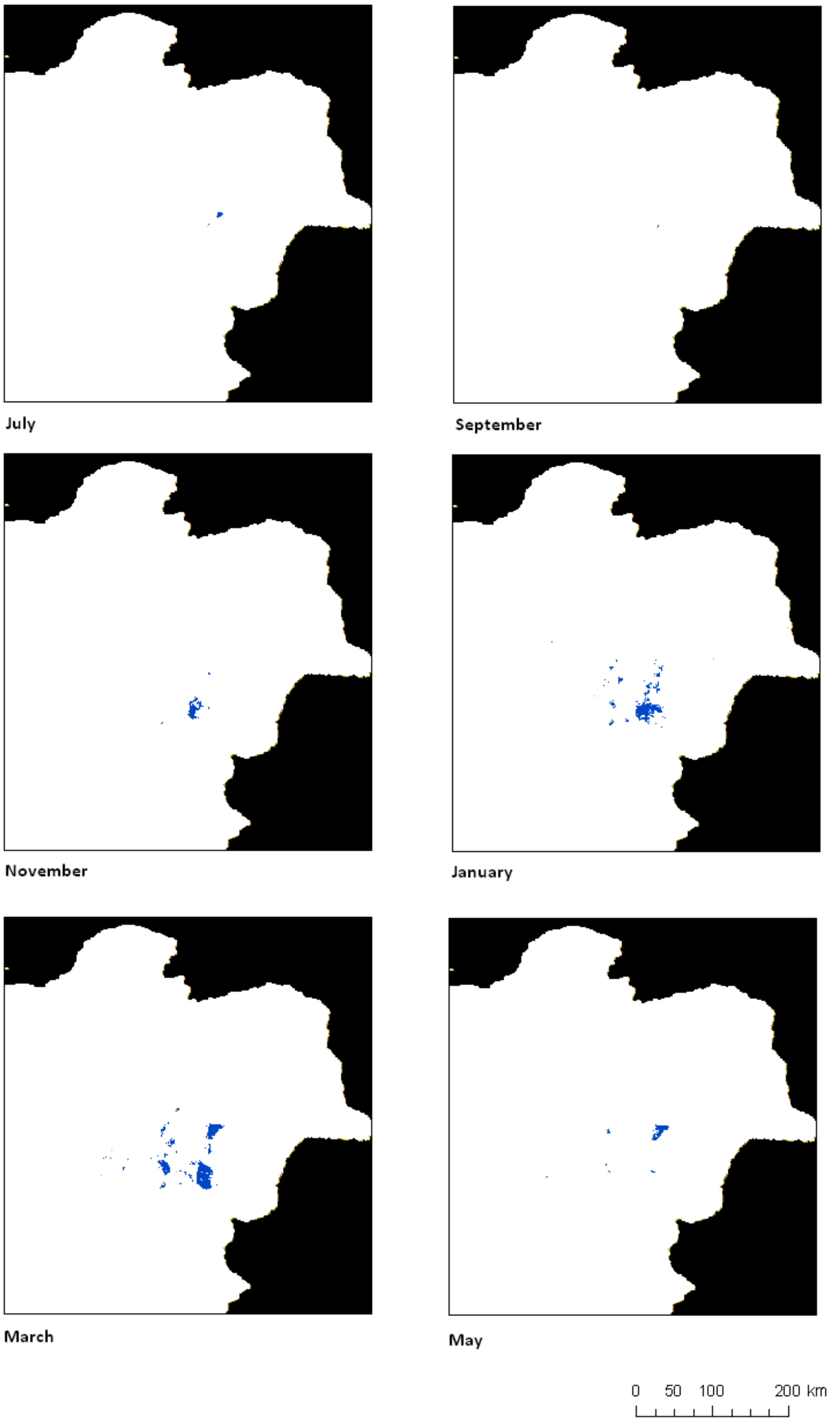


Figure 24. ETLook flowchart.

5.2 Adjustments to the general ETLook procedure

In order to increase the quality of the ETLook output for this specific area, a few adjustments were made to the standard modeling procedure as illustrated by the ETLook flowchart (Figure 24).

A static land/water mask was found to be inadequate for an accurate quantification of evapotranspiration in the Okavango basin. This is mainly due to the presence of the Makgadikgadi salt pans in the east of the basin, which have a water level varying highly through the hydrological year. To account for the pixels containing surface water for only part of the year, MODIS NDVI and albedo products were used to construct an individual land/water mask for every timestep of the modeling period. Figure 25 illustrates the varying extent of the Makgadikgadi salt pans through the hydrological year.



July

September

November

January

March

May

Figure 25. The extent of the Makgadikgadi salt pans (in blue) in the first week of a selection of months in the hydrological year 2007-2008.

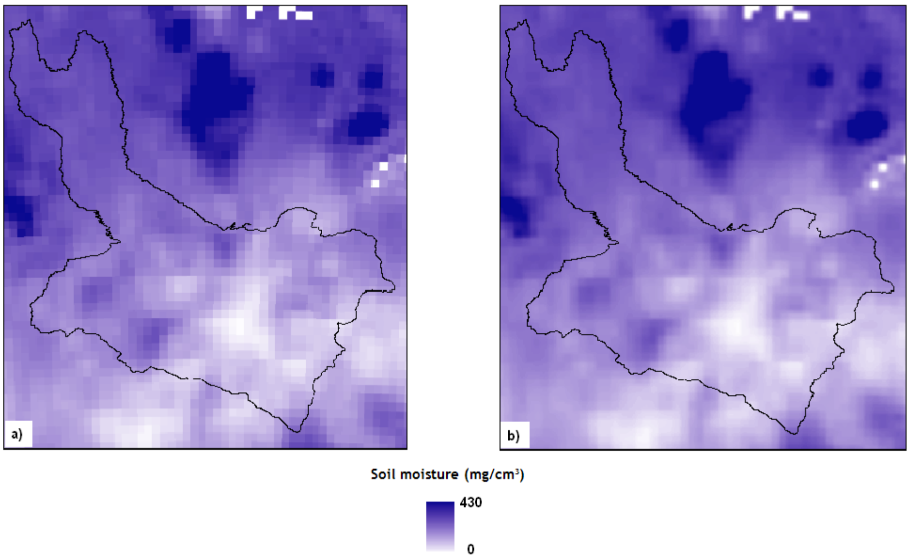


Figure 26. Actual soil moisture in the Okavango basin on 17/01/2008 prior to (a) and after (b) applying a lowpass filter.

AMSR-E soil moisture was smoothed using a spatial lowpass filter to compensate for its coarse 25 x 25 km spatial resolution. This action does not affect model outcomes for the overall water balance of the basin, but enhances the realism of the ETLook output on a pixel scale. Figure 26 presents a visualization of AMSR-E soil moisture data before and after application of the lowpass filter.

To further increase the accuracy of the model for open water, the linear relation between net incoming radiation Q* and water heat storage G_{water} (the soil heat flux for pixels classified as surface water) was determined specifically for the Okavango basin. Using Q* values resulting from an initial run of ETLook for a pixel containing surface water during the entire hydrological year, the relation between Q*and G_{water} was established by assigning a value of $G_{water} = 0$ to the yearly averaged Q*, a value of $G_{water} = 0.5 * Q^*_{max}$ to the highest occuring value of Q* and a value of $G_{water} = -0.5 * Q^*_{min}$ to the lowest occuring value of Q*. The obtained linear relation was assumed to be valid for pixels containing surface water in the entire basin.

Given the quality of the input data, ETLook was run on a temporal resolution of 8 days per time step and a spatial resolution of 1 x 1 km for the selected hydrological years. The model thus produces daily values of the output variables averaged over 8-day periods from July 1st, 2005 until June 30th, 2008.

5.3 Results

ETLook products that are of particular interest in the application of Water Accounting Plus (WA+) include actual evapotranspiration, separated into evaporation and transpiration, and biomass production. Table 3 presents the model results for these parameters in relation to the corresponding amount of rainfall for each hydrological year.

Figure 27 displays the spatial distribution of averaged daily evapotranspiration values for a typical 8-day period in the dry (12/07/2007 - 20/07/2007) and wet (17/01/2008 – 25/01/2008) period of the Okavango hydrological year. For the same periods, Figure 28 show the contribution of evaporation and transpiration to the daily evapotranspiration. The ETLook results show that transpiration from the vegetation in the Angolan highlands and the Okavango delta is the major contributing factor to evapotranspiration in the river basin during the dry winters. During the raining season, transpiration is higher in the entire basin due to the increased growth of vegetation. This is evidenced by the increase in biomass production visible in Figure 29. On the Makgadikgadi plains, evaporation values rise as the salt pans fill up with water during the wet summer period.

Table 3 Annual precipitation and relevant ETLook products for the selected hydrological years. Evapotranspiration is made up of Evaporation, Transpiration and Interception.

Year	Rainfall (mm)	Evapotranspiration (mm)	Interception (mm)	Evaporation (mm)	Transpiration (mm)	Biomass production (kg/ha)
2005(1)	768	647	45	224	378	18165
2006	493	625	39	188	398	15781
2007	647	634	42	211	381	16674

(1) 2005 refers to the hydrological year (1-Jul-2005 to 30-Jun-2006)

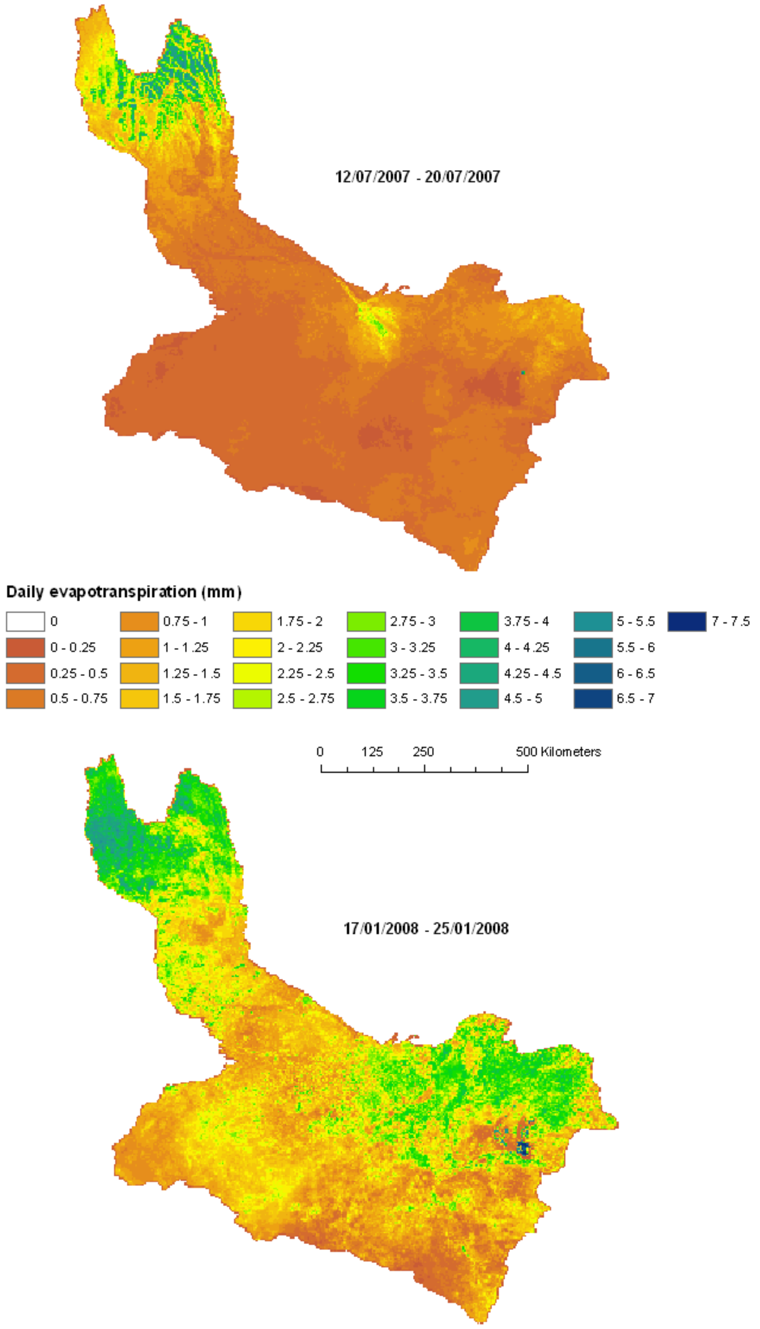
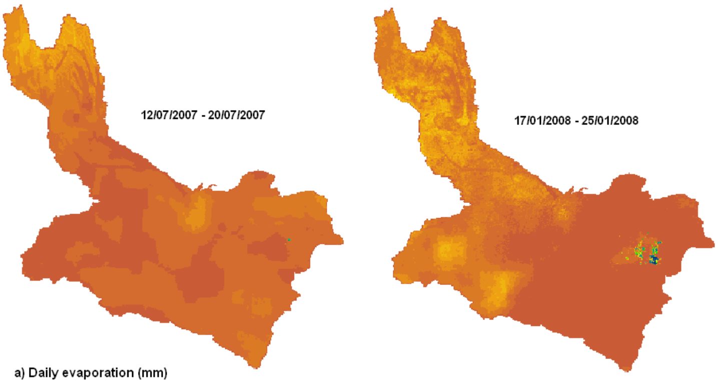
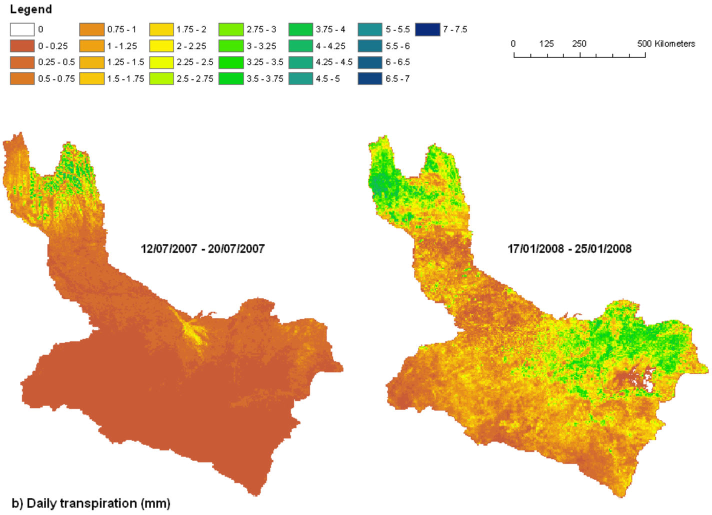


Figure 27. Daily evapotranspiration in the Okavango basin for the periods 12/07/2007 – 20/07/2007 and 17/01/2008 – 25/01/2008.



a) Daily evaporation (mm)



b) Daily transpiration (mm)

Figure 28. Averaged daily evaporation (a) and transpiration (b) in the Okavango basin for the periods 12/07/2007 - 20/07/2007 and 17/01/2008 - 25/01/2008.

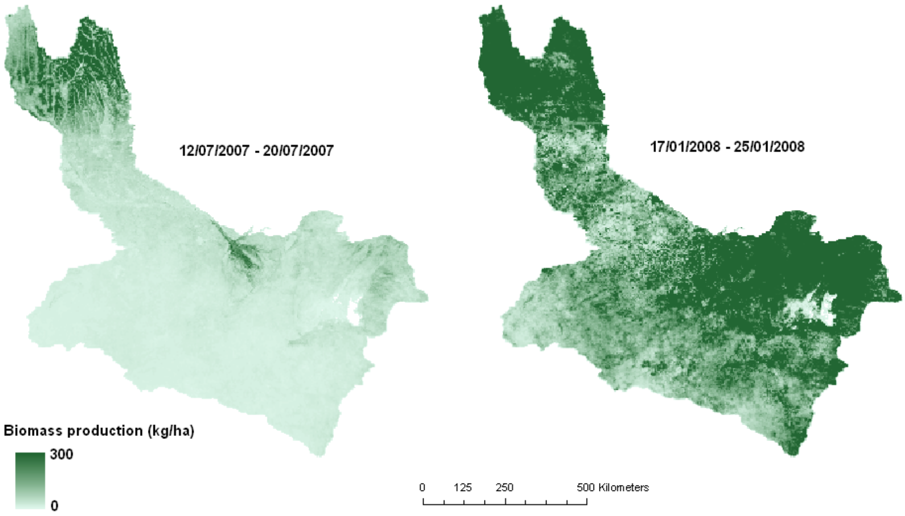
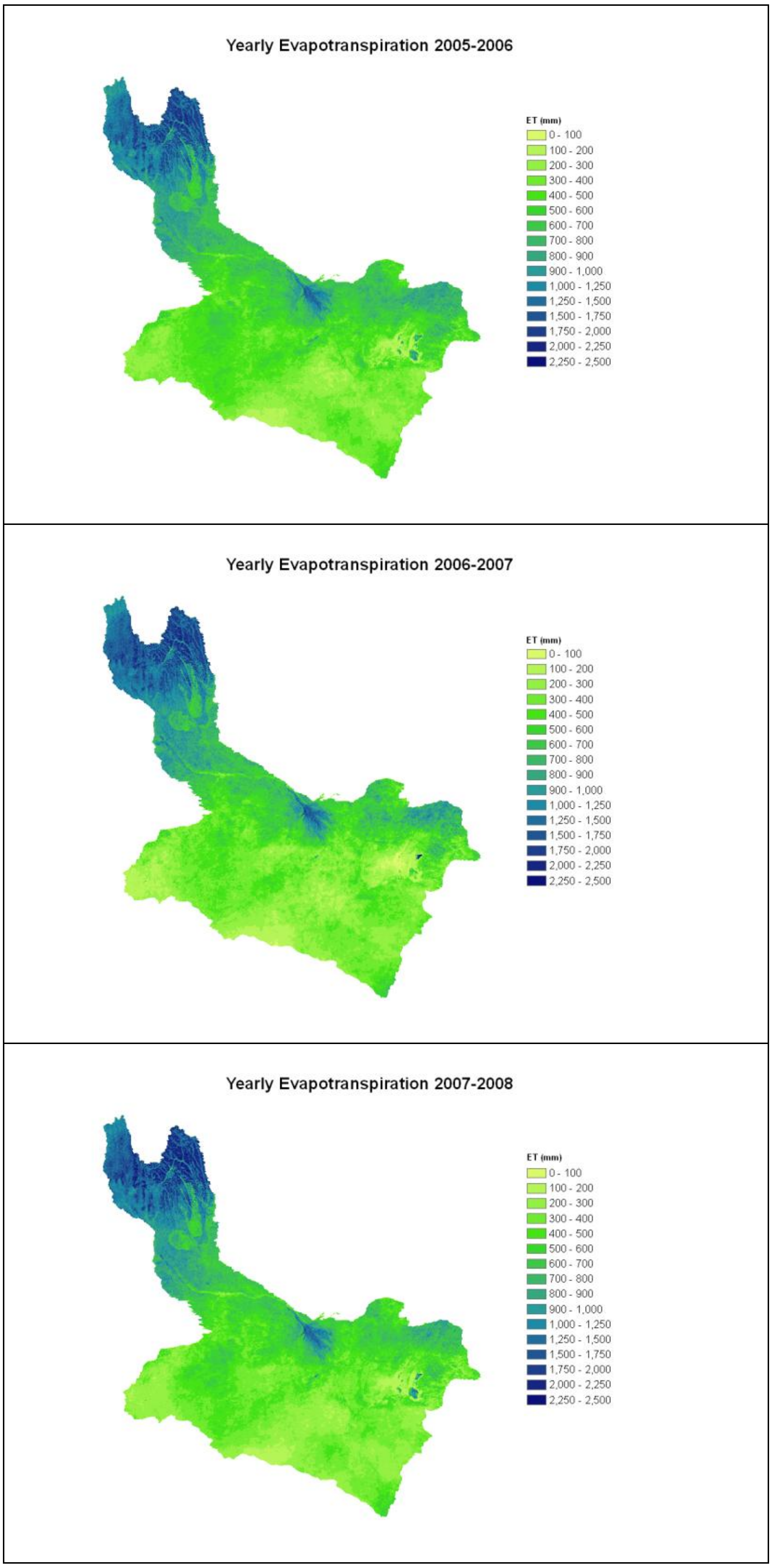


Figure 29. Averaged daily biomass production in the Okavango basin for the periods 12/07/2007 - 20/07/2007 and 17/01/2008 - 25/01/2008.



Yearly Evapotranspiration 2005-2006

Yearly Evapotranspiration 2006-2007

Yearly Evapotranspiration 2007-2008

Figure 30. Annual actual evapotranspiration Okavango basin for three years.

5.4 Evaluation

Literature provides little reference for assessing the quality of the evapotranspiration estimates. The lack of available measurements of actual evapotranspiration was encountered and described by Alemaw et al. (2003) and Wolski et al. (2005), amongst others. Two previous evapotranspiration modeling studies were found useful for comparison with the ETLook results.

Milzow *et al.* (2009) calculated the annual actual evapotransporation for the Okavango Delta using the simplified energy balance model S-SEBI (documented in Roerink *et al.* 2000), based on 98 NOAA-AVHRR images from the period 1990 - 2000. An illustration of their results is provided by Figure 31. Although their data were not available for a detailed comparison, their evapotranspiration map seems to be roughly in agreement with results of the current study in terms of relative differences within the area around the Okavango Delta. Absolute evapotranspiration values appear underestimated compared to the current study. A major drawback of the Milzow *et al.* (2009) methodology is the fact that the S-SEBI model can only be applied for cloud-free days, causing hazy and clouded imagery to be left out of the calculations.

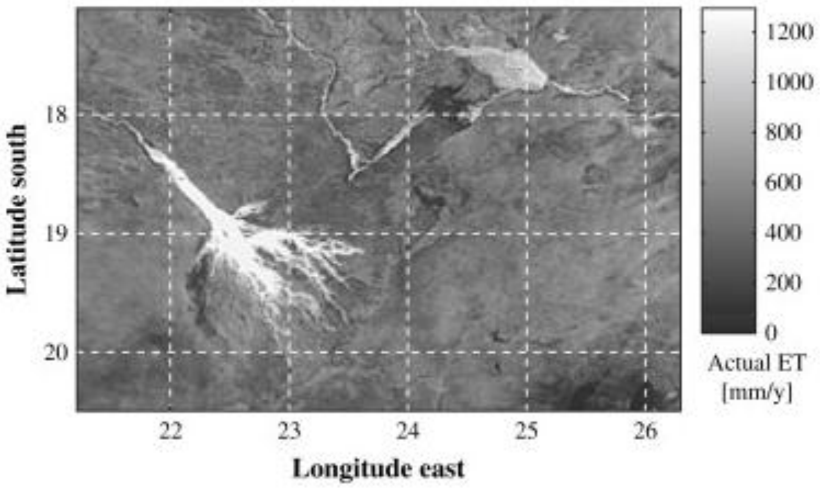


Figure 31. Evapotranspiration in the Okavango Delta area according to Milzow et al., 2009.

Timmermans *et al.* (2003) made use of a modified SEBAL model to quantify the different components of the surface energy balance in the Okavango basin for three days in September 2001. Adjustments to the original SEBAL formulation included separation of soil and canopy components, significantly improving the quality of the model output. Modeled energy fluxes were compared to measurement data from a meteorological flux tower and good results were obtained for net radiation, sensible heat flux and soil heat flux. The calculated latent heat flux, however, was found to differ substantially from ground observations. This could be partially attributed to the questionable quality of these measurements, since closure of the surface balance is never observed for these field data.

It can be concluded that, for calculating evapotranspiration over a number of years for the Okavango basin, the ETLook approach is suitable for the task at hand. Since the model is based on AMSR-E soil moisture rather than calculation of the surface energy balance, ETLook can be applied to the entire basin without the need for local atmospheric corrections. Whereas SEBAL and S-SEBI require the manual selection of pixels representing extreme conditions for every timestep, ETLook is more practical when performing calculations on a high temporal resolution over a longer period of time. The model is not restricted to the use of cloud-free imagery, which increases the quantity of usable satellite data. Another advantage over the conventional energy balance-based models is the separation of the soil and canopy components, which improves the quality of the results. The lack of reliable historical field data for the Okavango basin observed among others by Timmermans *et al.* (2003) is a general problem when applying models based on remote sensing, since validation of the model output is barely possible. General validation of ETLook is described in Appendix B.

6 Water Accounting Plus (WA+) Okavango

6.1 Introduction

One of the most important features of WA+ (Water Accounting Plus) is that required input can be generated easily to ensure that results are quickly available. A streamlined package has been developed which enables the production of water accounts for a specific area over a specific time frame in a standard manner. The following spatial distributed input is required:

- Precipitation
- Actual transpiration
- Actual evaporation
- Urban and industrial water consumption
- Land cover
- Inflow from outside of the area of interest
- Outflow out of the area of interest
- Change in storage of soil moisture, groundwater, surface water

As mentioned earlier, these various input data can be originating from various sources. The system itself is however developed to make use of readily available satellite observations, which can be converted to the required information on the fly. Chapter 4 and Chapter 5 described the sources of data for the Okavango WA+.

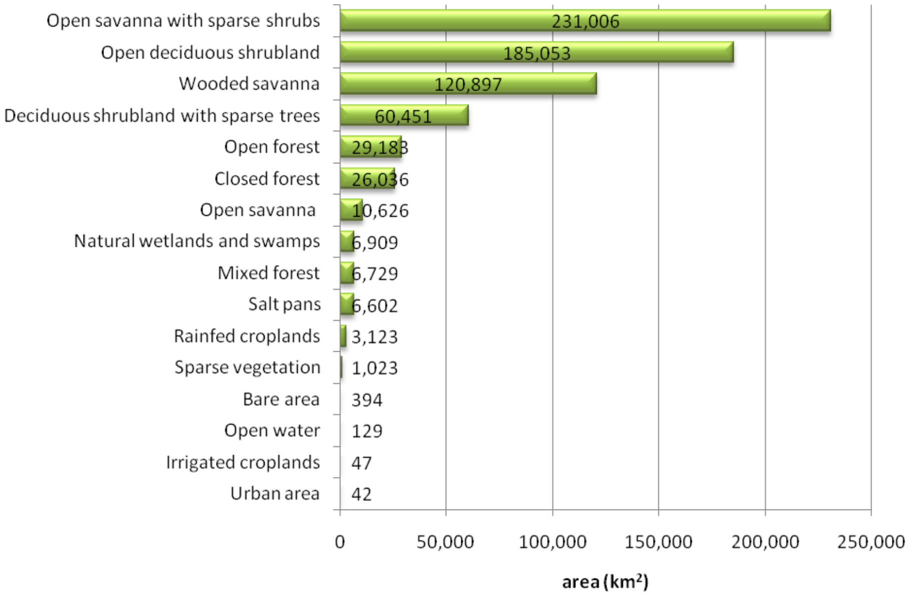


Figure 32: Land use Okavango Basin (km^2).

Land use is an important factor in WA+, as it determines the distinction between the four groups of land/water users: Conserved Land Use, Utilized Land Use, Modified Land Use and Managed Water Use. In most cases the standardized GlobCover dataset is sufficient accurate to be used as land cover / land use (LULC). As described in Chapter 4 the standard GlobCover was modified to ensure that especially data on irrigated lands was included correctly. The resulting LULC has 16 classes and the area per class is plotted in Figure 32 and depicts the general landscape of the Okavango: open with some patchy vegetation. Converting these 16 classes in the four land/water users reveals that the classes Modified Land Use (MLU) and Modified Water Use (MWU) are relatively small and cover less than 0.5 percentage of the entire area (Table 4). This indicates that there is currently very little human intervention in the basin.

Table 4 Areas per Land/Water Users for the Okavango Basin.

	km^2	%
Conserved Land use (CLU)	75,590	10.98
Utilized Land use (ULU)	609,451	88.55
Modified Land use (MLU)	3,165	0.46
Managed Water use (MWU)	47	0.01
Sum	688,253	100

6.2 Water Accounting Plus (WA+) Okavango Basin

The Water Accounting Plus (WA+) framework is meant to provide a quick overview of water and land performance in a region. This quick overview is provided by two main outputs (i) a set of sheets and (ii) indicators. The set of sheets include the Resource Base Sheet, the Consumption Sheet and the Production Sheet. Analyses were undertaken for three hydrological years: 2005-2006, 2006-2007 and 2007-2008. The resulting WA+ Sheets have been included in Appendix A.

6.2.1 Resource Base Sheet, 2005

To demonstrate the use of the three WA+ Sheets a detailed discussion for the hydrological year 2005 (1-Jul-2005 to 30-Jun-2006) will be given here (see Appendix A for the corresponding WA+ sheets). The Resource Base Sheet provides a quick overview of all incoming and outgoing flows for the entire basin and the four Land/Water Uses. Since the Okavango Basin as a whole is analyzed, the inflow and outflow is zero. Although some debate on inter-basin groundwater flows is ongoing in scientific literature, this was not incorporated in the WA+. Obviously, if details regarding these quantities are available then these can be included in the framework. The same arguments can be used for some overland flows in the Southern part of the Basin: there are discussions regarding the quantities of these flows and once known it can be included in the framework.

Since no inflows or outflows occur in the Okavango Basin, the only amount of water available in the basin is the precipitation and changes in storage. Over longer time frames changes in storage are close to zero unless unsustainable groundwater depletion occurs. For this particular wet year 2005, the storage changes in surface and groundwater are positive and are about 86,000 MCM. This change in storage is a result of the WA+ analysis and is the closing term between total water availability (precipitation) and total water use (evapotranspiration). If these data are observed independently they could be included in the analysis. This positive change in storage of 86,000 MCM convert to an average water depth of 125 mm over the entire basin. This is quite a substantial amount, however, one should realize that the hydrological year 2005 was a very wet one with average rainfall over the entire basin of 771 mm. A simple calculation assuming a vadose zone of 200 cm and a soil porosity of 0.40 indicates that 800 mm of water can be retained, making a change of 125 mm within the physical limits. Also, a large amount of water can be stored in the wetlands of the Okavango Delta, which are known to vary in extent.

LULC	Type	P (mm)	ET (mm)
Closed forest	CLU	954	1823
Open forest	CLU	888	1161
Mixed forest	CLU	882	1019
Natural wetlands and swamps	CLU	835	1165
Open water	CLU	819	773
Salt pans	CLU	617	350
Deciduous shrubland with sparse trees	ULU	860	956
Open deciduous shrubland	ULU	780	653
Wooded savanna	ULU	737	512
Open savanna with sparse shrubs	ULU	728	431
Open savanna	ULU	694	324
Sparse vegetation	ULU	615	255
Bare area	ULU	648	260
Urban area	MWU	507	311
Rainfed croplands	MLU	894	918
Irrigated croplands	MWU	746	767

Table 5 Annual precipitation and evapotranspiration (including interception) per land use/land cover in 2005. This table is included per subbasin in Appendix C.

Table 4 presents accumulated P and ET values for the wet hydrological year 2005. In general, values seem plausible, especially for the abundant shrubland and savanna classes and the croplands. More counter-intuitive are the rainfall shortages in the forest classes. Especially in the closed forest class there is a substantial difference. When investigating this phenomenon, it is found that the annual ET of 1823 mm can be explained by the NDVI which is high throughout the year for the Closed Forest (varying between 0.65 – 0.8). For such a dense vegetation cover, a daily average ET of 1823 / 365 = 4.9 mm is very well possible. Daily ET would have to drop below the unrealistic value of 2.6 mm/day for P to exceed ET. A possible cause of this phenomenon is an underestimation of precipitation by FEWS, which is calibrated by data from measurement stations. It is a global problem that densely vegetated areas with a high elevation are generally under-represented in terms of spatial distribution of precipitation stations. This could explain an underestimation of P in the forests of the Okavango basin, and a generally feasible relation between P and ET in other classes.

Since salt pans are only formed in areas of high ET, a higher value of ET (exceeding P) could be expected for this class. However, also for the dry and average years, this is not the case. This phenomenon can be explained by the unequal distribution of rainfall throughout the year, which mainly takes place during a select number of large events. Due to the formation of brines, with physical properties different from fresh water, ET remains relatively low.

Appendix C contains a version of Table 4 per subbasin.

The Resource Base Sheet shows that Utilized Land Use is the dominant Water/Land Use in the basin, followed by Conserved Land Use. Modified Land Use and especially Managed Water Use are only of minor importance in the basin. This indicates that the basin can be classified as hardly influenced by humans. However, the fact that the surface of Utilized Land Use is rather large indicates that potential changes might be expected on the long term, as the definition of Utilized Land Use includes an optional change to Modified Land Use or even Managed Water Use. The feasibility of such a land use change in terms of water resources, and subsequent shifts in the water balance, can be deduced from the average P and ET amounts of Utilized Land Use and Modified Land Use. It should be noted that the average precipitation over three years is higher for Modified Land Use than for Utilized Land Use (760 mm vs. 616 mm), as well as evapotranspiration (847 mm vs. 508 mm). Since an average P of 616 mm is insufficient to facilitate the current average ET of the rainfed croplands in the Okavango Basin (847 mm), the success of such a land use shift is doubtful and may for example depend on the crop choice, location within the basin and the exact land use class that is transformed (see the high variation in P for the different ULU classes in Table 4).

It is observed that Modified Land Use not only relies on rainfall, but also extracts water from the surface and groundwater storage. The Okavango is characterized by large areas receiving water from upstream which is used directly by vegetation growing in low areas close to the groundwater and/or surface water. Also, some areas might be classified as rainfed agriculture, while in reality farmers do apply small quantities of water to their field. Overall, this use of surface and groundwater is relatively small and accounts for about 3% of all water consumed. The Conserved Land Use shows the same pattern, a substantial extraction of surface and groundwater from natural vegetation. For the Conserved Land Use this is even about 30% of total consumption.

Overall the Resource Base Sheet is an excellent tool to get a quick insight in the main water and land issues for an area. It clearly flags particular issues relevant for the basin for a specific time frame.

6.2.2 Consumption Sheet, 2005

The Consumption Sheet provides an overview of what happens with the total consumption in an area. If we take the hydrological year 2005 again as example it is clear that of the total consumption only 1% is actually managed or available to be managed. It should be noted here that it is assumed that for Modified Land Use water can be managed, following the concept that in rainfed agriculture water can be managed to a certain extent by issues like rainwater harvesting, mulching, cropping patterns, weeds, etc.

The Consumption Sheet provides also information whether water is consumed beneficially or non-beneficially (benefits of water consumption are determined per land cover, see paragraph 2.3). A substantial amount of water is used non-beneficially by interception or soil evaporation. It was decided that not all soil evaporation or open water evaporation should be considered as non-beneficial, as for example open water evaporation from wetlands will contribute to the environment. Similar, soil evaporation from Conserved Land Use can be considered as beneficial, and even having an economic value, as the Conserved Land Use will support wild life and tourism.

From the Consumption Sheet it is also clear that most beneficial use of water in the Okavango is for the environment, followed by the economic use. Most economic use is here defined as water use that is beneficial to tourism.

6.2.3 Production Sheet, 2005

The last sheet of WA+ is the Production Sheet. It provides a summary on the various uses of water that is consumed. Again, results are presented by the four Land/Water Use classes and for each class some key parameters are given. For the Conserved and Utilized Land Use the total biomass production (in kg/ha dry matter) is given, but no actual harvested yield can be attributed to these two classes. Interesting is that the biomass production of Conserved Land Use is much higher than the one for Managed Water Use. This can be explained by the fact that Conserved Land Use is for a large fraction fast growing natural forests receiving a substantial amount of water.

The biomass production (in kg/ha dry matter) of the Modified Land Use is, somewhat surprisingly, higher than the one for Managed Water Use. However, if the actual harvested yield is considered by applying a harvest index, the two classes perform equally. Most likely, Managed Water Use is dominated by high value crops such as vegetable, for which the total biomass production is relatively low compared to the harvested product. For the Modified Land Use, mainly rainfed, the opposite holds.

Finally, the Production Sheet gives also water productivity values for biomass and for harvested yield. The interesting component here is that water productivity for Managed Water Use is somewhat higher than Modified Land Use, indicating a system where the irrigated agriculture is performing better than the rainfed agriculture in terms of water use. It should be emphasized here that the water productivity as applied here relates to yield over actual water consumed.

6.2.4 Indicators, 2005

The Water Accounting Plus (WA+) results include a table with key parameters describing the entire system in a straightforward way. In Table 6 the indicators for the three years are given, but here we will first discuss the year 2005 only. The first two items, ET Fraction and Stationarity Index, are key parameters to characterize the area under consideration. An ET Fraction of 84% indicates that not all rainfall is consumed so that surplus of rainfall is used to increase in storage and/or generate outflow out of the area. The Stationarity Index indicator describes which percentage of the consumption is originating from the surface and groundwater store. A positive indicator value, like the 19% for the year 2005, means that no water is depleted from the store and that water use can be considered as sustainable for this particular year. The Basin Closure percentage indicates which portion of the total inflow of water is actually used or remains in the area, increasing the storage. The percentage of 100 indicates that no water is leaving the Okavango Basin.

The second set of indicators in Table 5 focuses on the actual amount of water that is currently managed, or is available to be managed. The total amount of Available Water is given in total volumes and is about 86,000 MCM for the year 2005. From this total amount only 1 MCM is actually managed and is the amount of water that is diverted to support irrigated agriculture.

The third set of indicators shows for which purpose water is used in the Okavango Basin. First of all, it is clear that there is limited scope for actual water savings as 93% is considered to be beneficial. It is also clear that agriculture consumes hardly any water in the basin and that most water has an important environmental as well as economic component.

The last set of WA+ indicators compares the current year with the long-term averages. For the Okavango Basin only three years were available to serve as average, however these three years represent a wet, a dry and an intermediate year. Interesting is that for the hydrological year 2005, a relatively wet year, overall beneficial consumption increases only slightly by 1.5%. Agricultural consumption was even slightly lower compared to average conditions, most likely due to somewhat less favorable growing conditions in terms of cloud cover and/or temperatures.

Table 6 Water Accounting Indicators for the entire Okavango Basin.

	2005	2006	2007	*average*
ET fraction (%)	84	125	97	*102*
Stationarity Index (%)	19	-20	3	*1*
Basin Closure (%)	100	100	100	*100*
Available Water (MCM)	86,102	-86,855	13,176	*4,141*
Managed Water (MCM)	1	4	0	*2*
Managed Fraction (%)	0	0	0	*0*
Beneficial Consumption (%)	93	94	93	*93.2*
Agricultural Consumption (%)	0	1	0	*0.5*
Environmental Consumption (%)	71	72	71	*71.4*
Economic Consumption (%)	29	28	28	*28.2*
Deviation Beneficial Consumption (%)	1.5	-1.3	-0.3	*0.0*
Deviation Agricultural Consumption (%)	-1.0	3.5	-2.5	*0.0*
Deviation Environmental Consumption (%)	0.5	-0.4	-0.1	*0.0*
Deviation Economic Consumption (%)	4.1	-3.5	-0.6	*0.0*

6.2.5 Three years period

The previous sections analyzed in detail the usefulness of the three WA+ Sheets and the set of Indicators for the hydrological year 2005. Analyses were performed for three years and results are presented in Appendix A and in Table 6.

The Resource Base Sheets for the three years confirm that the hydrological year 2005 is wet, the year 2006-2007 is dry and the year 2007-2008 is somewhat average in climate conditions. This is clearly reflected in changes in surface and groundwater storage between these three years. Especially the differences in flows from and to the surface and groundwater storage between the wet and dry year is striking. For example the flow from the Utilized Land Use to the surface and groundwater in the wet year (2005-2006) is about 30% of the incoming rainfall, while for the dry year (2006-2007) this is virtually zero. At the same time the natural abstraction from the groundwater by roots for this Utilized Land Use in the dry year is about 13%, while in the wet year this is less than 2%.

The Consumption Sheets for the three years indicate that overall water consumption, expressed as total ET, does not show big differences and are between 430,000 and 445,000 MCM. The main reason for this is the quite large surface and groundwater buffer capacity of the basin. The overall distribution of consumption between the various uses is more or less constant between the three years. Interesting is that in the dry year (2006-2007) more water is consumed by agriculture compared to the wet year (2005-2006). Most likely, the demand for water was higher because of higher temperatures and less clouds while at the same time still sufficient water was available for irrigation.

Table 6 presents the WA+ indicators for the three years. The ET Fraction and the Stationarity Index indicators reflect again the three contrasting years. The average ET Fraction over these three years is 102%, indicating that slightly more water was consumed than what was supplied by precipitation. This is also indicated by the Stationarity Index indicator: the percentage of total consumption originating from the surface and/or groundwater storage.

6.3 Subbasin analysis

The developed Water Accounting Plus (WA+) framework is flexible in terms of applications at various scale levels. The Okavango Basin is divided in six sub-basins (Figure 8). The use of WA+ at sub-basin level will be demonstrated here for the Okavango sub-basin, which encompasses the famous Okavango Delta marshlands. This sub-basin was selected as it has the most interesting and vulnerable areas in terms of wildlife and tourism and has been focus for many local studies. Again, the corresponding sheets are included in Appendix A.

In contrast to the entire Okavango Basin, the sub-basin is not closed and inflow and outflow occurs. Inflow might happen from the two upstream catchments Cuiot and Cubango, while outflow to the Makgadikgadi basin might occur. Outflow from the Cuito and Cubango catchment was reported to be 4329 MCM and 5307 MCM, respectively (Figure 34 based on OKACOM). These numbers represent the long-term averages and do not reflect the existing year-to-year variation due to prevailing weather conditions. It was therefore decided to use the difference between precipitation and actual evapotranspiration as proxy for outflow from the two catchments (Figure 36). For the three years considered it is clear that a huge variation exists between those three years with virtually no outflow during the dry year 2006.

A complicating factor for the Okavango sub-basin is that the storage changes in groundwater and surface water are unknown. Advanced remote sensing techniques might be used to observe these changes, but are beyond the scope of the current study. These techniques include the use of altimeters for measurement of surface water levels and deviations in gravitational force for total storage changes. In this study, it was assumed that the storage changes observed over the entire Okavango Basin are proportional divided over the entire basin.

The areas of Modified Land Use and Managed Water Use are very low (Figure 33) for the Okavango Sub-Basin and consumption levels are consequently almost negligible (Resource Base Sheet and Consumption Sheet). WA+ indicator values for the sub-basin are shown in Table 8. The Basin Closure indicator (Table 8) indicates that the Okavango Sub-Basin is still not closed and is on average 92%, with the remaining water flowing towards the Makgadikgadi and/or Okwa sub-basins. From a policy point of view this indicates that there might be scope to develop some additional Managed Water Use areas. Obviously, this depends not only on available water resources, but also on socio-economic and, especially for this location, on environmental considerations. The other indicator values for the Okavango Sub-Basin are more or less comparable to the ones for the entire Okavango Basin (Table 6).

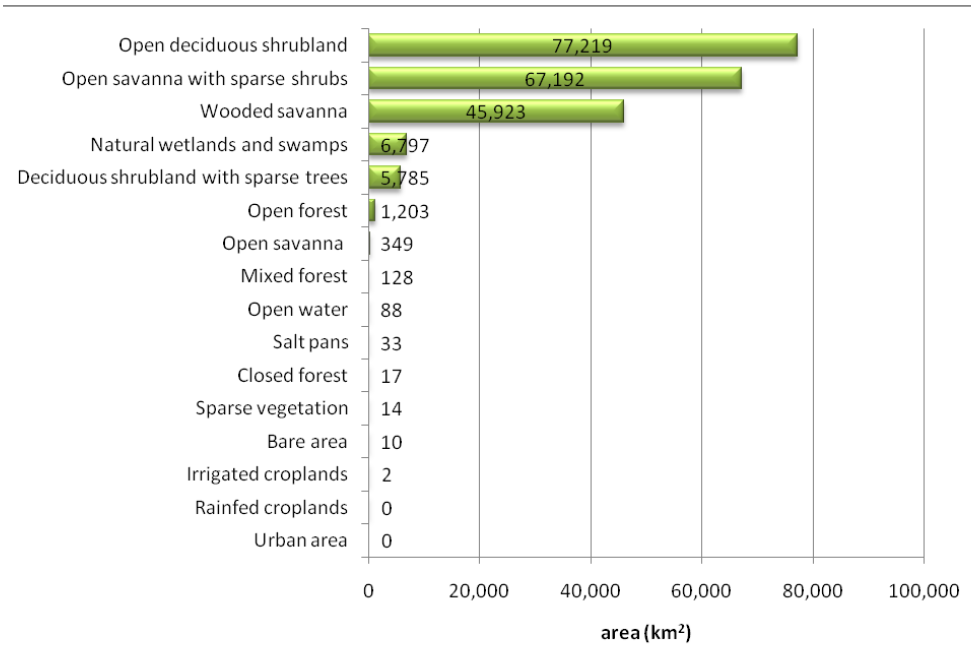


Figure 33: Land use Okavango sub-basin, using the modified land map (km^2).

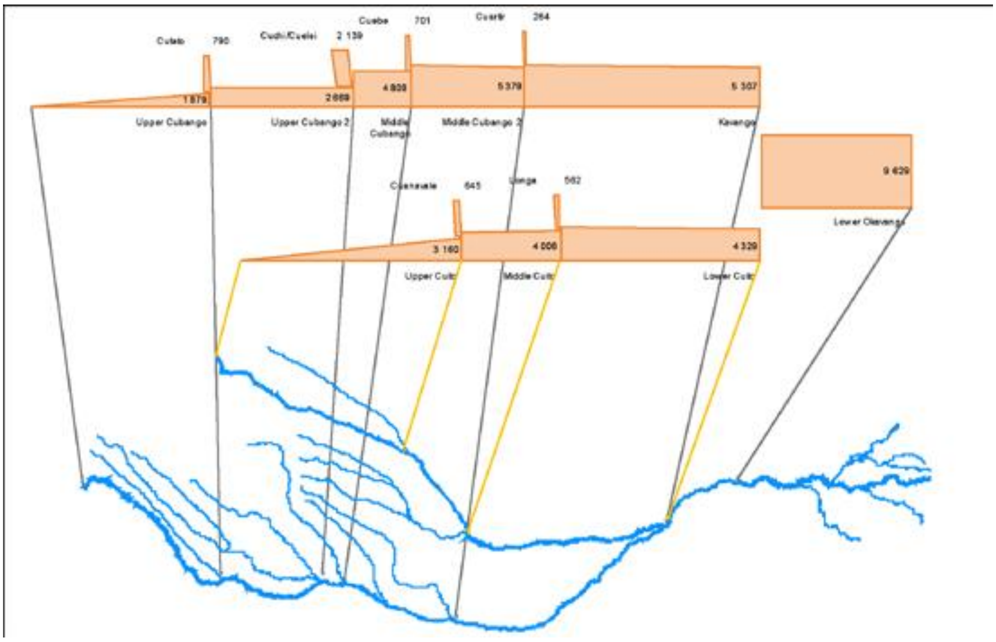


Figure 34. Annual average flows in MCM (source: OKACOM).

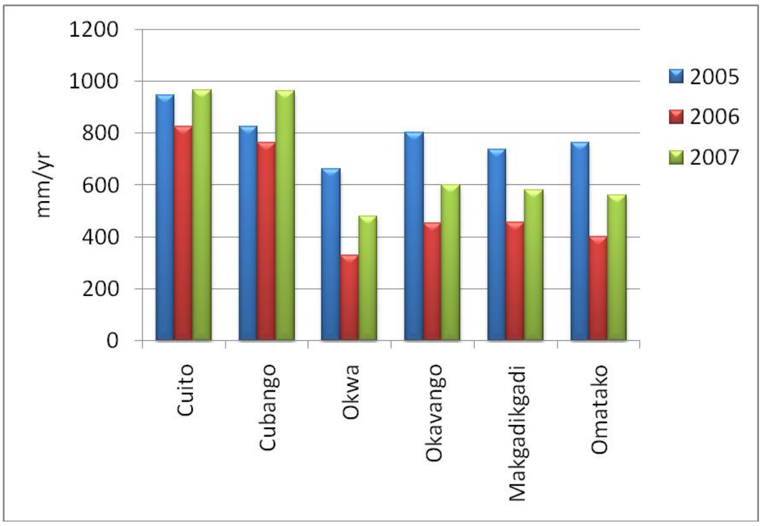


Figure 35: Annual precipitation for the six sub-basins.

Table 7. Inflow into the Okavango Sub_basin in MCM.

	2005	2006	2007
Outflow Cuito	1770	6	2521
Outflow Cubango	195	15	3534
Total = Inflow Okavango Sub-Basin	1965	21	6055

Table 8. Water Accounting Indicators for the Okavango Sub-Basin.

	2005	2006	2007	*average*
ET fraction (%)	75	120	91	*95*
Stationarity Index (%)	21	-23	4	*0*
Basin Closure (%)	91	92	94	*92*
Available Water (MCM)	40,329	-18,098	11,193	*11,141*
Managed Water (MCM)	0	0	0	*0*
Managed Fraction (%)	0	0	0	*0*
Beneficial Consumption (%)	93	94	94	*93.5*
Agricultural Consumption (%)	0	0	0	*0.0*
Environmental Consumption (%)	68	69	68	*68.1*
Economic Consumption (%)	32	31	32	*31.9*
Deviation Beneficial Consumption (%)	7.0	-3.9	-3.1	*0.0*
Deviation Agricultural Consumption (%)	11.8	-0.4	-11.4	*0.0*
Deviation Environmental Consumption (%)	6.9	-3.2	-3.6	*0.0*
Deviation Economic Consumption (%)	7.4	-5.4	-2.0	*0.0*

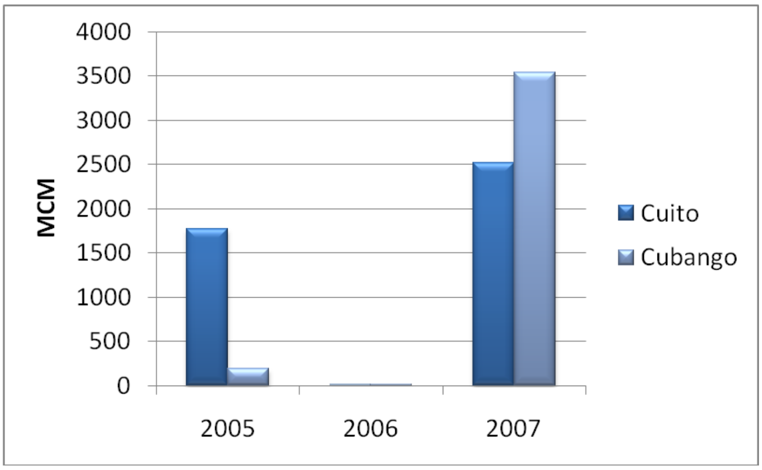


Figure 36: Outflow of the two catchments based on the difference between precipitation and actual evapotranspiration.

7 Conclusions

Water Accounting is considered by an increasing group of water managers, policy makers and donors to be an essential tool to ensure that the precious water resource will be better understood and managed. However, adoption of water accounting as a standard normal practice, like financial accounting, has still not been taking place due to various reasons. The most two important ones are (i) limited focus on decision makers need and (ii) lack of data.

The first point has been overcome in the approach presented here by making a clear differentiation between the four types of land/water managed: (i) Conserved Land Use: no changes in land and/or water management are possible, (ii) Utilized Land Use: land where vegetation is not managed on a regular base, (iii) Modified Land Use: vegetation and/or soils are managed, but water supply not, and (iv) Managed Water Use: water from surface water and/or groundwater is applied.

The second reason for slow uptake of Water Accounting, lack of data, has overcome in the proposed WA+ by relying heavily on satellite data. These remote sensing techniques have been developed over the last years from the domain of academic research into practical applications.

The demonstration case for the Okavango has shown that the selection of three years (wet, dry and average) is a relevant approach when performing WA+, with the average ET fraction approaching 100% as would be expected for the basin on the longer term. From the selected years, average yearly precipitation is quantified as 634 mm/yr. Average yearly evapotranspiration is calculated at 593 mm/yr.

This study has shown that the quality of the land use / land cover data is an important factor in determining the quality of the final water accounting results. For the Okavango basin, no standard existing dataset has proven sufficient and the construction of a combined LULC product was necessary. The land use classified as Utilized is quite extensive in the Okavango basin. In future WA+ studies, it may be sensible to distinguish an additional class based on the intensity of human activity and management.

WA+ results provide the water manager with an overview of information directed at taking measurements to improve the sustainability of water use in a basin. Appendix D provides a list of actions that could be undertaken by a water manager to solve a problem related to water resources with the WA+ results in hand. If, for example, there exists a need for increased food production to improve food security in the Okavango Basin, WA+ results indicate that a transformation of part of the utilized land use into modified land use may be possible depending on the choice of crop and the exact land use class that is transformed. To actually fill out the form in Appendix C for a certain basin and identify the problems and fitting recommendations, cooperation with the local management authorities is necessary.

It should be noted that WA+ was particularly designed with open basins in mind, with a significant surface area of Modified Land Use and/or Managed Water Use. In such a complex system of water flows, with substantial (possibilities for) human intervention, strengths of the WA+ approach can be used to full advantage.

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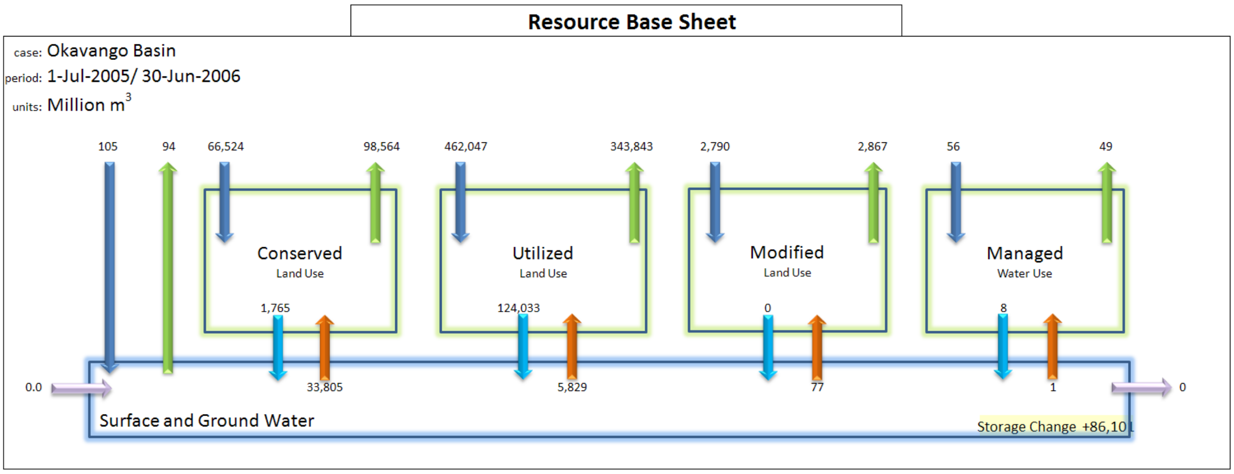
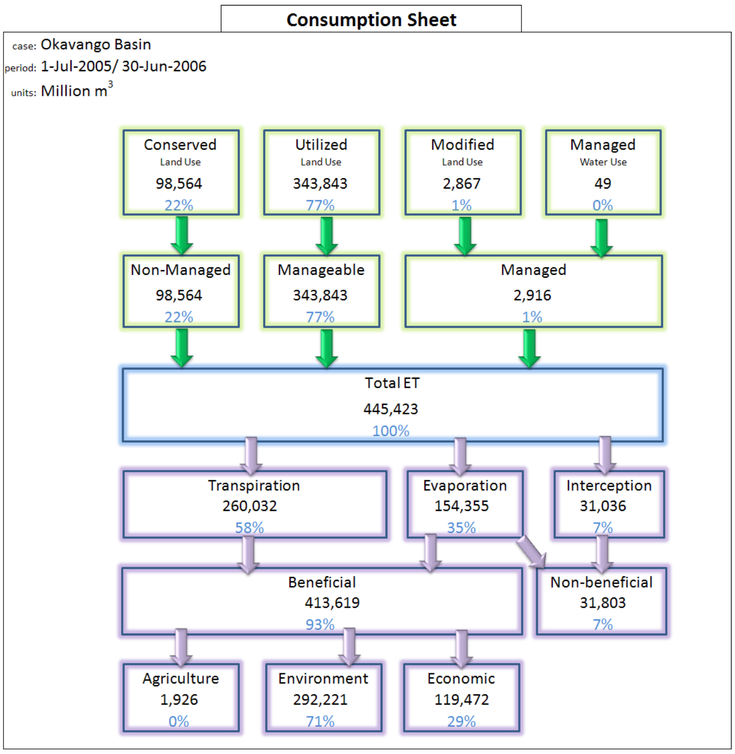
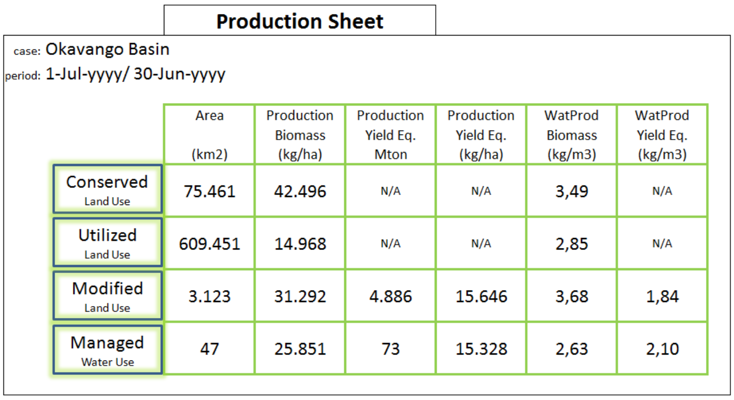
Appendix A: Water Accounting Plus (WA+) Sheets





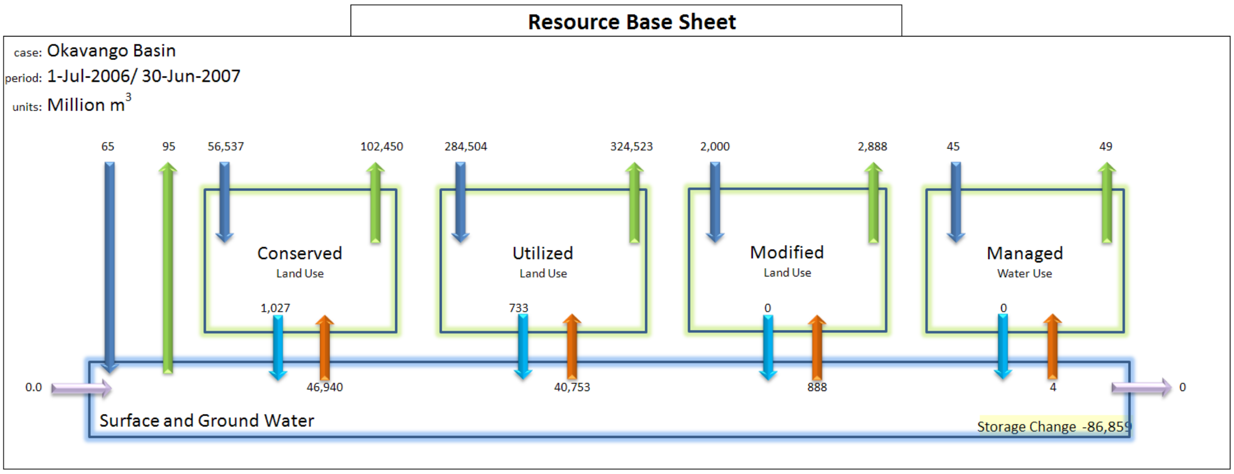


Production Sheet

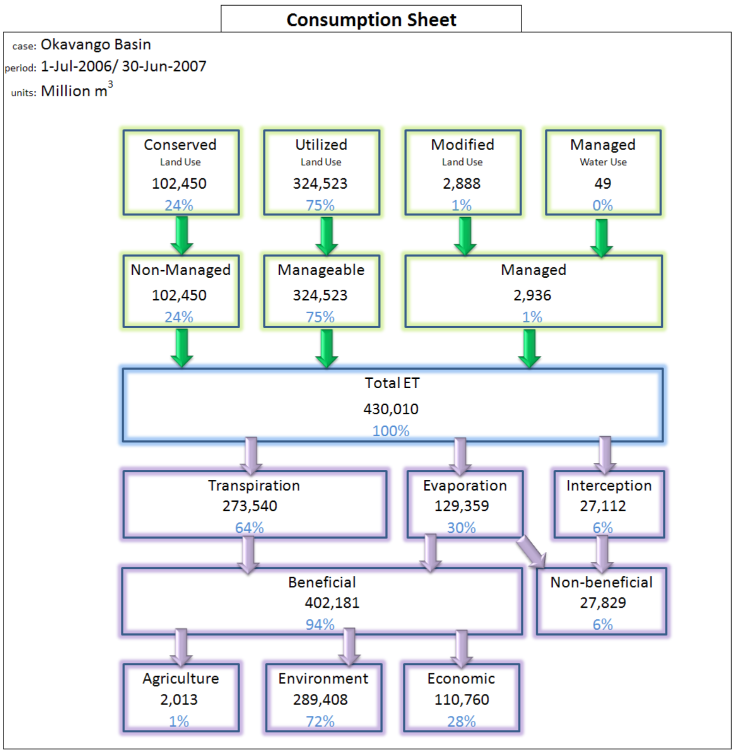
case: Okavango Basin
period: 1-Jul-yyyy/ 30-Jun-yyyy

	Area (km2)	Production Biomass (kg/ha)	Production Yield Eq. Mton	Production Yield Eq. (kg/ha)	WatProd Biomass (kg/m3)	WatProd Yield Eq. (kg/m3)
Conserved Land Use	75.461	42.496	N/A	N/A	3,49	N/A
Utilized Land Use	609.451	14.968	N/A	N/A	2,85	N/A
Modified Land Use	3.123	31.292	4.886	15.646	3,68	1,84
Managed Water Use	47	25.851	73	15.328	2,63	2,10

Resource Base Sheet



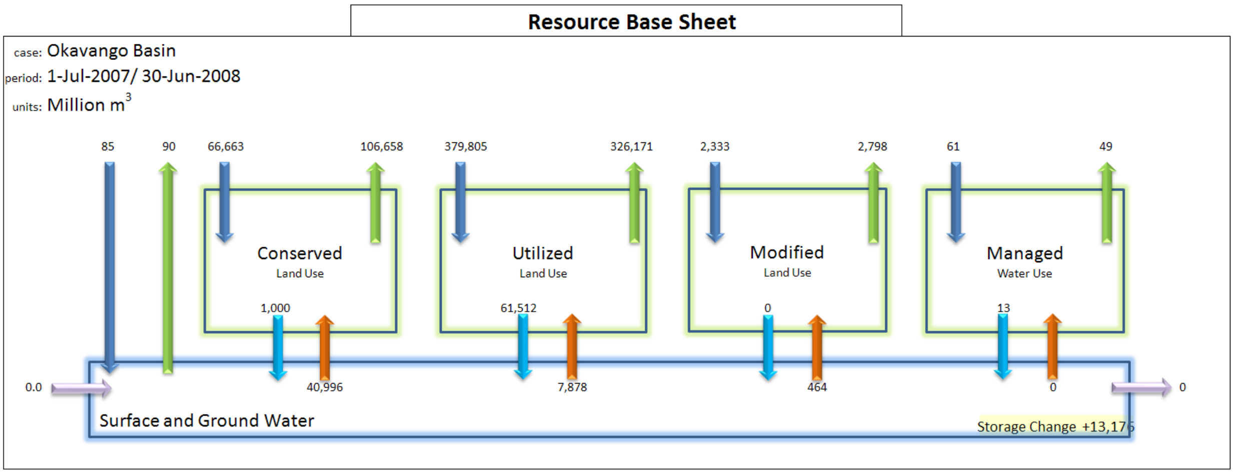
Consumption Sheet

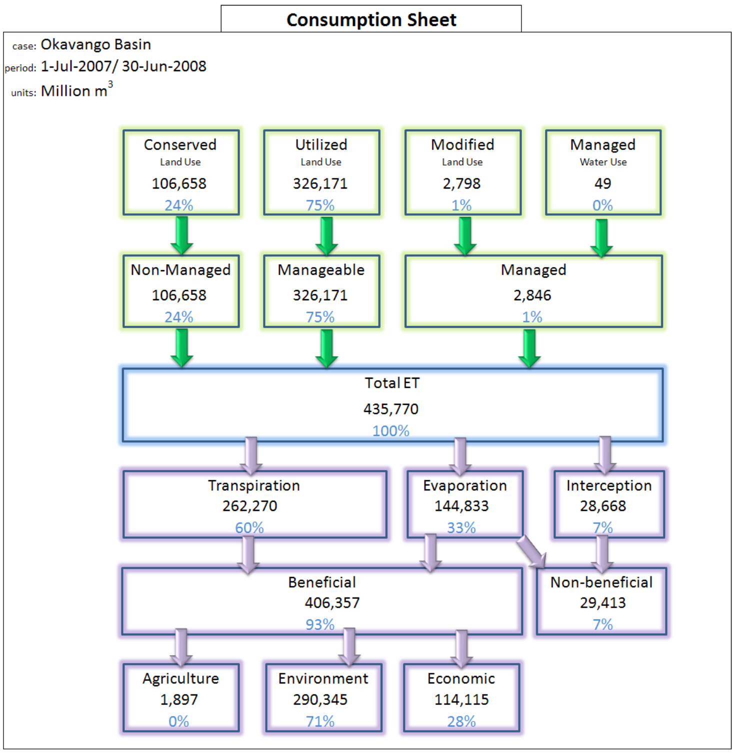


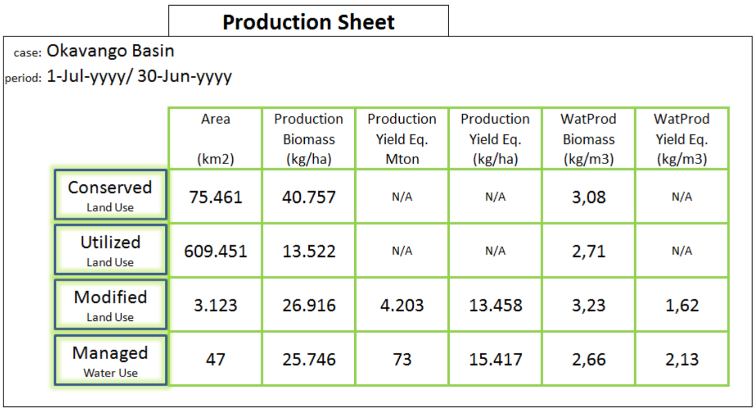
Production Sheet

case: Okavango Basin
period: 1-Jul-yyyy/ 30-Jun-yyyy

	Area (km2)	Production Biomass (kg/ha)	Production Yield Eq. Mton	Production Yield Eq. (kg/ha)	WatProd Biomass (kg/m3)	WatProd Yield Eq. (kg/m3)
Conserved Land Use	75.461	40.842	N/A	N/A	3,20	N/A
Utilized Land Use	609.451	12.486	N/A	N/A	2,50	N/A
Modified Land Use	3.123	26.678	4.166	13.339	3,10	1,55
Managed Water Use	47	21.523	65	13.753	2,22	1,92



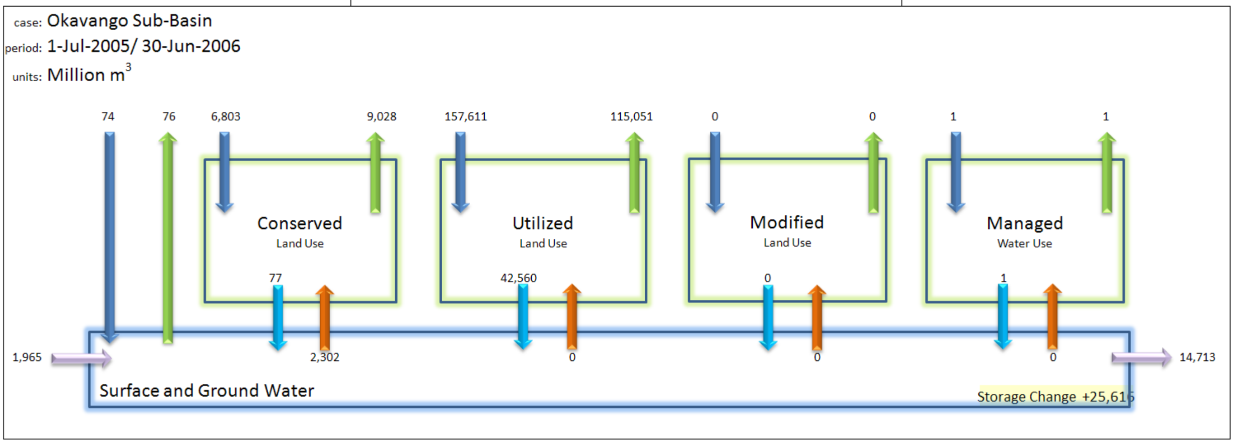



Production Sheet

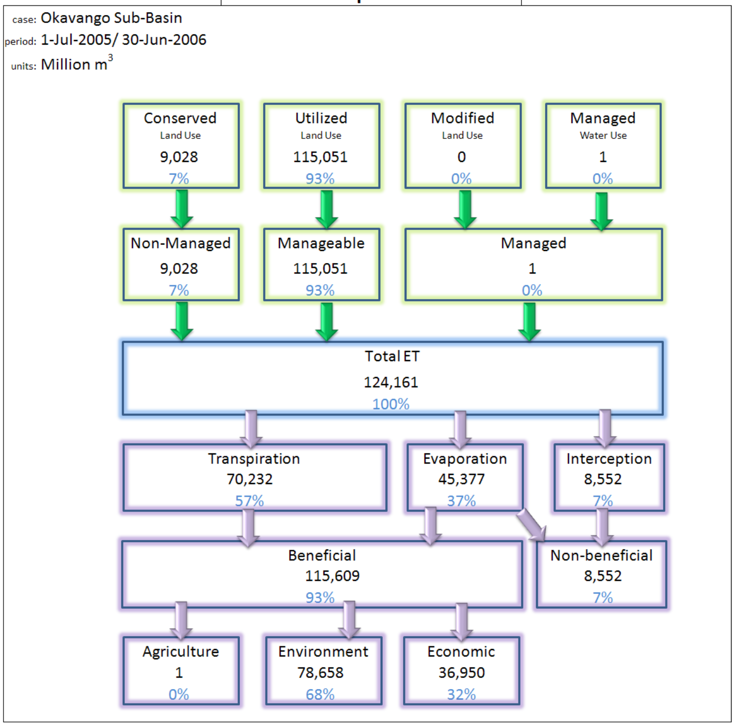
case: Okavango Basin
period: 1-Jul-yyyy/ 30-Jun-yyyy

	Area (km2)	Production Biomass (kg/ha)	Production Yield Eq. Mton	Production Yield Eq. (kg/ha)	WatProd Biomass (kg/m3)	WatProd Yield Eq. (kg/m3)
Conserved Land Use	75.461	40.757	N/A	N/A	3,08	N/A
Utilized Land Use	609.451	13.522	N/A	N/A	2,71	N/A
Modified Land Use	3.123	26.916	4.203	13.458	3,23	1,62
Managed Water Use	47	25.746	73	15.417	2,66	2,13

Resource Base Sheet



Consumption Sheet

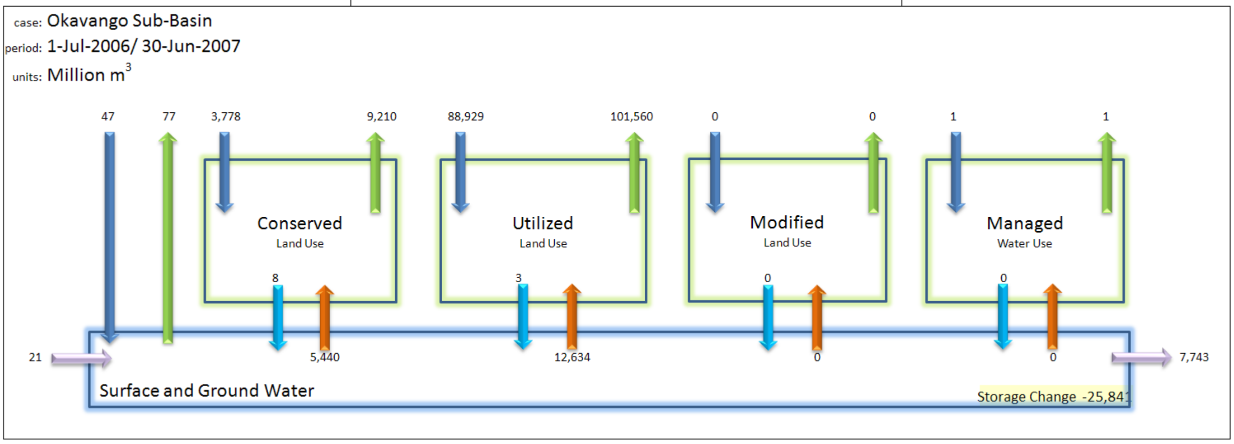


Production Sheet

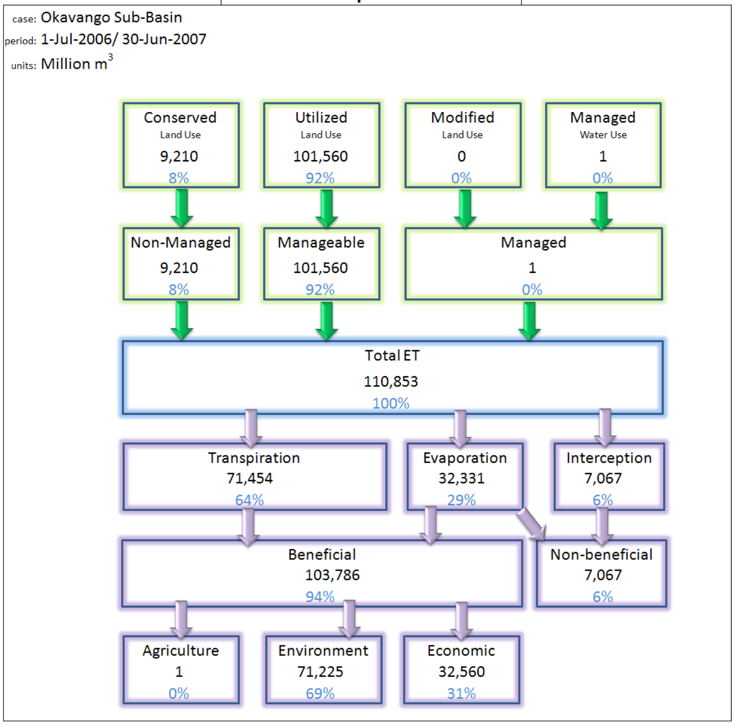
case: Okavango Sub-Basin
period: 1-Jul-2005/ 30-Jun-2006

	Area (km2)	Production Biomass (kg/ha)	Production Yield Eq. Mton	Production Yield Eq. (kg/ha)	WatProd Biomass (kg/m3)	WatProd Yield Eq. (kg/m3)
Conserved Land Use	8,179	34,342	N/A	N/A	3.28	N/A
Utilized Land Use	196,492	15,205	N/A	N/A	2.79	N/A
Modified Land Use	0	21,878	0	10,939	5.58	2.79
Managed Water Use	2	14,844	2	11,875	3.11	2.49

Resource Base Sheet



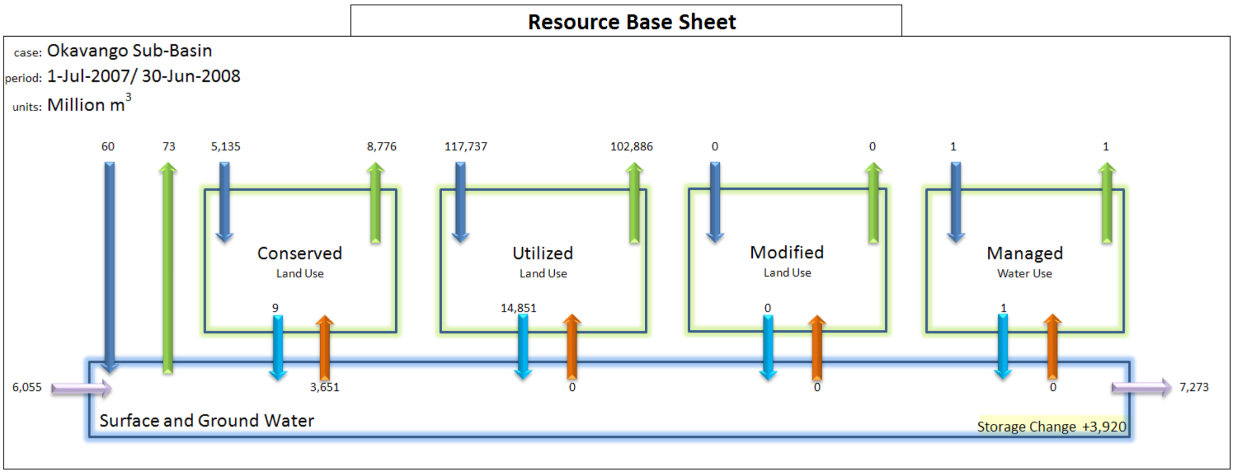
Consumption Sheet

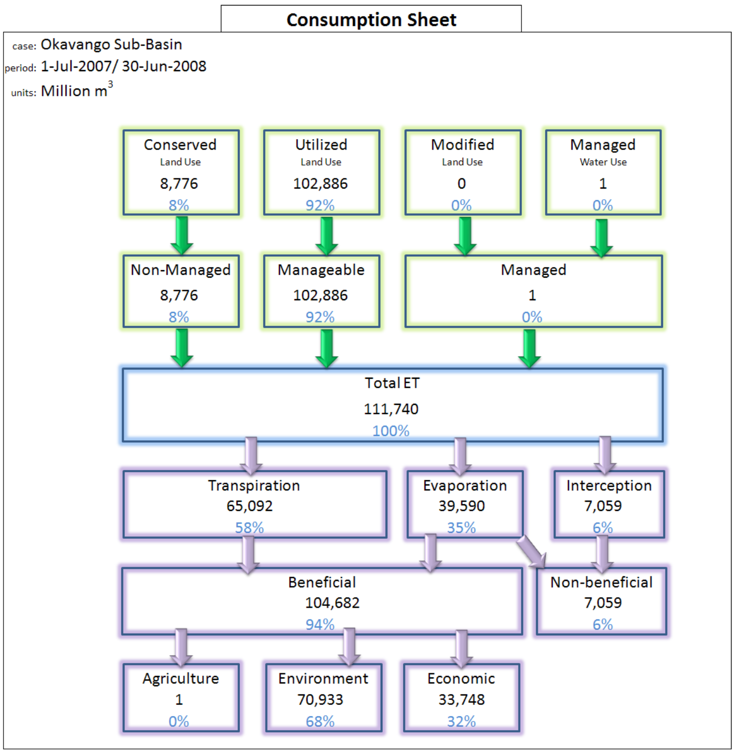


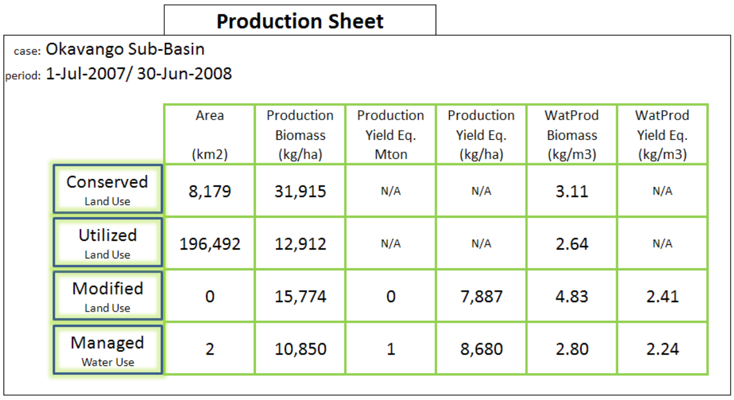
Production Sheet

case: Okavango Sub-Basin
period: 1-Jul-2006/ 30-Jun-2007

	Area (km2)	Production Biomass (kg/ha)	Production Yield Eq. Mton	Production Yield Eq. (kg/ha)	WatProd Biomass (kg/m3)	WatProd Yield Eq. (kg/m3)
Conserved Land Use	8,179	30,296	N/A	N/A	2.82	N/A
Utilized Land Use	196,492	11,643	N/A	N/A	2.41	N/A
Modified Land Use	0	14,682	0	7,341	4.28	2.14
Managed Water Use	2	10,709	1	8,567	2.47	1.98







Production Sheet

case: Okavango Sub-Basin
period: 1-Jul-2007/ 30-Jun-2008

	Area (km2)	Production Biomass (kg/ha)	Production Yield Eq. Mton	Production Yield Eq. (kg/ha)	WatProd Biomass (kg/m3)	WatProd Yield Eq. (kg/m3)
Conserved Land Use	8,179	31,915	N/A	N/A	3.11	N/A
Utilized Land Use	196,492	12,912	N/A	N/A	2.64	N/A
Modified Land Use	0	15,774	0	7,887	4.83	2.41
Managed Water Use	2	10,850	1	8,680	2.80	2.24

Appendix B: Details ETLook

Remote Sensing and Hydrology 2010 (Proceedings of a symposium held at Jackson Hole, Wyoming, USA, September 2010) (IAHS Publ. 3XX, 2011). 1

ETLook: a novel continental evapotranspiration algorithm

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Abstract ETLook is a newly developed algorithm to compute the evapotranspiration of large areas using an array of remote sensing data: moderate resolution visible and near infrared data from the MODIS sensor and low resolution estimates of soil moisture from the AMSRE sensor. The Penman-Monteith equation is solved separately for vegetation and soil, enabling the division of evapotranspiration into transpiration and evaporation. The ETLook algorithm has been applied in Australia, China and the Indus basin.

Key words evapotranspiration; remote sensing; microwave; river basin

INTRODUCTION

Numerous algorithms based on actual evapotranspiration (ET_{act}) mapping using visible, near infrared and thermal data exist. ET mapping of river basins and continents at a moderate resolution (1 km) is important to detect the spatial heterogeneity of ET and it's response to weather events (rainfall or drought). Surface energy balance techniques like RSEB (Kalma and Jupp, 1990), SEBI (Menenti and Choudhury, 1993), SEBAL (Bastiaanssen et al., 1998), SEBS (Su, 2002), and METRIC (Allen et al., 2007) estimate ET_{act} as a latent heat flux (residual term in surface energy balance). The major drawback of these techniques is the need for thermal infrared data to assess surface temperature. Thermal infrared data cannot provide reliable estimates on surface temperature under cloudy or hazy conditions, rendering the algorithms less useful in temperate climates. The visible and near infrared data are used to provide information on vegetation conditions and surface albedo for absorbed solar energy. These parameters are less critical to cloudy conditions, as their variation is not as large and irregular as the surface temperature. Verhoef (1996) showed that missing data of NDVI and surface albedo can be estimated using observations from other data.

ETLook is specifically developed to map ET_{act} for large areas on a daily to weekly basis for longer time periods with a resolution of 1 km. Typical outputs consist of yearly ET_{act} with an interval of one week associated with biomass growth with an interval of two weeks for large watersheds. Sufficient detail within the watersheds can be used to monitor local differences in water management.

ETLook is a newly developed algorithm to compute ET_{act} of large areas using soil moisture estimates from the passive microwave sensor AMSRE. The advantage of using passive microwave sensor data is that its signal is not affected by clouds. A drawback of the passive microwave sensor data is the low resolution of the data. Downscaling in ETLook is achieved by linking the soil moisture estimates from the AMSRE 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 uses moderate resolution visible and near infrared data from the MODIS sensor for determining surface albedo and vegetation cover. Routine meteorological measurements (wind speed, air temperature and relative humidity) at a number of stations within the area are used to infer the current 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. Therefore the algorithm can be used operationally, making it useful for real time hydrological modelling and operational land surface models.

THEORY

The Penman-Monteith equation is solved separately for vegetation and soil in order to split the evapotranspiration into transpiration (T) and evaporation (E):

$$T = \frac{\Delta(Q^*_{canopy}) + \rho c_p \frac{\Delta_e}{r_{a,canopy}}}{\Delta + \gamma(1 + \frac{r_{canopy}}{r_{a,canopy}})} \qquad E = \frac{\Delta(Q^*_{soil} - G) + \rho c_p \frac{\Delta_e}{r_{a,soil}}}{\Delta + \gamma(1 + \frac{r_{soil}}{r_{a,soil}})}$$

where Δ is the slope of the saturation vapour pressure curve [mbar K^{-1}], Δ_e vapour 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 [Wm^{-2}], Q^*_{canopy} and Q^*_{soil} [Wm^{-2}] are the net radiation for canopy and soil respectively, r_{canopy} and r_{soil} [sm^{-1}] are the canopy and soil resistance respectively, $r_{a,canopy}$ and $r_{a,soil}$ [sm^{-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 microwave measurements. The canopy resistance r_{canopy} is a function of the leaf are index and four dimensionless stress functions. Three of the stress functions are related to meteorological conditions: temperature stress, vapour 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 unstable conditions. The Monin-Obukhov theory (1954) is used to parameterize the effects of shear stress and buoyancy.

APPLICATIONS AND VALIDATION

The algorithm has been tested for different climatological conditions and locations. It has been tested for continental Australia for three years (2002-04 and 2005-06), China (2009) and the Indus Basin (2007). Some first results are presented hereafter.

Australia

ETLook has been run for three years (2002-04 and 2005-06) for the whole of Australia. The E and T were calculated on a weekly basis. Figure 1 shows the results for a cropland pixel south of Griffith, NSW Australia, for the period of July 2004 - June 2005. The growing season is from August 2004 to November 2004 and in the remainder of the period no crops are grown. In the beginning of this period transpiration is dominant while in the remainder of the period ET is equally partitioned between E and T. After intensive rainfall events an increase in E is observed. A dry-down period in spring 2005 can also be detected by a monotonic decrease in E.

Figure 2 shows the agreement between the mean yearly ET measured by ETLook for the year 2005 and the mean yearly ET reported by the National Water Commission of Australia (Australian Water Resources 2005 - A baseline assessment of water resources for the National Water Initiative, level 2, National Water Commission (www.water.gov.au) for the same period for a large number of priority water balance areas in Australia. There is generally a good agreement between both data sources. The average error, taking into account the various sizes of area of each waterboard, is 26 mm/year.

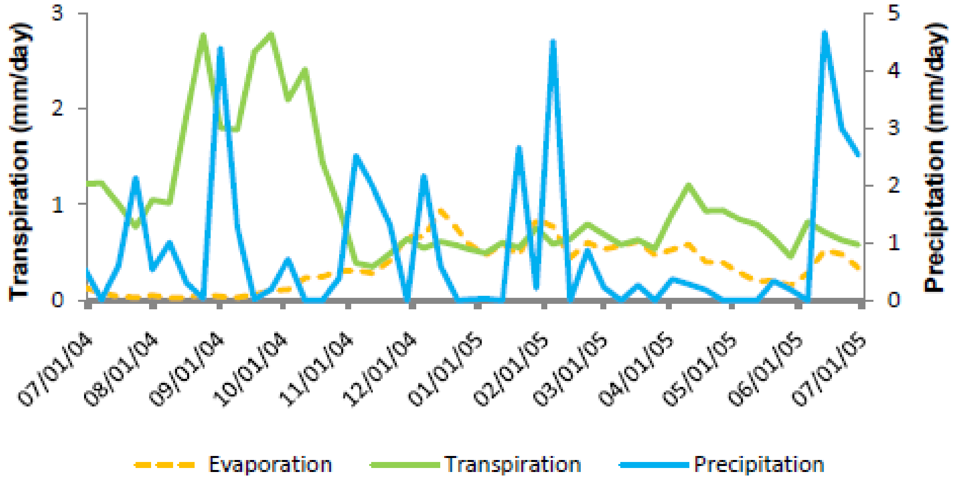

Fig. 1 Time series of ETLook evaporation, transpiration and measured precipitation for a cropland near Griffith NSW, Australia.

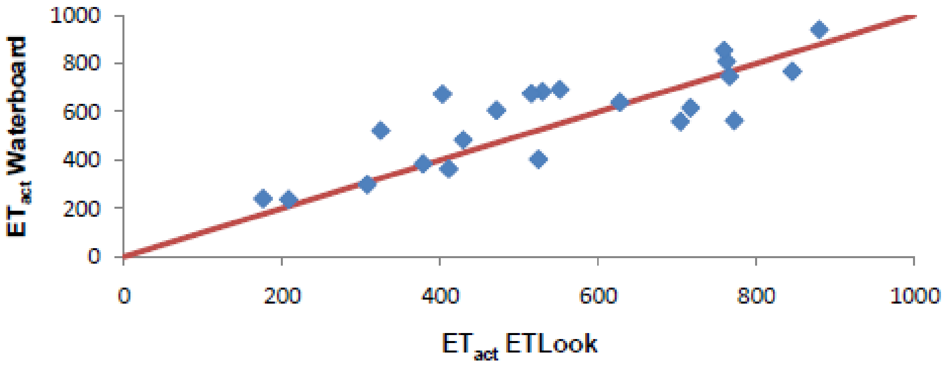

Fig. 2. Comparison of mean actual evapotranspiration as reported by Australian Water Resources Study 2005 and ETLook for 22 priority water balance areas

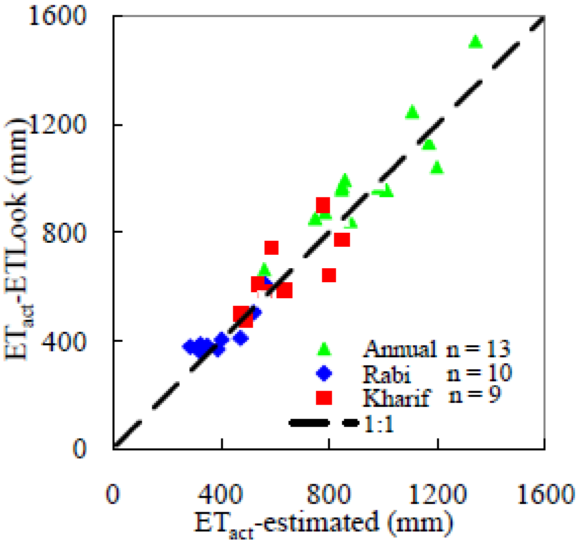

Fig. 3. Comparison of evapotranspiration estimated by previous studies and ETLook for different seasons measured at different locations in the Indus Basin.

Indus Basin

The Indus basin is located between 25° to 37° N and 66° to 82° E. The basin exhibits complex hydrological processes due to variability in topography, rainfall, and land use. The elevation ranges from 0–8000 m. The mean annual rainfall varies from approximately 200 to 1500 mm.Figure 4 shows the comparison of actual ET estimated by ETLook and actual ET compiled from different data sources for the annual ET and for the two main growing seasons in the Indus basin: Rabi and Kharif. Also here there is good agreement between both data sources in spite of climatic differences between the considered years. The correlation coefficient (R^2) for annual, rabi and kharif season is 0.76, 0.60 and 0.47, respectively with the regression line fitted through the origin.

China

ETLook was used to estimate 20-day actual ET in 2009. The uncalibrated results were compared to Eddy correlation measurements of actual evapotranspiration at Haibei Flux Research site.

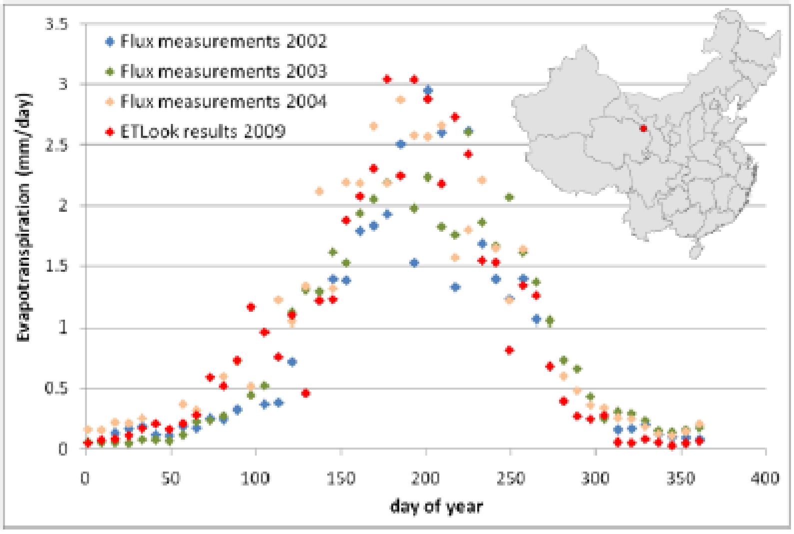

Fig. 4. Comparison of 10-day actual evapotranspiration estimated by an Eddy correlation station in Haibei (data courtesy of Fluxnet) and uncalibrated ETLook for different years.

The magnitude of the evapotranspiration during the year 2009 as predicted by ETLook corresponds well with the measurement for previous years.

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Appendix C: Subbasin ET and P per landcover (2005/2006)

Omatako		
LULC	**P (mm)**	**ET (mm)**
Closed forest	947	597
Open forest	777	556
Mixed forest	571	590
Open water	828	477
Deciduous shrubland with sparse trees	646	594
Open deciduous shrubland	676	543
Wooded savanna	707	500
Open savanna with sparse shrubs	784	391
Open savanna	739	381
Sparse vegetation	653	304
Bare area	321	262
Urban area	694	428

Okwa		
LULC	**P (mm)**	**ET (mm)**
Open forest	655	547
Mixed forest	657	523
Open water	681	372
Salt pans	607	220
Deciduous shrubland with sparse trees	653	495
Open deciduous shrubland	645	401
Wooded savanna	646	355
Open savanna with sparse shrubs	673	357
Open savanna	680	302
Sparse vegetation	633	304
Bare area	689	324
Urban area	654	318

Makgadikgadi		
LULC	**P (mm)**	**ET (mm)**
Closed forest	752	825
Open forest	820	789
Mixed forest	830	706
Open water	751	454
Salt pans	617	350
Deciduous shrubland with sparse trees	789	643
Open deciduous shrubland	748	619
Wooded savanna	686	462
Open savanna with sparse shrubs	705	425
Open savanna	612	262
Sparse vegetation	607	220
Bare area	626	224
Urban area	573	228
Rainfed croplands	876	740

Cuito		
LULC	**P (mm)**	**ET (mm)**
Closed forest	996	1902
Open forest	970	1238
Mixed forest	934	925
Natural wetlands and swamps	789	691
Open water	1124	1612
Deciduous shrubland with sparse trees	951	1040
Open deciduous shrubland	897	820
Wooded savanna	885	761
Open savanna with sparse shrubs	933	849
Sparse vegetation	931	485

Cubango		
LULC	**P (mm)**	**ET (mm)**
Closed forest	898	1822
Open forest	875	1283
Mixed forest	872	1115
Natural wetlands and swamps	777	644
Open water	741	984
Deciduous shrubland with sparse trees	860	1113
Open deciduous shrubland	776	883
Wooded savanna	750	776
Open savanna with sparse shrubs	740	708
Open savanna	690	366
Sparse vegetation	948	797
Bare area	716	300
Rainfed croplands	935	1485
Irrigated croplands	747	802

Appendix D: Standard Water Accounting Evaluation and Remedy Sheet

Concern	Evaluation			General remedies
	No problem	Average	Problem	
Storage change SW being negative				• Reduce ET of managed water use • Reduce landscape ET • Reduce non-beneficial ET
Storage change GW being negative				• Reduce ET of managed water use • Reduce landscape ET • Reduce non-beneficial ET
Insufficient available water resources				• Decrease landscape ET and enhance their runoff and recharge • Increase transboundary net inflows • Reduce positive storage changes
Demand managed water use not met				• Increase available water resources • Reduce reserved flow • Reduce utilizable flow • Install water treatment plants • More water recycling • Increase water productivity
Committed outflow not met				• Increase available water resources • Reduce utilized flow • Increase water productivity • Reduce utilizable flow
Navigation not feasible				• Increase available water resources • Reduce utilized flow • Increae water productivity • Reduce utilizable flow
Environmental flow requirements not met				• Increase available water resources • Reduce utilized flow • Increase water productivity • Reduce utilizable flow
Flood occurrence				• Increase storage of surface water • Increase storage of groundwater • Expand utilized land use temporally • Increase ET managed water use • Increase utilizable flow
Drought occurence				• Remove water from storage (surface water and groundwater) • Decrease ET managed water use • Decreas utilizable flow • Increase water productivity • Reduce non-beneficial ET

Abundant utilizable outflow				• Increase managed water use by means of water resources development • Commit more transboundary flows
Significant flow to sinks				• Transform utilized land use to modified land use • Install water treatment plants and promote recycling
Water quality degradation				• Construct water treatment plants and recycling • Increase artificial recharge and groundwater storage
Food security threatened				• Expand agricultural land acreage by increasing area with modified land use and managed water use (ha) • Increase crop yield (kg/ha)
Insufficient environmental services				• Increase acreage conserved land use for natural heritage and habitats • Increase acreage utilized land use • More carbon sequestration • More vegetation cover variability
Economical benefits				• Increase acreage modified land use (rainfed crops, pastures) • Increase acreage managed water use (industry zones, irrigated crops, pastures) • Reduce non-beneficial ET
Unattractive living comfort				• Increase urban areas • Increase leisure (indoor, outdoor recreation, sport) • Hydropower generation from dam sites