Water Accounting Plus (WA+) in the Awash 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.

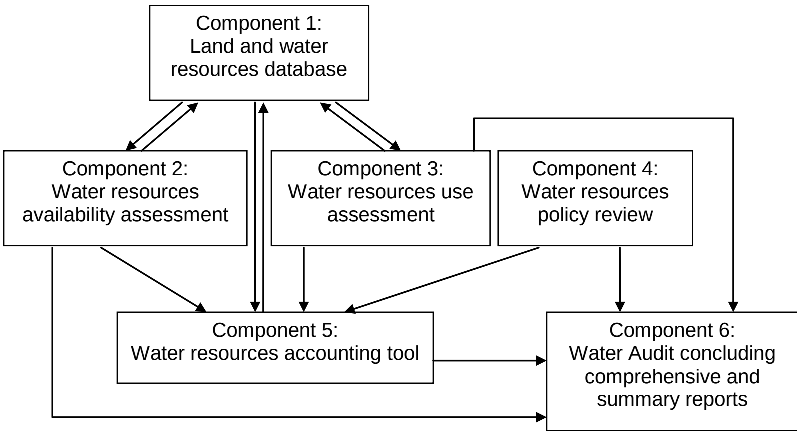


Figure 1 FAO-Water Audit project.

One of the Water Audit case studies will be implemented in the Awash 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 of the water accounts.

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 Awash 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 National Water Audit project team and other existing national water accounts, and specifically compare with the Awash River Basin Water Audit results;
- Attend two meetings, of two days each to coordinate the project and discuss results.

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 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 United Nations framework SEEAW is known to many water resources policy makers, but the significant amount of input data required refrains several entities of implementing it. 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, 2012)
- 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) (Kirby, et al., 2010).

These water accounting frameworks have been proven to be useful during specific studies, often with a strong research focus. 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. Consumptive use and return flows are ignored with misplaces a key aspect of river basins, being the upstream – downstream chain of water users.
- Most frameworks are location specific rather than universal applicable.
- Limited focus on the magnitude of intervention options by decision makers. Most frameworks present results without a differentiation between managed, manageable and non-manageable water flows.
- A link between land use and water flows is absent. This prohibits a proper planning of land resources and the role of that on the hydrological cycle.

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 (WA+) – 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; Karimi et al., 2012). WA+ is based on Remote Sensing data and will therefore be easily applicable in ungauged and poorly gauged basins.

Because of the wide variability of options, WA+ divides the river basin landscape into four main land and water groups is used:

- **Conserved Land Use**: areas where changes in land and/or water management practices are prohibited by law. Typical examples include national parks, ramsar sites etc.
- **Utilized Land Use**: areas where vegetation is basically responding to natural processes. The human interference is minimal; typical examples include forests, natural pastures, and savannas.
- **Modified Land Use**: areas where vegetation and/or soils are planned and managed by mankind, but all water flows are natural (rainfall, infiltration, runoff); typical examples include urban areas, rainfed agriculture, forest plantations.
- **Managed Water Use**: areas with water use sectors that abstract water from surface water and/or groundwater resources; 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) Evapotranspiration 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 demonstrates that every land use category has a certain surplus between rainfall (P) and ET. When P > ET applies, and area produces water that will go to streams, lakes and aquifers. When ET > P applies, a withdrawal must occur as consumptive use cannot be explained by rainfall. The withdrawal can be manmade with diversion dams, pumping stations etc, or it can occur naturally by seepage zones or inundation of rivers.

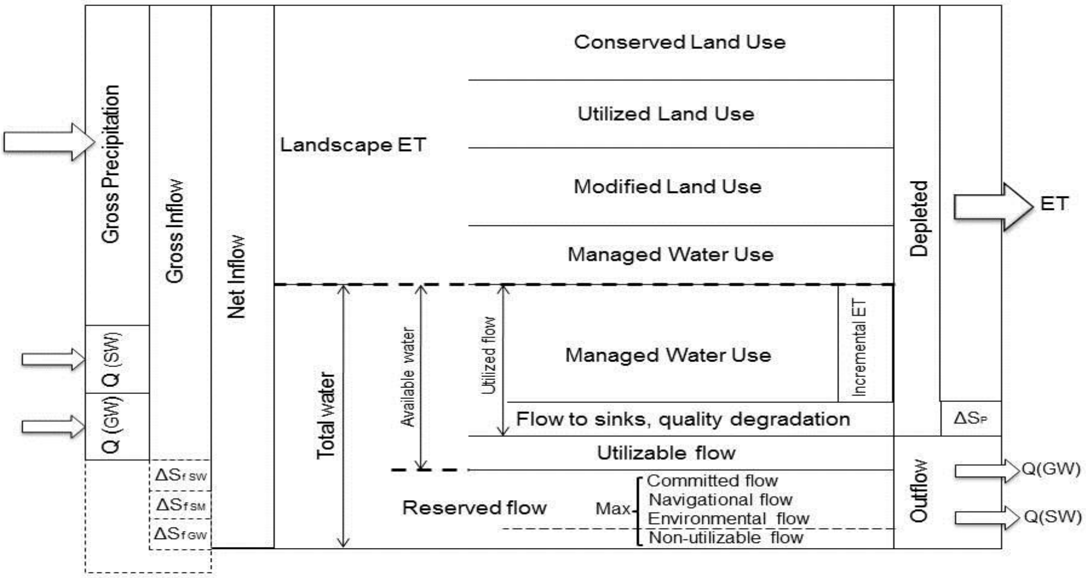


Figure 2 Water Accounting Plus: Resource Base Sheet (sw = surface water, sm = soil moisture, gw = groundwater, ΔSf = storage of fresh water, dSp = storage of polluted water), see Karimi et al. (2012)

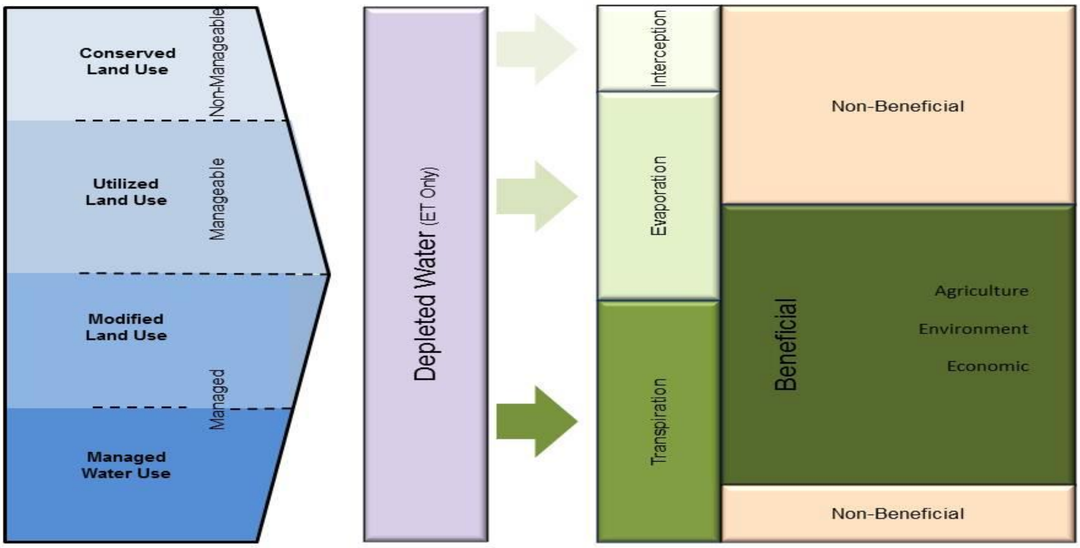


Figure 3 Water Accounting Plus: Evapotranspiration Sheet.

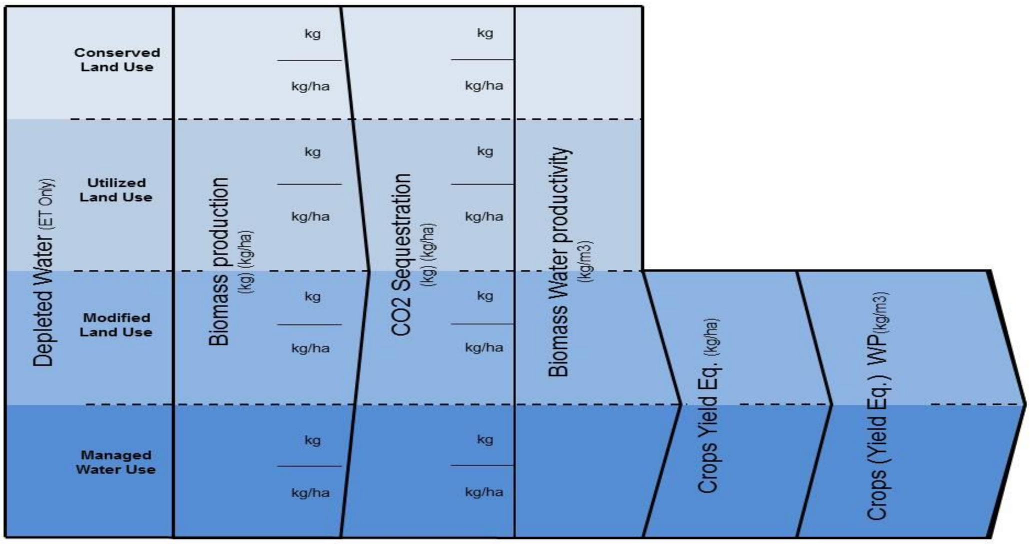


Figure 4 Water Accounting Plus: Productivity Sheet.

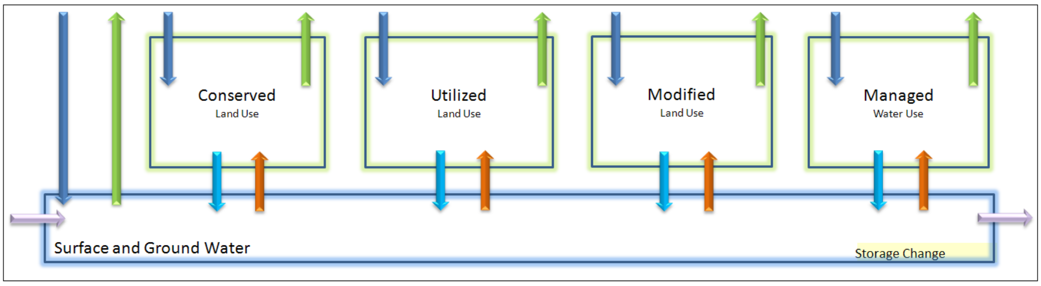


Figure 5 Resource Base calculation framework.

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. These indicators have been defined in consultation with the Land and Water Division of FAO. They are not necessarily identical to the indicators proposed by Karimi et al. (2012).

The first set of indicators can be related to the Resource Base Sheet:

- 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) = Total Water – 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 are 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 value.

- 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 Awash River Basin

Ethiopia is a landlocked country in the horn of Africa. With over 82 million inhabitants, it is the second-most populated nation in Africa. Ethiopia is often referred to as the "water tower" of Eastern Africa because of the many rivers that pour off the high tableland. It has the greatest water reserves in Africa, but only 1.5% of this is used for irrigation, the main farming systems are rainfed. (Wikipedia, 2012)

At approximately 50% of the GDP, agriculture, contributes by far the largest part of the economy and is currently growing on average 5% per year. Ethiopia has an estimated 3.7 million hectares of irrigable land, yet only about 200,000 hectares (5.4%) is presently irrigated and only provides approximately 3% of the country's food crop requirements (Taddese, 2012). Most of the irrigation developed to date in Ethiopia is located in the Awash basin.

The Awash River starts in Central Ethiopia and flows to Lake Abbe on the border with Djibouti. It is the 4th largest river basin in Ethiopia. The river is approximately 1200 kilometers long and tributaries include the Logiya, Mille, Borkana, Ataye, Hawadi, Kabenna and Durkham Rivers (Wikipedia, 2012). The Awash River basin (Figure 6) is according to the watershed boundaries 116,449 km^2 large. According to FAO, Awash has a mean annual runoff of 4.6 km^3 resulting in an irrigation potential of 205,400 hectares (FAO, 1997). It is an example of a closed drainage basin, hence outflow does not occur. The ultimate destination of Awash river is Lake Abbe at the border with Djibouti. It is one of a chain of six connected salt lake (Gargori, Laitali, Gummare, Bario and Afambo). Lake Abbe has an average size of 34,000 ha open water, surrounded by 11,000 ha of salt flats. The area is shrinking during dry years. The water level can drop up to 5 meters. The maximum depth is 36 m.

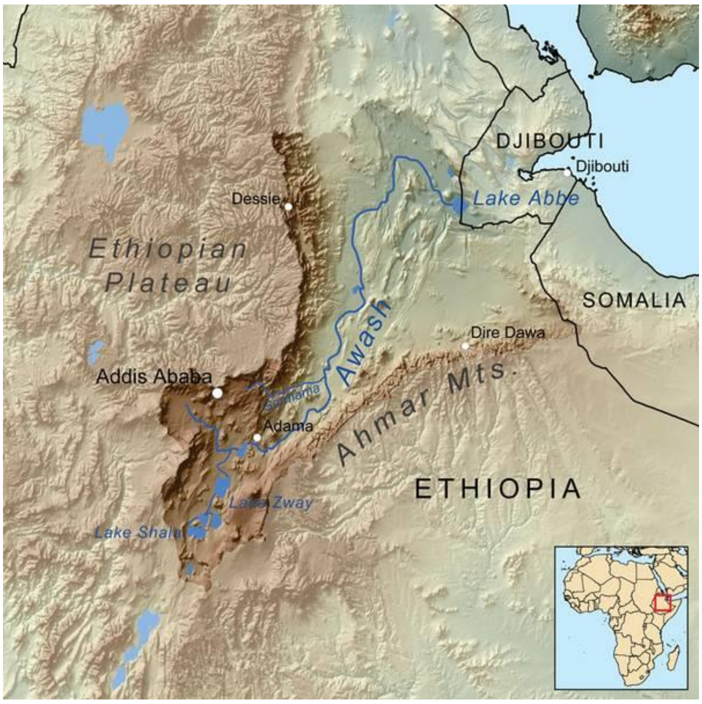


Figure 6 Awash River Basin (Wikipedia, 2012).

4 Spatial data

4.1 Land use

A new land use product customized for applying the Water Accounting concept in the Awash basin was generated from various sources. The emphasis on the new classification was on the separation of rainfed and irrigated agriculture.

4.1.1 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/jpg/ag/dl/forschun/MIRCA/index.html). MIRCA contains data from the 1999 – 2002 period and has a spatial resolution of 5 arc minutes (± 10 km). The maximum cropped area is defined as the sum of the maximum monthly growing areas for all rainfed crops. The total area identified with rainfed agriculture for the Awash basin is 920,717 ha (figure 7).

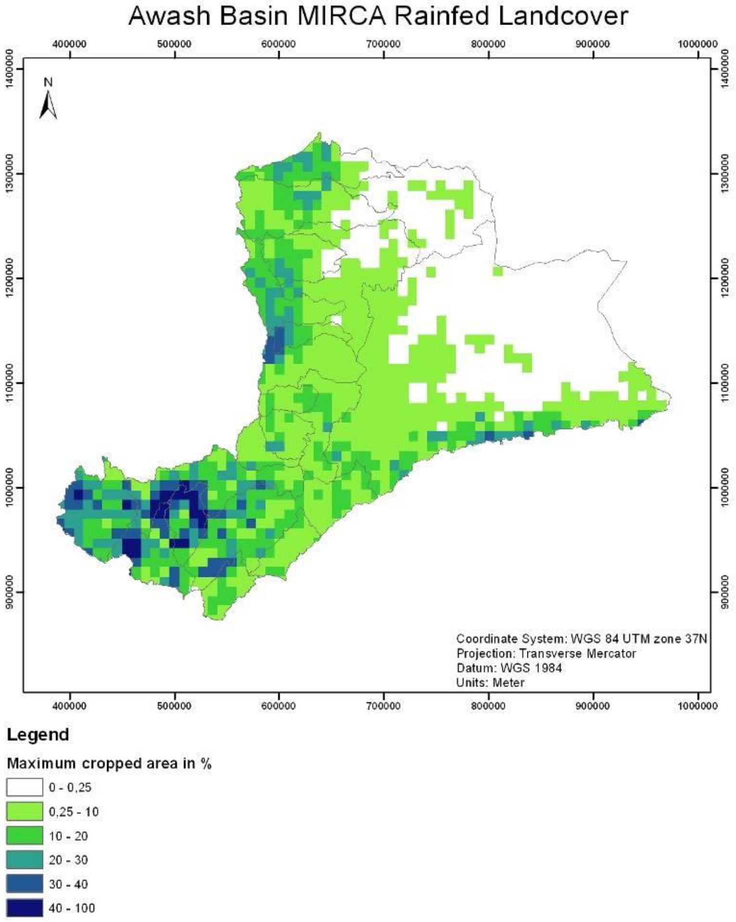


Figure 7 Displays an excerpt of the global MIRCA maximum cropped area for the Awash basin.

4.1.2 GAEZ

The International Institute for Applied Systems Analysis (IIASA) and FAO have been developing the Agro-Ecological Zones methodology over the last 30 years and this information has been available in the Global Agro-Ecological Zones (GAEZ) database. The GAEZ database provides information on rainfed cultivated land at a spatial resolution of 5 arc-minute (± 10 km). For the land cover rainfed cultivated land an iterative procedure of remote sensing data and geographic datasets were used and the procedure is documented at http://gaez.fao.org/Main.html. The area identified with rainfed agriculture for the Awash basin is 2,182,894 ha (figure 8), two times more as found for MIRCA.

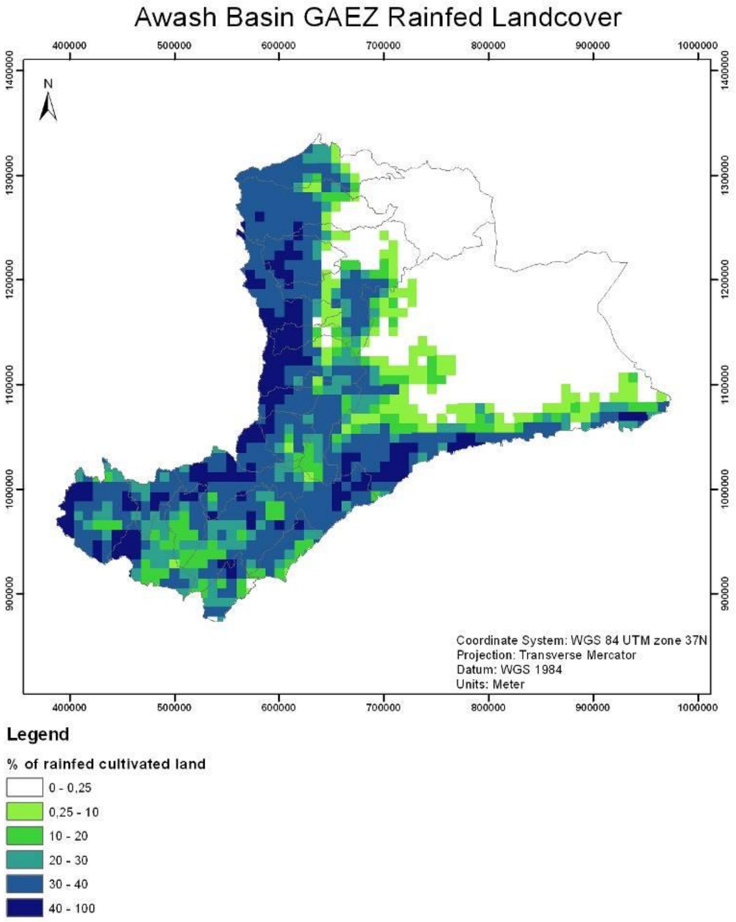


Figure 8 Percentage of rainfed cultivated land for the Awash basin from GAEZ.

4.1.3 MoA

A land cover map for the Awash basin was produced during the development of the agro-ecological map of Ethiopia by the Ministry of Agriculture and Rural Development (MoA) and FAO. This map was produced in 2000. The total area defined as intensively and moderately agriculture is 3,036,431 ha (figure 9).

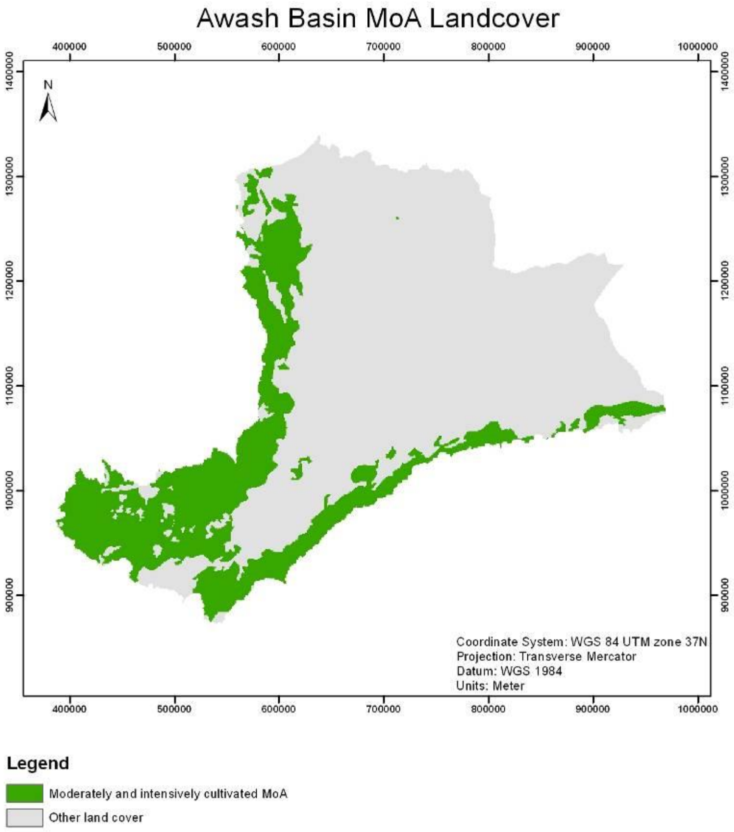


Figure 9 Moderately and intensively cultivated areas from MoA for the Awash basin.

4.1.4 GlobCover

GlobCover was used to identify pixels being classified as rainfed croplands, mosaic cropland/vegetation and mosaic vegetation/cropland. These classes were merged into one single class rainfed croplands. The total area for the Awash basin classified as rainfed cropland after merging the aforementioned classes is 2,330,300 ha (figure 10), a value more in tune with GAEZ.

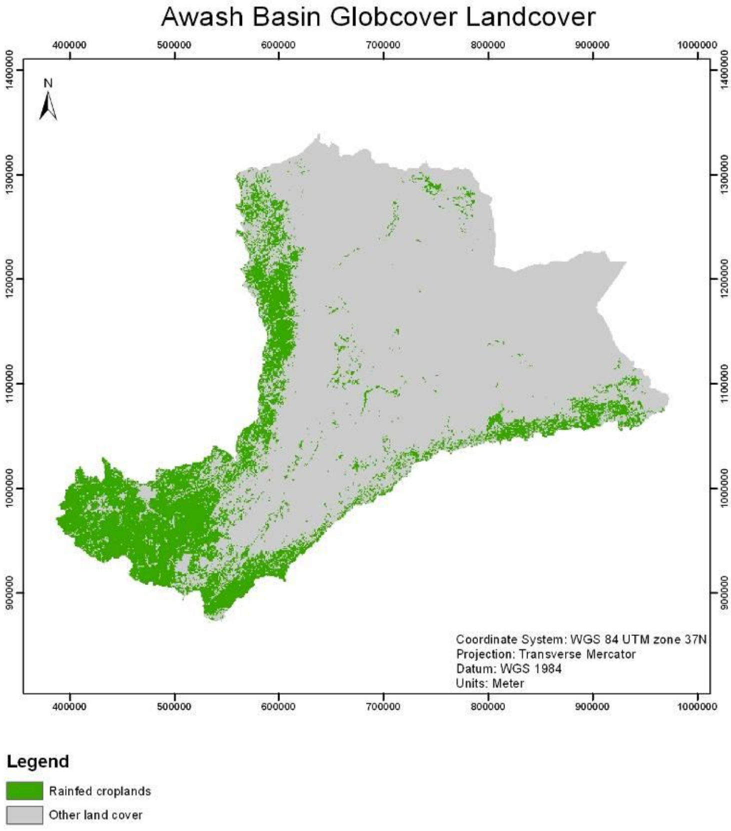


Figure 10 Rainfed croplands from Globcover for the Awash basin.

4.1.5 NDVI

In addition to existing spatial datasets on rainfed crops, NDVI information was analyzed to depict areas that might be classified as cultivated lands during the rainy season from May until November 2009. For this purpose, NDVI composite products reflecting time increments of 8 days and 250 m pixel detail were used to calculate the accumulated NDVI for the rainy season of 2009. Areas displayed as cultivated in MIRCA, GAEZ, MoA and Globcover datasets were singled out to calculate the average accumulated NDVI and standard deviation. An average of 12.5 and a standard deviation of 2.0 were used to set the range of 10.5 to 14.5 to redefine the rainfed cropland using the accumulated NDVI value for the rainy season. The total area identified as cultivated for the Awash basin is 2,706,300 ha (figure 11).

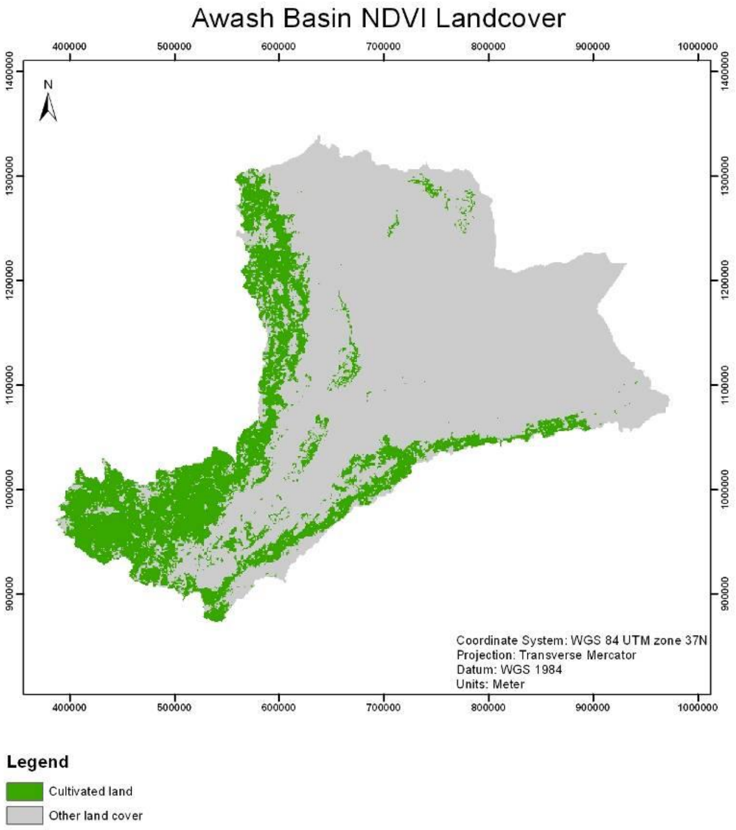


Figure 11 Cultivated lands from the accumulated NDVI for the rainy season 2009.

4.1.6 Final land use product

Table 1 presents the total area for irrigated crop lands from different sources. The information of MIRCA and MoA present the smallest and highest estimations, respectively. Estimations of GMEZ, Globcover and NDVI are of the same order of magnitude but the information on rainfed croplands presented on the Globcover data contains the most recent data as well as having the highest level of spatial detail. Therefore, the combination of NDVI sum and Globcover has been selected as the best source of information for describing irrigated crop land in the Awash basin.

Table 1 Total area for irrigated crop lands

Source	Hectares
MIRCA	920,717
GAEZ	2,182,894
MOA	3,036,431
Globcover	2,330,300
NDVI	2,706,300

The irrigated dataset was provided by FAO based on GMIA data and field information from FAO projects. Figure 12 shows the resulting locations of irrigated and rainfed croplands in the Awash basin. The area of irrigated croplands is 216,900 ha and the area of rainfed croplands is 2,258,500 ha. The irrigated acreage is close to the irrigation potential of 205,400 ha, which suggests that most potential land is exploited already.

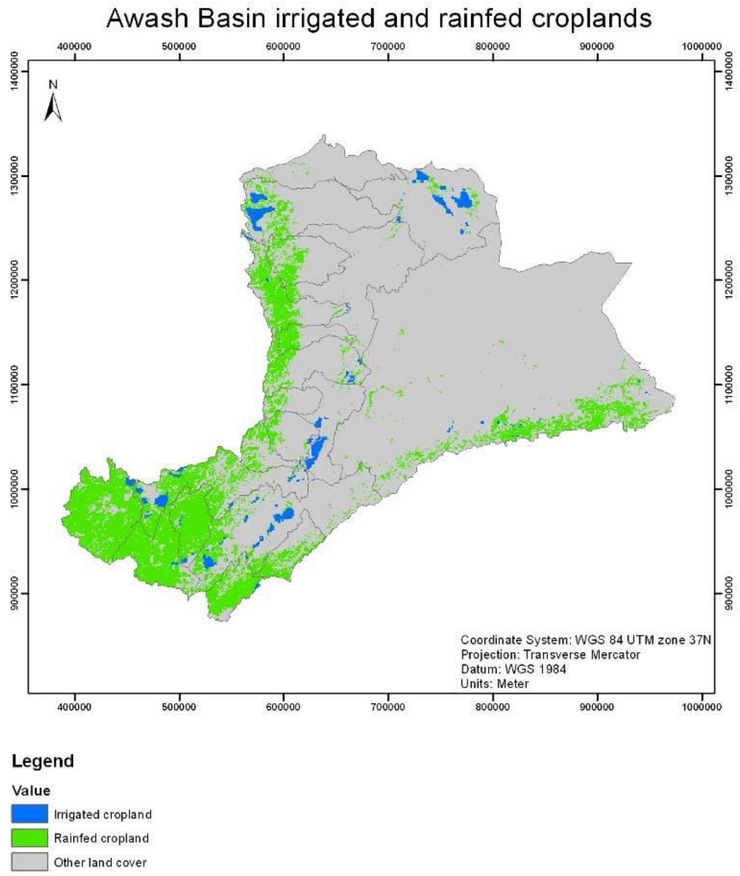


Figure 12 Locations of rainfed (green) and irrigated (blue) crop lands in the Awash basin.

The difference between the Globcover and the combined rainfed and irrigated map can be explained by the definition of irrigated crop lands in surveys reports. Areas equipped for irrigation are defined as irrigated crop land for FAO and in the Globcover might be defined as rainfed crop lands. The final land cover product is presented in Figure 13.

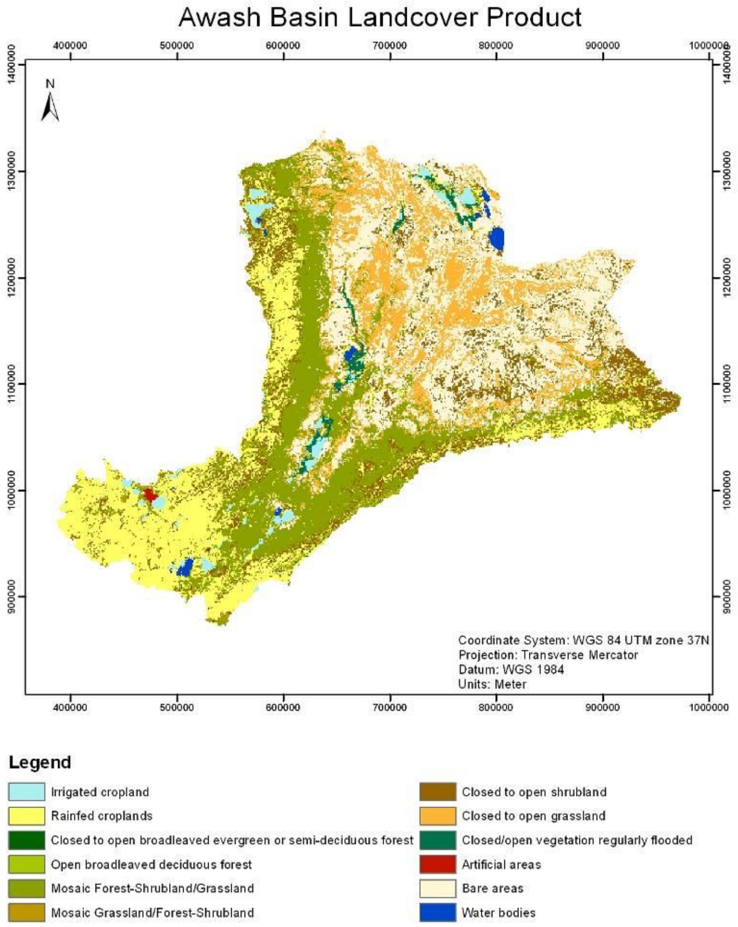


Figure 13 Combined land cover classification used for WA+ in the Awash basin

4.2 Precipitation

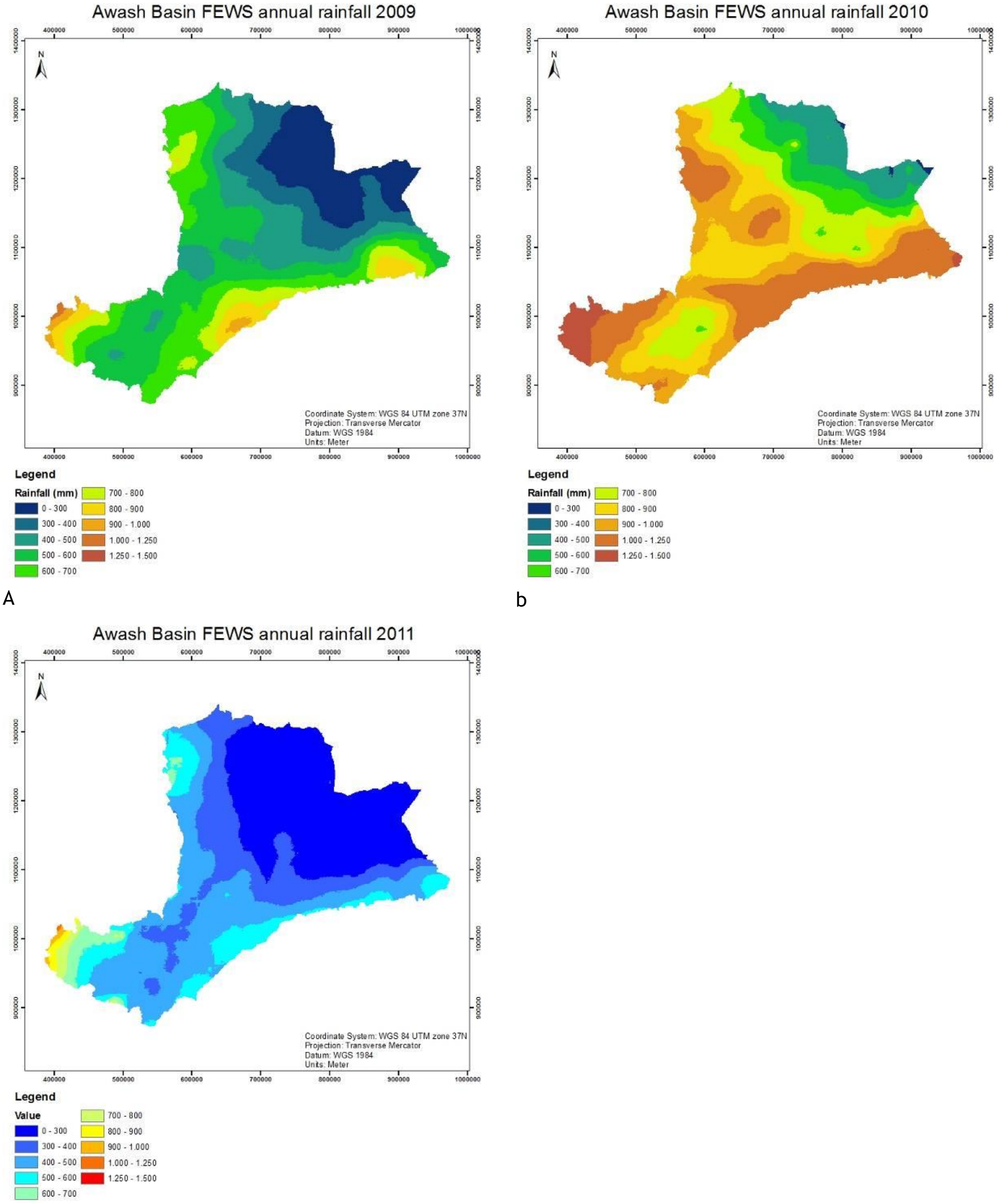
Daily rainfall data were obtained from the U.S. Agency for International Development (USAID) Famine Early Warning Systems Network (FEWS NET). This is an information system designed to identify problems in the food supply system that potentially lead to famine or other food-insecure conditions in sub-Saharan 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 uncalibrated 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.

Table 2 Annual average precipitation in the Awash basin according to FEWS rainfall data. The data has not been calibrated against measured rain gauge data

Year	Precipitation (mm)		
	Mean	Min	Max
2009⁽¹⁾	515	122	1086
2010	865	332	1503
2011	366	81	1043

(1) 2009 refers to the year (1-Jan-2009 to 31-Dec-2010)

The year 2009, 2010 and 2011 (figure 14) were identified as average, wet and dry years respectively, the values are summarized in Table 2.



A

b

C

Figure 14 FEWS annual rainfall in the Awash basin for the years 2009 (a), 2010 (b) and 2011 (c).

4.3 Air temperature, wind speed and relative humidity

The meteorological input parameters air temperature, wind speed and relative humidity were based on METEOLook outputs. METEOLook uses point measurements from ground meteorological stations to generate a distribution of the aforementioned variables based on flux profiles relationships, regression analysis to elevation, radiation, vegetation index, distance to the sea and a geo-statistical distribution method. Figure 15 presents the average air temperature for the year 2009 and shows the location of the 28 meteorological stations used in this study.

4.4 Atmospheric transmissivity

Valus for the 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 solar radiation data is available starting May 2005, on a spatial resolution of 1 km x 1 km at the equator, and 3 km x 3 km in Europe.

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, and their standard datasets have been used. The same data archive provides also 8-daily albedo products. The albedo and NDVI data has a spatial resolution of 1 km x 1 km.

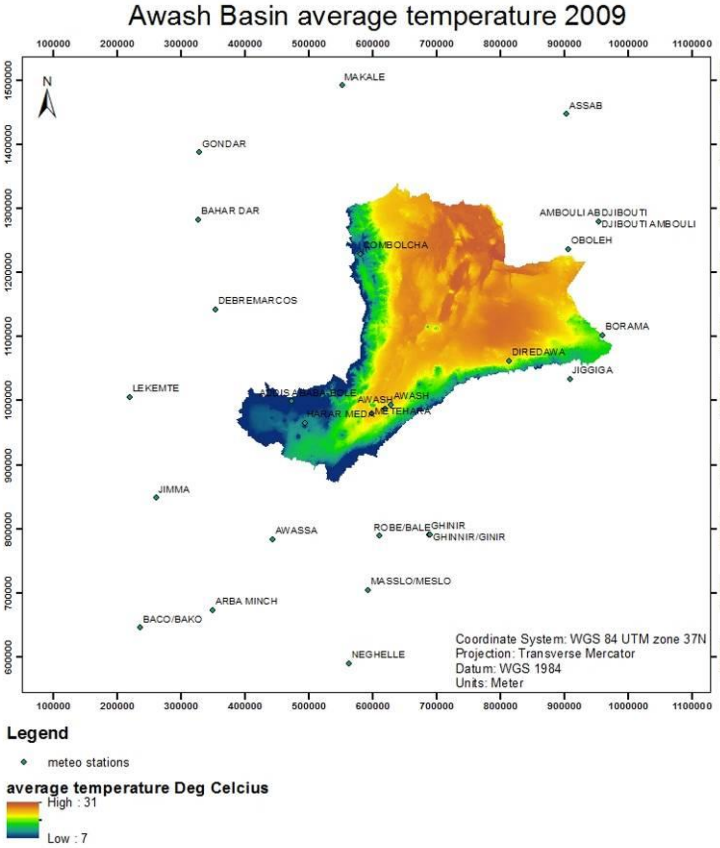


Figure 15 Average air temperature in the Awash river basin over the year 2009. Green dots indicate locations of measurement stations.

4.6 Soil moisture

Surface soil moisture was collected by the Advanced Scatterometer (ASCAT) on board the meteorological operational (MetOp) satellites. ASCAT soil moisture data are produced daily with a spatial resolution of 12.5 km. Daily ASCAT soil moisture data were averaged for the 8 day period. This information was used to calculate the soil resistance of the top soil and subsoil moisture, both inputs of ETLook and important to calculate the evaporation of the soil.

5 Satellite Derived Actual Evapotranspiration

5.1 ETlook

ETLook is an algorithm developed by WaterWatch (Pelgrum et al., 2010; Bastiaanssen et al., 2012) 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 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 16 illustrates the main concepts of ETLook. A pixel is divided in two compartments. One component describes the physical processes in the canopy, and the other component the soil physical processes. 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 of the atmosphere is used to determine the actual amount of incoming solar radiation that reaches the land surface. The Leaf Area Index(LAI) is used to partition the total net radiation Q* into the soil and canopy part. The energy dissipation associated with the interception evaporation of wet leaves is taken into account.

The Penman-Monteith equation has a few key resistances that need to be solved for every pixel. The soil resistance (r_{soil}) describes the process of soil evaporation and the canopy *resistance* r_{canopy} is the major regulator for the actual transpiration process. The turbulent processes for the transport of water vapor and heat in the lower part of the atmosphere are governed by the aerodynamic resistance r_a, and r_a is solved separately for soil and canopy (see equation above). This approach enables ETLook to compute transpiration T, soil evaporation E, as well as the interception evaporation from wet leaves. The evaporation for water bodies is computed with a Penman type of equation, taking into account the annual cycle of heat storage changes.

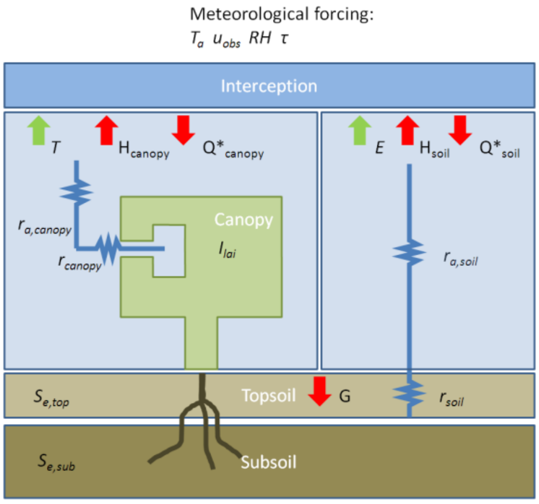


Figure 16 Overview ETLook algorithm.

The outputs of ETLook consist of reference evapotranspiration ET_0, actual and potential transpiration T_{act} and T_{pot}, actual evaporation E_{act} for soil, water and wet leaves. Interception is computed as a function of the Leaf Area Index (LAI) and the number of rainfall days. 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.

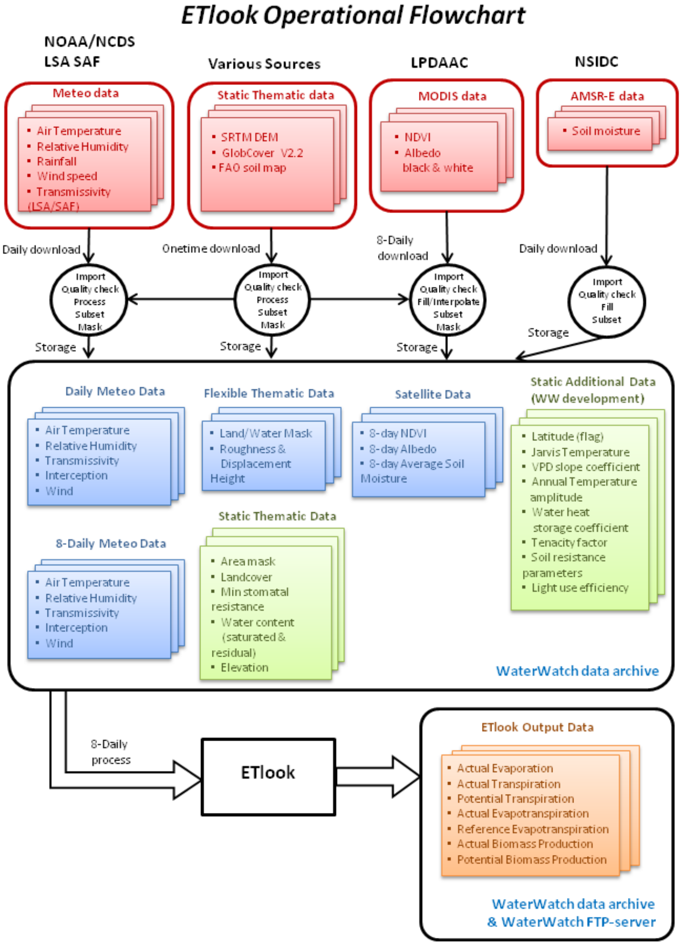
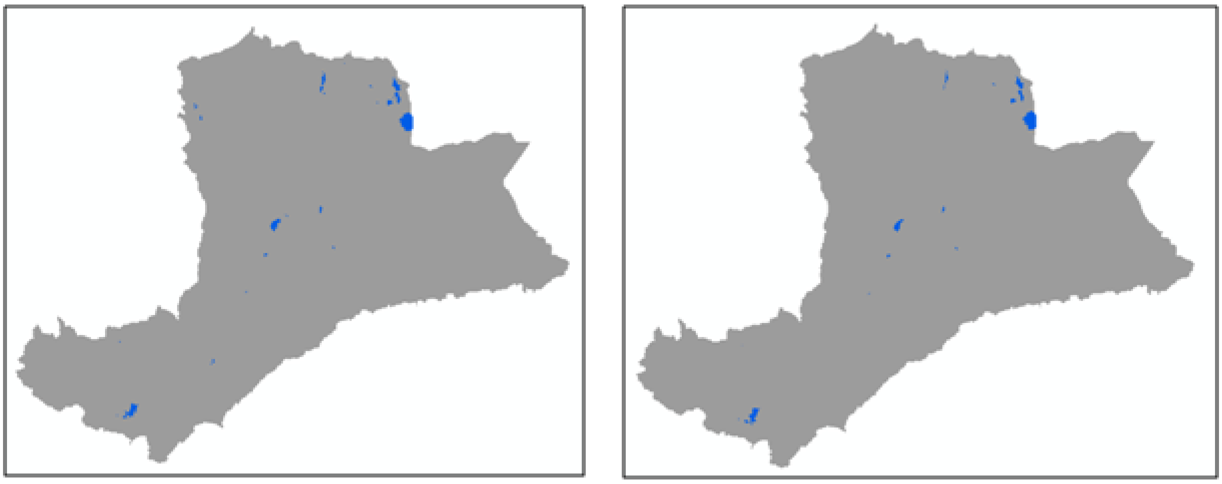


Figure 17 ETLook flowchart.

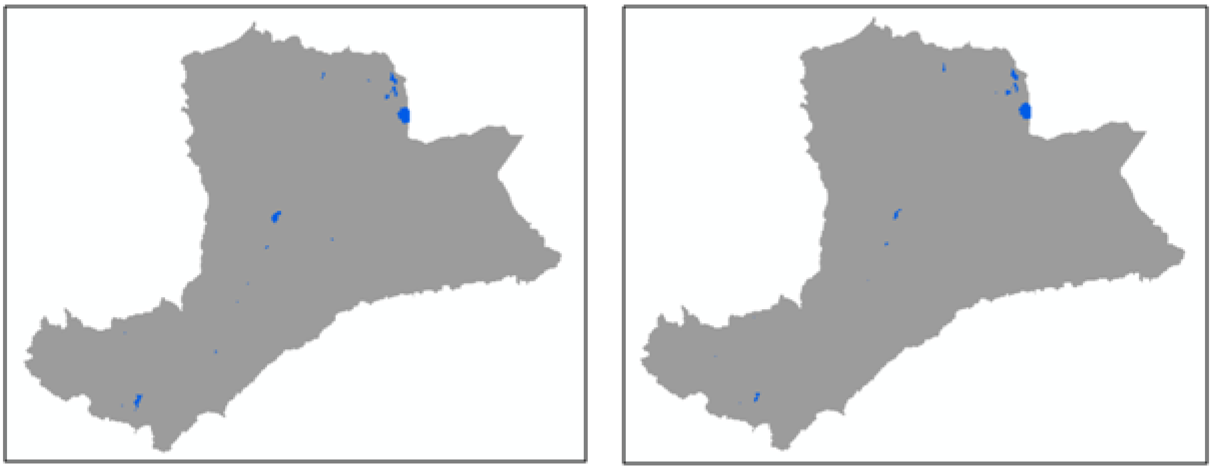
5.2 Adjustments to the general ETLook procedure

The ETLook structure for the Awash basin included some adjustments to ensure the quality of the estimations as illustrated in ETlook flowchart (figure 17). The variation of water bodies during the different years was taken into account for improving the estimations of evapotranspiration. In every time step the MODIS NDVI and albedo products were used to spatially map the extent of the water bodies for each 8 day period. In figure 18 differences on the water bodies are depicted through the year 2009 for the sake of demonstration. The variability can be ascribed to changes in catchment rainfall, river flows and the lake evaporation rates.



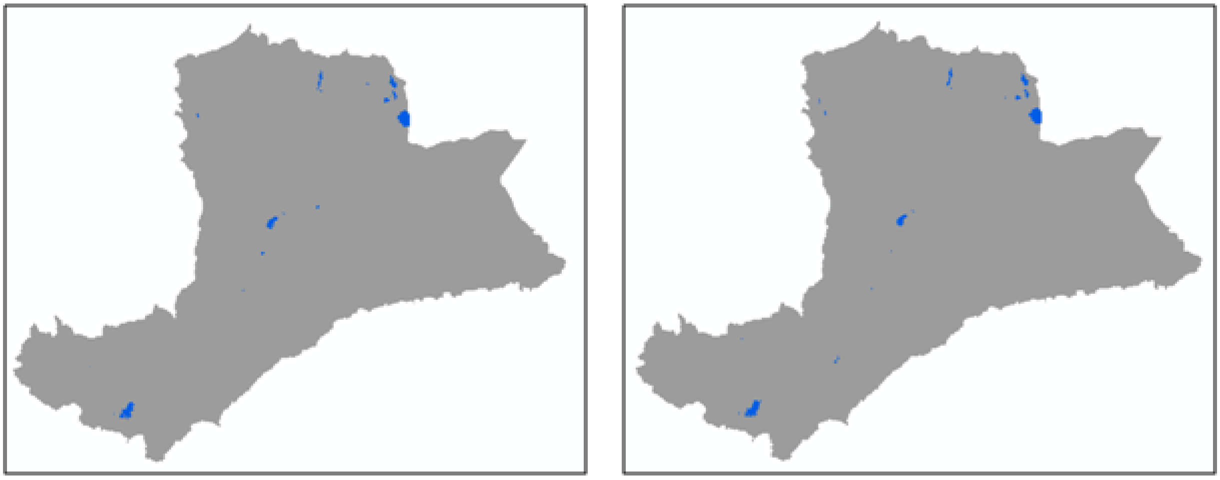
January 2009

March 2009



May 2009

July 2009

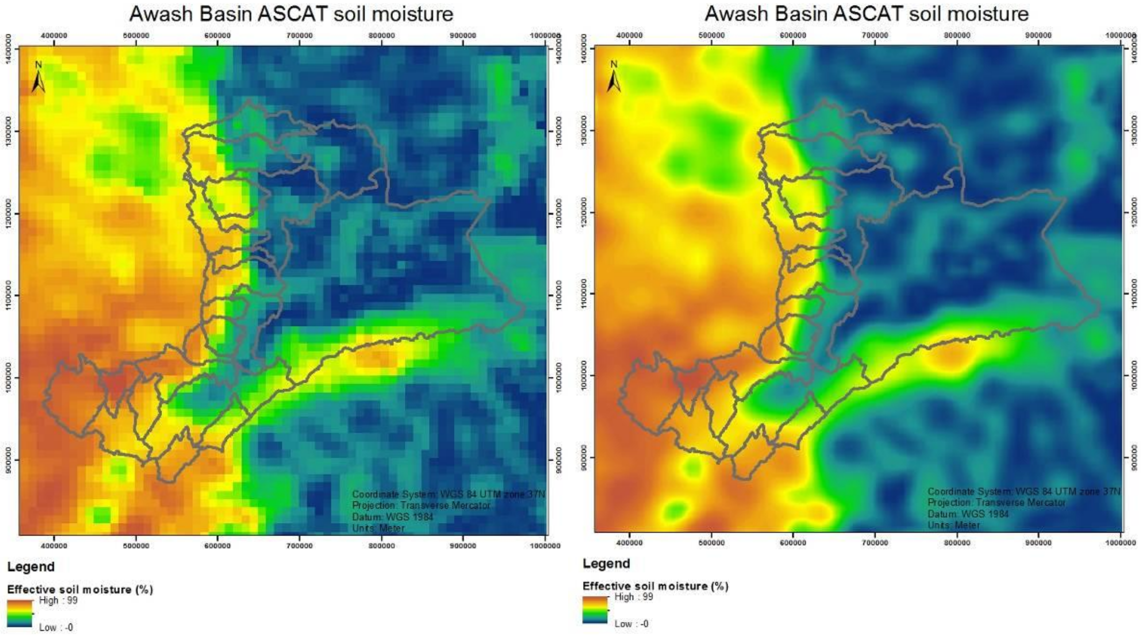


September 2009

November 2009

Figure 18 Water bodies distribution for the year 2009.

ASCAT soil moisture data were resampled from 12.5 km to 1 km to match the spatial resolution of the project. In order to keep the spatial information and reduce the coarse patterns depicted in the original ASCAT 12.5 Km dataset, a bilinear interpolation was implemented for the ASCAT data. This procedure does not affect the model outcome for the overall water balance of the basin, but enhances the spatial information of soil moisture as depicted in figure 19.



A

B

Figure 19 Effective ASCAT soil moisture for the 8 day period 05/08/2009-12/08/2009. Prior bilinear interpolation (a) and after bilinear interpolation (b).

In order to increase the accuracy of ETLook, the soil resistance and canopy resistance were adjusted for the basin. The soil resistance was adjusted to acquire a realistic relationship between soil moisture and soil evaporation. An iterative procedure was carried out to calibrate two empirical parameters for r_{soil}. The minimum stomatal resistance was adjusted for each land cover type of the basin.

Based on the temporal resolution of the input data, ETLook ran on a temporal resolution of 8 days per time step and a spatial resolution of 1 km for the selected years. The model produced daily values on biomass production, evaporation, transpiration and evapotranspiration, among other variables. This information was averaged for 8 day periods and then summed for the years 2009, 2010 and 2011.

5.3 Results

Table 3**Error! Reference source not found.** presents the ET data in relation to the corresponding amount of rainfall for each hydrological year. Neither the rainfall, nor the ET data has been calibrated against in site measurements. The average rainfall for these 3 years is 582 m/yr, while the average ET is 507 mm/yr. These numbers are entirely based on remote sensing technologies. The standard deviation of the rainfall is with 256 mm substantially larger than the standard deviation of ET (41 mm). The magnitude of ET is apparently dampened, which is likely to be related to compensating effects of atmospheric demand and soil moisture availability. Dry years have a higher potential ET, but the ET reduction due to soil moisture stress is higher also, and these two phenomena partially compensate each other yielding to temporal stable ET rates. Dry years can consume water carried over from a previous wetter year, so this is physically possible.

Many national and international sources report a mean annual surface runoff of 4.6 km^3/yr for Awash basin. This data is based on measured discharge rates. These exploitable surface water resources are internally re-distributed among irrigation systems, wetlands, inundation areas and lakes. The annual flow at the Awash station in the middle of the basin is lower (0.4 to 0.8 km^3/yr) than the flow rate at the escarpments at the upstream end. The non-utilized water from Awash river flows into the saline depressions at the downstream end of the basin, and gets subsequently evaporated. The year 2009 was the average rainfall year of this study, and for 2009 the total evaporation from all natural lakes was 622 Mm^3/yr, while the rainfall over these lake areas is 278 Mm3/yr. This difference of 344 Mm^3/yr is to a large extent the rest flow of the network of streams. Hence, most (93%) of the renewable surface water resources have been consumed, and the remaining 7% evaporates from lakes and sinks (brines and salt flats). This finding reflects that Awash basin is consuming most of its surface water resources (this remark does not apply to groundwater resources).

Table 3: Annual total precipitation and ET averaged for the Awash basin during 2009, 2010 and 2011. Rainfall and ET data are based on remote sensing. The actual evapotranspiration is partitioned into Evaporation, Transpiration and Interception.

Year	Rainfall	ET	Interception	Evaporation	Transpiration	Biomass production
	(mm)	(mm)	(mm)	(mm)	(mm)	(kg/ha)
2009	515	480	18	310	152	5744
2010	865	554	26	308	220	8570
2011	366	486	18	293	175	6455
Average	582	507	21	304	182	6923

Hence, all river flow is evaporated inside the basin and thus included in our total ET value of 507 mm that reflects the entire basin area (i.e. all land use classes, wetlands and water bodies). Hence, the difference of 75 mm (582 – 507 mm) or 8.7 km^3/yr is not related to surface runoff, but must go somewhere else. The closed drainage basin features arising from the volcanic formations surrounding the downstream salt lakes suggests that surface outflow does not occur. The only possible outlet is basin discharge via the underground. Taddese, Kai and Pedon provided a few sources on groundwater recharge: According to their paper published by ILRI, UNDEP (1973) estimated the total groundwater recharge in Awash to be 3.8 km^3/yr, while EDSA (1989) estimated 4.1 km^3/yr. Ayenew et al (2008) reported a basin wide average recharge value of 30 mm, which is equivalent to 3.5 km^3/yr. The average number is 3.8 km^3/yr, and we will use this number in the subsequent water balance computations.

There is an unexplained difference between 8.7 km^3/yr outflow and a groundwater recharge of 3.8 km^3/yr. The upstream end of the basin has an elevation of 2200 m where the majority of the rainfall and recharge occurs. The soils and geological formations are permeable. Groundwater flows towards the downstream end of the basin at Lake Abbe, where the elevation is 240 m only. Ayenew et al. (2008) suggest a regional groundwater flow into the direction of the Afar Depression. A total of 8.7 km^3/yr corresponds to 23 Mm^3/d, which for a basin width of more than 300 km and a hydraulic gradient of 0.005 m/m is physically feasible. An amount of 3.8 km3/yr or 10 Mm^3/d is however more likely. We therefore assume that interbasin outflow into the sea and other depressions located outside the basin occurs. The amount is more likely related to the 3.8 than to the 7.8 km^3/yr.

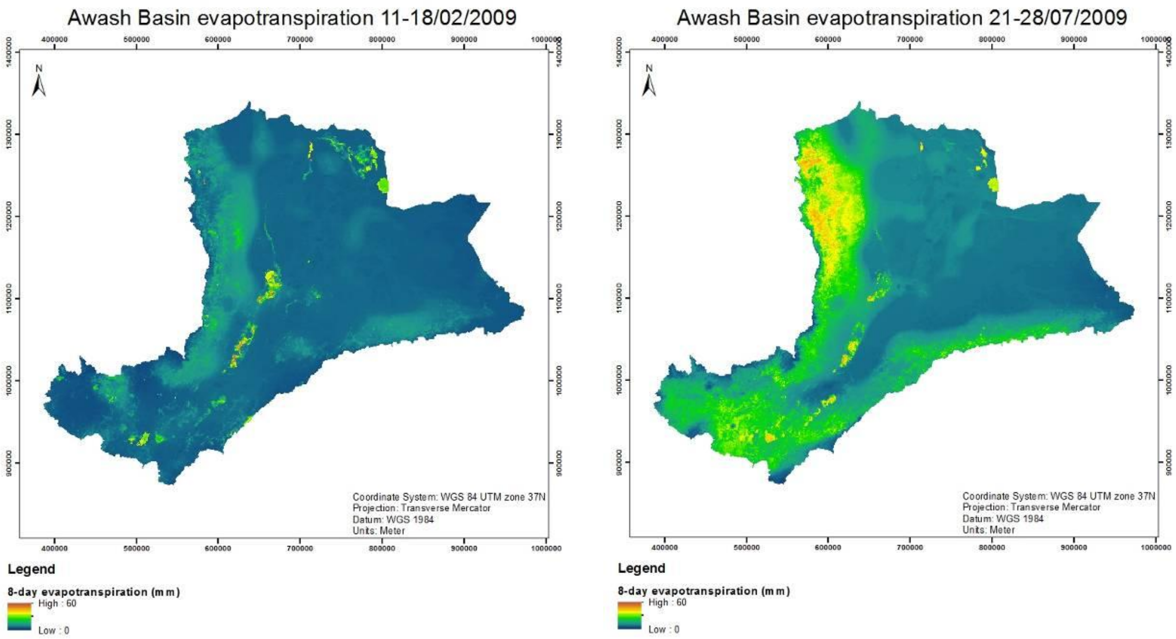
While the 3.8 km^3/yr can be considered as underground interbasin transfer, the remaining 4.9 km^3/yr needs more discussion. One possibility is that a positive storage changes occurs during the 3 years investigated, mainly due to the rather non-occasional wet year 2010 where abundant recharge must have taken place and water levels must have risen. An amount of 4.9 km^3/yr would be equivalent to 42 mm, or a rise in water levels of 42 to 60 cm (specific yield 0.1 to 0.15). This is physically feasible. It also feasible that rainfall is overestimated by 42 mm. At an average rainfall of 582 mm, this would imply an error of 7%. Without calibration of FEWS-NET, this is certainly within the range of uncertainty. ET can be underestimated as well, although new literature (Karimi et al., 2013) suggests that rainfall from satellites is generally less accurate than ET from satellites.

Since groundwater flow is usually rather stationary, the difference between rainfall and ET would not translate immediately into interbasin transfer. A quasi-steady state basin outflow is acceptable, but only with limited fluctuation that reflect storage changes (see Table 4). One of the major principles that we have decided upon, is that the longer term basin outflow is assumed identical to the longer term groundwater recharge. We have assumed further – without scientific underpinning computations – that the basin outflow should respond to changes in storage. A 50% change was assigned (see Table 4). The storage changes among years must be significant, and this is also reported by changing water levels in lakes and reservoirs. These storage changes physically occur in the modifications of the lake and reservoir volumes, as well as in the aquifers that can be thick in the Awash Basin. This analysis shows that water accounting studies should cover multiple years for gaining a more comprehensive understanding of the water flows.

Table 4 Annual water balance of Awash basin for the selected hydrological years. The basin area is 116,449 km^2

Year	Rainfall	ET	Basin outflow	Storage change
	(km^3)	(km^3)	(km^3)	(km^3)
2009	59.8	56.4	3.8	-0.4
2010	100.5	65.1	5.7	+29.7
2011	42.4	57.2	2.5	-17.3
Average	67.6	59.6	3.9	4.1

Another interesting observation is that soil and water evaporation (304 mm) exceed transpiration (182 mm). The relative low values of e.g. interception, transpiration and biomass production can be explained by the reduced fractional vegetation cover, especially during the dry season. A large portion of the basin has barren land. Figure 20 displays the spatial distribution of the accumulated evapotranspiration values for a typical 8-day period in the dry (11/02/2009 - 18/02/2009) and wet (21/07/2009 – 28/07/2009) period of the Awash hydrological year. For the same periods, figure 21 show the contribution of evaporation and figure 22 of transpiration. The ETLook results show that transpiration from the vegetation in the Western and Southern part of the basin and the irrigated croplands are the major contributing factor to evapotranspiration in the river basin during the dry winters. During the raining season, transpiration is higher in the same regions due to the increased growth of vegetation. This is evidenced by the increase in biomass production visible in figure 23. On the eastern plains, evaporation values rise as the soil fill up with water during the wet summer period, while the transpiration remains low due to the low vegetation cover.



A

b

Figure 20 Evapotranspiration during a 8 day period in the dry (a) and wet (b) season.

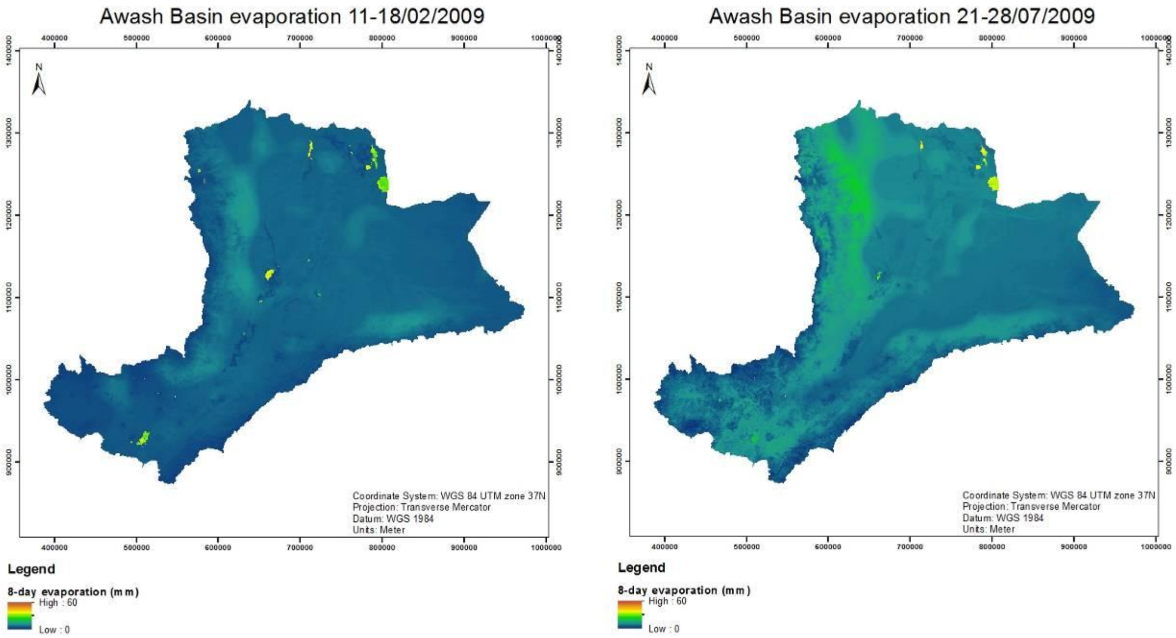


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Figure 21 Evaporation during a 8 day period in the dry (a) and wet (b) season.

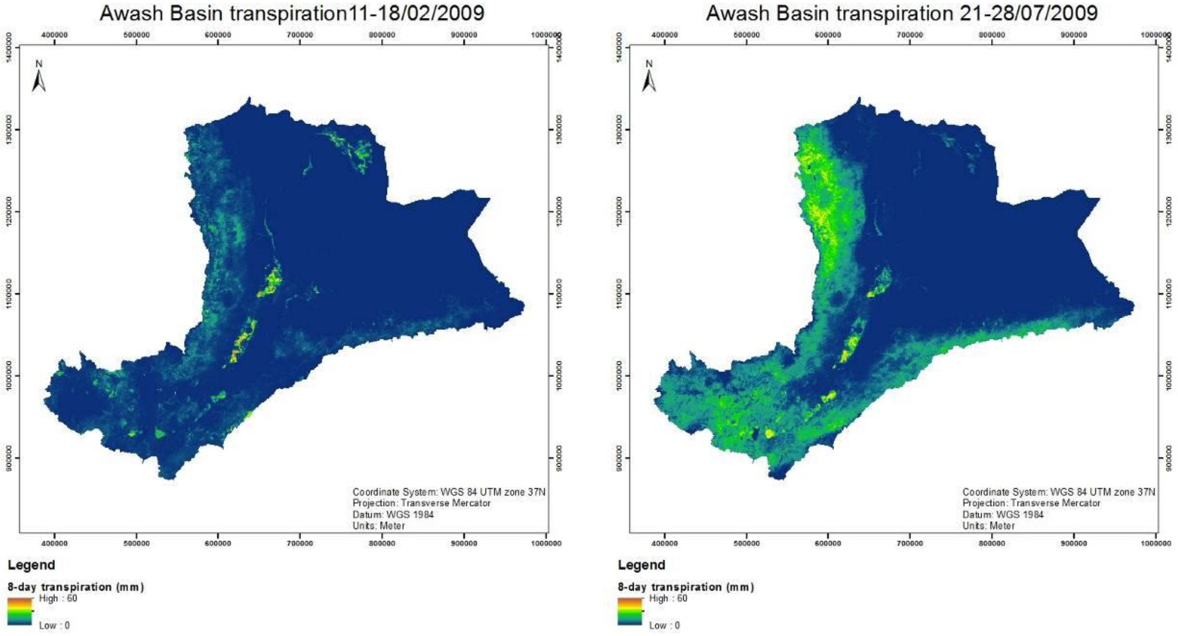

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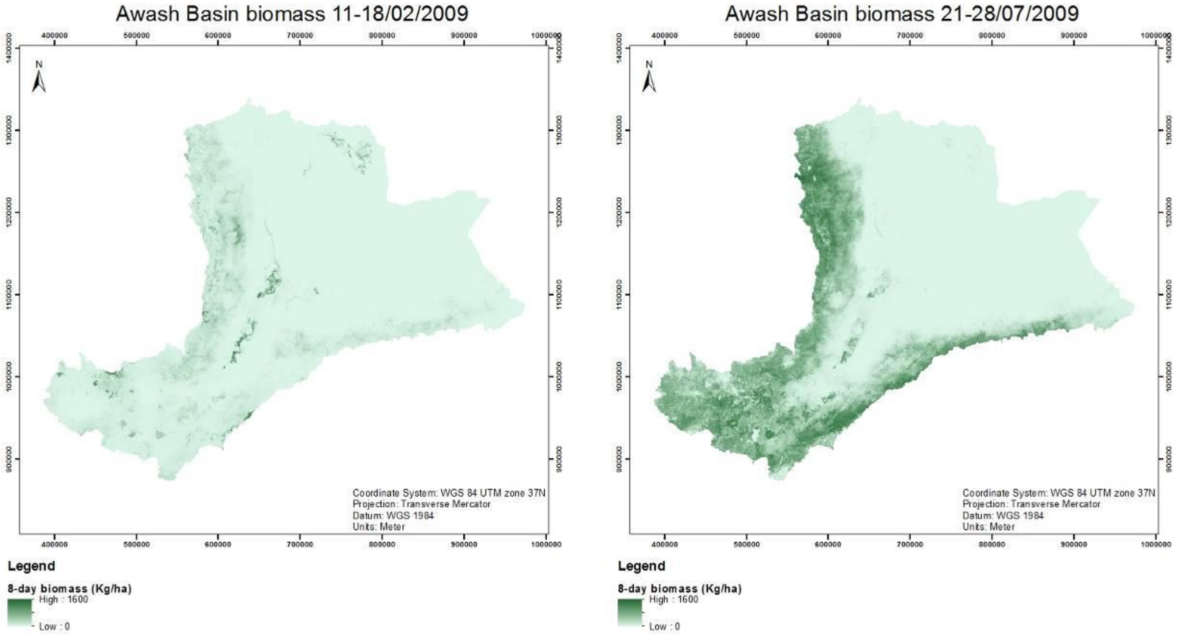
Figure 22 Transpiration during a 8 day period in the dry (a) and wet (b) season



A

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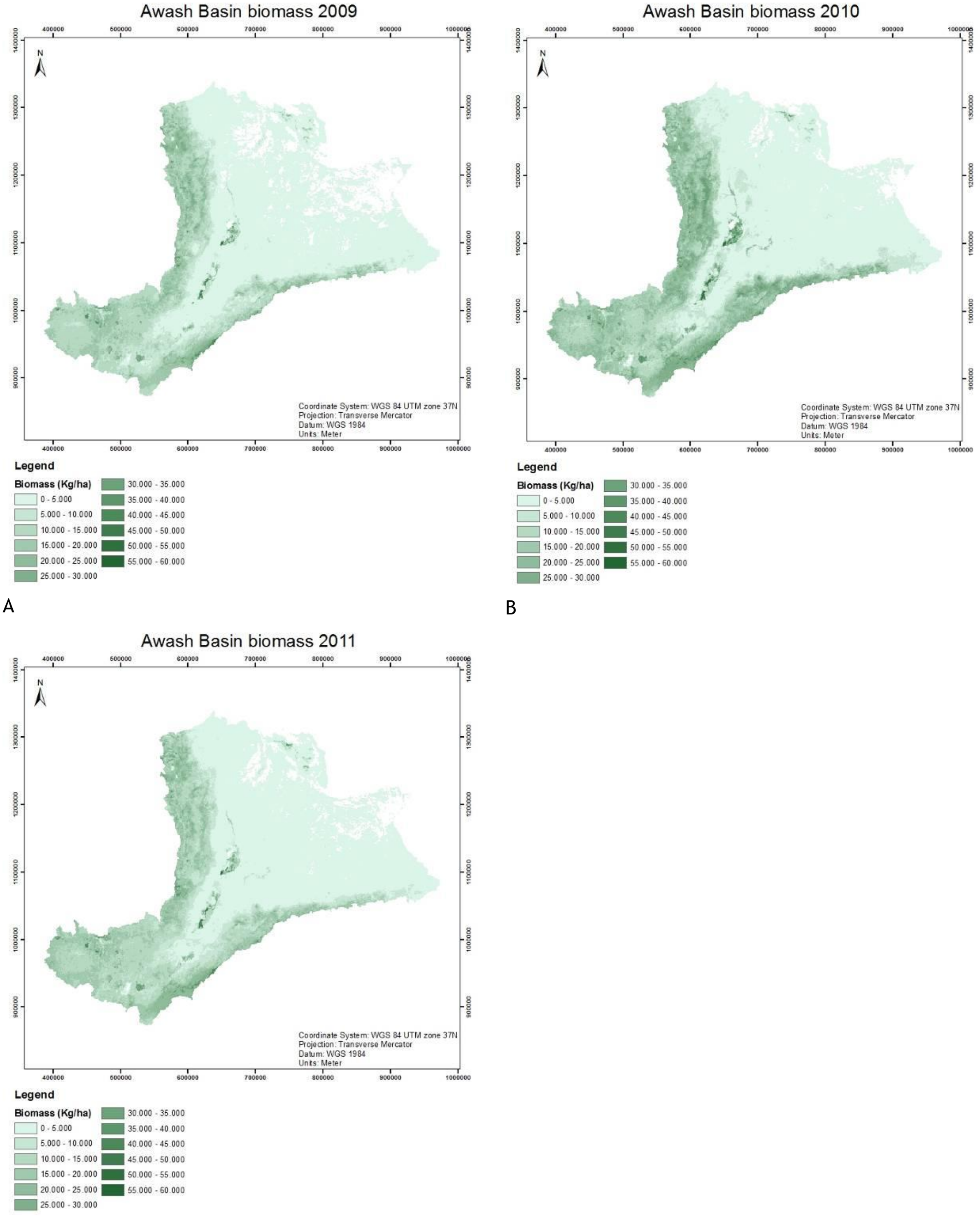
Figure 23 Biomass growth during a 8 day period in the dry (a) and wet (b) season.

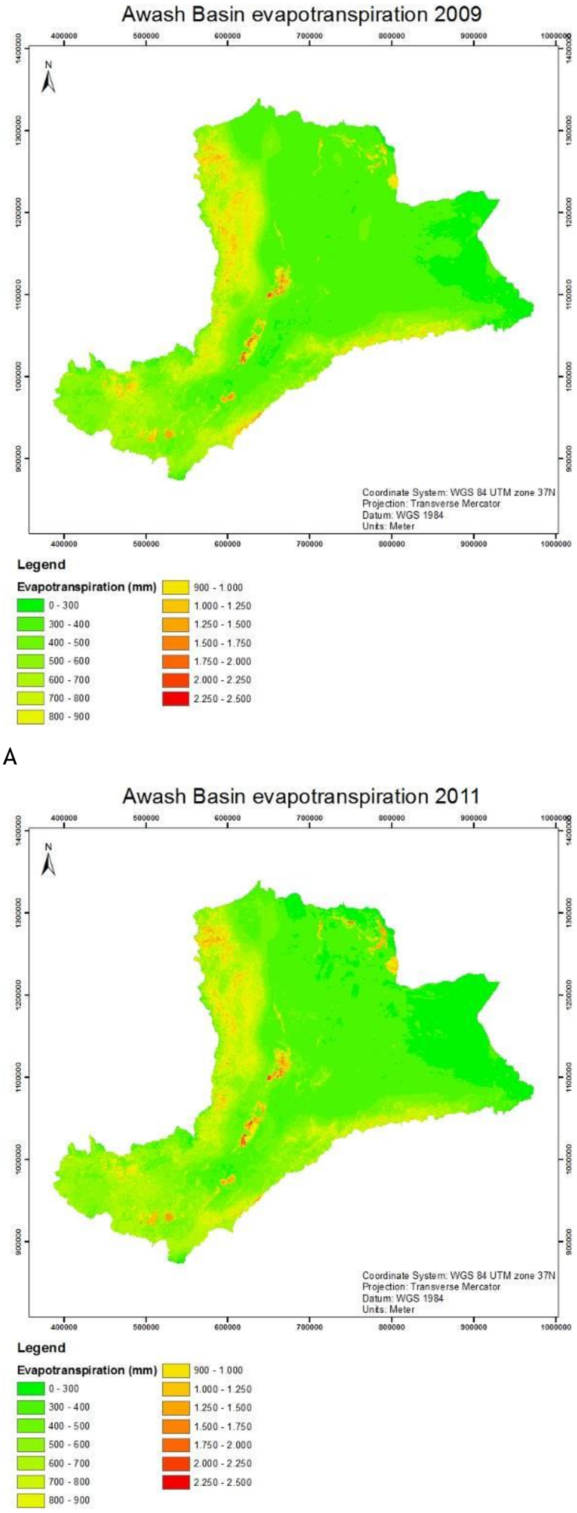


A

B

C

Figure 24 Yearly biomass production in the Awash basin in the year 2009 (a), 2010 (b) and 2011 (c).



A

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Figure 25 Annual actual evapotranspiration in the Awash basin in the year 2009 (a), 2010 (b) and 2011 (c).

5.4 Evaluation

Remote sensing is an attractive data source in absence of reliable field measurements over long time series, or to complement field measurements. The two major components of the water balance are rainfall and ET. Rainfall is measured at rain gauges, but these gauges are not representative for large areas. Generally ET information is very scant, and there is not much literature available on the ET of the Awash basin. This is among the first studies that assess actual ET values.

The outputs of ETlook were validated using sugarcane fields in terms of biomass production from the Agricultural Sample Survey 2009/2010 of Ethiopia (CSA, 2010). In this survey the sugarcane crops present and average yield of 35.500 kg/ha, which corresponds with the ETLook based estimations for sugarcane fields for the three years: 30,000 (2009, normal year), 36,000 (2010, wet year) and 28,000 (2011, dry year).

The ETlook estimations of evapotranspiration for sugarcane was 1382, 1386 and 1470 mm/yr for 2009, 2010 and 2011 respectively. These values corresponds well with the literature that provides values of an average evapotranspiration of 1460 mm/year (Inman-Bamber, 2003). Also, earlier validations of ETLook outside the Awash basin (see Appendix B), showed a good agreement between measured and estimated evapotranspiration values.

As such, the ETLook approach is suitable for the calculation of evapotranspiration over a number of years for the Awash basin. Since the model is based on the Advanced Scatterometer (ASCAT) soil moisture data, ETLook can be applied to the entire basin, also under cloudy conditions. ETLook is therefore more practical when performing ET calculations for vast basins, cloudy conditions, small time steps and for a longer period of time. Another advantage of ETLook is that conventional energy balance-based models do not consider the separation of water, soil, wet leaves and canopy components in the total ET. Canopy evaporation is essential for biomass production and for determining the beneficial use of water.

6 Water Accounting Plus (WA+) Awash

6.1 Introduction

One of the most important features of WA+ is that the input data demand is low, and that the system can be applied to data scarce countries such as Ethiopia. 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 spatially distributed input is required:

- Precipitation
- Actual transpiration
- Actual evaporation (including interception)
- Urban and industrial water consumption
- Land Use Land Cover
- Inter-basin inflow (surface water & groundwater)
- Inter-basin outflow (surface water & groundwater)
- Change in storage of soil moisture, groundwater, surface water

These input data sets can be originating from various sources. The system itself is however developed to make use of readily available earth observations. Chapter 4 and Chapter 5 described the sources of data for the Awash WA+.

Land use is an important factor in WA+, as it determines whether water is manageable or non-manageable. In most cases the standardized Globcover dataset is sufficient to be used as land use / land cover (LULC). In this study, the standard Globcover was modified to ensure that data on irrigated and rainfed classes were correctly included (see Chapter 4). The 12 resulting LULC classes (figure 26) are re-grouped into four land/water relevant classes for implementing WA+. Conserved Land Use class was defined from Protectplanet.net as categories I and II of the World Database on Protected Areas from the IUCN and UNEP-WCMC. For Ethiopia, protected areas with category I were not reported and protected areas with category II for the Awash basin are depicted as Conserved in the land and water use map of Figure 27. The total area under Conserved Land Use is 3940 km^2 only. The map in Figure 27 reveals that the classes Managed Water Use (MWU) and Conserved Land Use (CLU) are relative small and cover 2 and 3 % respectively of the entire area. The Modified Land Use class (MLU) covers 20% and the Utilized Land Use class (ULU) is by far the largest class covering 75% of the basin area (figure 27). From here we can learn that the majority of the area is having a light utilization of the land and water resources. This utilization exists mainly of grazing for livestock, firewood, wildlife, fish and tourism. Modified Land Use is geographically located upstream of the Utilized Land Use, because more rainfall occurs in the higher elevated areas where farmers have settled. Mountainous agriculture can be a hazard for soil erosion, hence this is not the necessary best practice. The floor of the Central Rift Valley can however also be prone to floods, and farming communities have decided to settle on the conversion areas between the flood plain and the mountains.

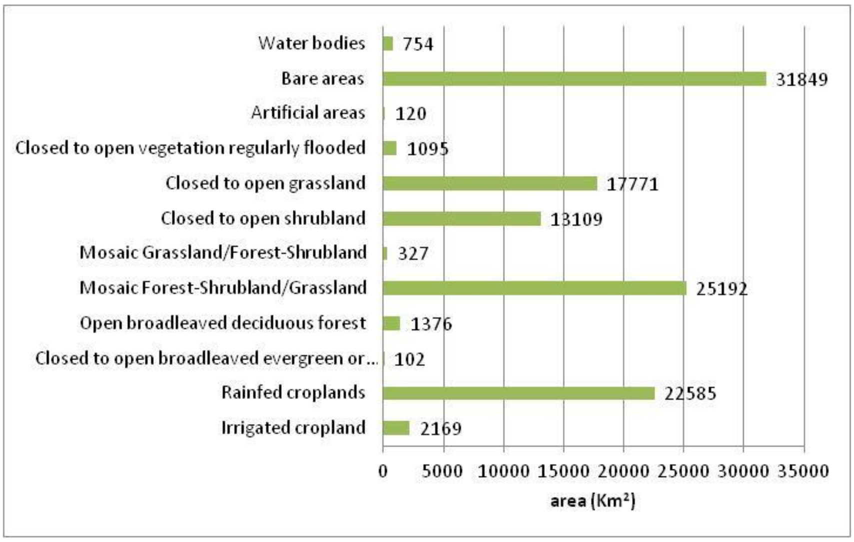

Figure 26 Land use Awash Basin (km^2).

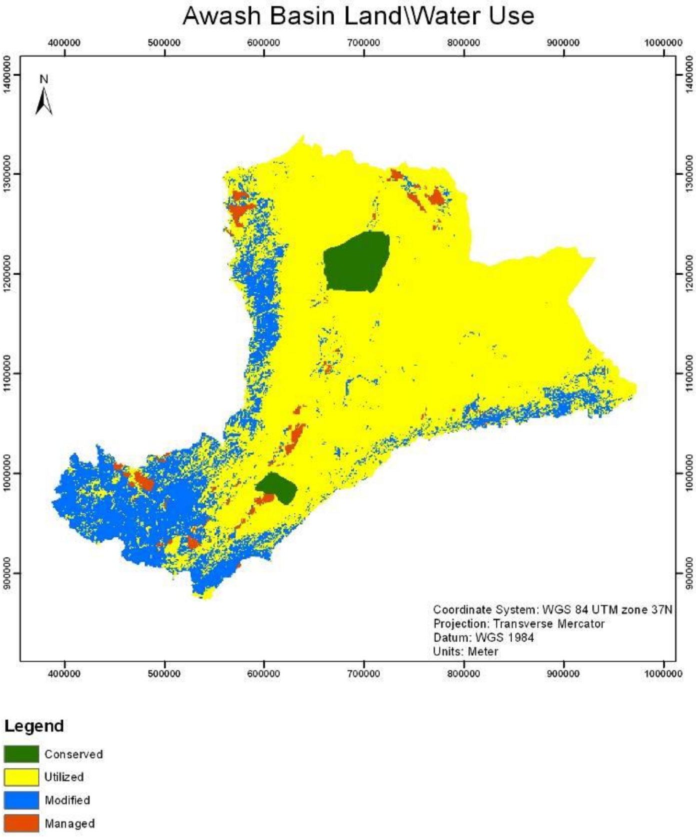

Figure 27 Land and water use map for the Awash Basin.

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

	km^2	%
Conserved Land use (CLU)	3,940	3
Utilized Land use (ULU)	87,690	75
Modified Land use (MLU)	22,546	20
Managed Water use (MWU)	2,273	2
Sum	116,449	100

6.2 Water Accounting Plus (WA+) Awash Basin

The Water Accounting Plus (WA+) framework provides a quick overview of the water and land resources within a river basin. The results are expressed by (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 years: 2009, 2010 and 2011. The resulting WA+ Sheets have been included in Appendix A.

Table 5 presents accumulated P and ET values for the normal hydrological year 2009 by land cover class. In general, values seem plausible, especially for the abundant shrubland and savanna classes and the croplands. A rainfall shortage is observed in the utilized “Closed to open vegetation regularly flooded” class. This may be explained by temporary flooding of the Awash stream that injects extra water into these plain areas. The large P-ET differences in the utilized “Water body” areas are caused by excessive evaporation of the open water bodies being located in an arid climate. The relative low evaporation from water bodies in the conserved class might be explained by mixed pixels of water being mixed and surrounded by marshland vegetation, resulting into a lower ET value.

Table 5. Annual precipitation and evapotranspiration (including interception, water evaporation, soil evaporation and transpiration) per land use/land cover class in 2009.

LULC	**Area**	**Type**	**P**	**ET**	**P – ET**
	(km^2)		**(mm)**	**(mm)**	**(mm)**
Artificial areas	120	Managed	703	514	189
Bare areas	30579	Utilized	387	338	49
Bare areas	1270	Conserved	352	339	13
Closed to open broadleaved evergreen or semi-deciduous forest	102	Utilized	637	885	-248
Closed to open grassland	16132	Utilized	413	345	68
Closed to open grassland	1639	Conserved	362	334	28

Closed to open shrubland	12936	Utilized	557	465	92
Closed to open shrubland	173	Conserved	343	324	19
Closed/open vegetation regularly flooded	1078	Utilized	426	893	-467
Closed/open vegetation regularly flooded	17	Conserved	356	380	-24
Irrigated cropland	2145	Managed	550	792	-242
Irrigated cropland	24	Conserved	674	752	-78
Mosaic Forest-Shrubland/Grassland	24414	Utilized	608	487	121
Mosaic Forest-Shrubland/Grassland	778	Conserved	631	350	281
Mosaic Grassland/Forest-Shrubland	327	Utilized	690	774	-84
Open broadleaved deciduous forest	1376	Utilized	678	650	28
Rainfed croplands	22546	Modified	638	646	-8
Rainfed croplands	39	Conserved	520	352	168
Water bodies	746	Utilized	373	830	-457
Water bodies	8	Conserved	667	498	169
AVERAGE	116449		582	507	75

6.2.1 Resource Base Sheet, 2009

The Resource Base Sheet provides a quick overview of all incoming and outgoing flows for the entire basin and the four Water User Groups identified. The longer term average inter-basin groundwater outflow in 2009 was 3.8 km^3/yr, and assumed equal to the total groundwater recharge. It is possible that certain groundwater pockets in the Afar depression are saline, and that fresh groundwater cannot be used after the water quality has degraded. By absence of supporting data on salinized groundwater, this aspect has been ignored and the sink term is set to zero. The evaporation from the salt lakes is also a flow to the sink, but it is consumed and no longer available for usage. Since this is included in the evaporation of Utilized Land Use – and it cannot be double accounted – the flow to sink is zero.

Over longer time frames, the changes in water storage are close to zero unless unsustainable groundwater depletion occurs. Awash appears to be characteristic for significant carry over amounts of water storage between consecutive rainfall years. The average rainfall is 582 mm and the standard deviation is 256 mm (Coefficient of Variation is 44 %). For the average rainfall year 2009 investigated, the storage changes in surface and groundwater are negligible small (-400 Mm^3/yr being 0.5 % of the net inflow).

The Resource Base Sheet shows that Utilized Land Use controls the water balance of the basin (ET: 37.7 km^3/yr), followed by the class Modified Land Use (ET: 15.5 km^3/yr). Managed Water Use (ET: 1.9 km^3/yr) and Conserved Land Use (ET: 1.4 km^3/yr) play a minor role in the basin evapotranspiration values. The area Utilized Land Use is rather vast, and land use changes may occur in these areas, especially on the long term. Utilized Land Use could be converted into Modified Land Use, especially when the ET remains similar. The expected effects from land use changes can be estimated by comparing P and ET. It should be noted that the annual average precipitation of 2009 is higher for Modified Land Use than for Utilized Land Use (638 mm vs. 530 mm), as well is the annual ET (646 mm vs. 630 mm). Since an annual average P of 530 mm is insufficient to facilitate the average ET of the rainfed croplands (646 mm) during 2009, the success of such a land use shift may 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).

The ET of the class Modified Land Use from rainfall and withdrawals are about equal. The total incremental ET is 1.0 km^3/yr, which at a total irrigation efficiency between river diversions and the root zone of irrigated fields of 40%, implies that approximately 2.5 km^3/yr is extracted from the river. The non-consumed flow (diversion minus ET) will return back into the stream flow or recharges the deeper aquifer. It is also feasible that – instead - water is abstracted from the aquifer for the purpose of irrigation. Since surface water and groundwater are not separated in the Resource Base Sheet, this will not have any impact. We allowed some groundwater basin outflow, and more attention should be given whether this non-utilized water could be intercepted. Research on current and future situation of groundwater dependent irrigation systems is recommended, after a numerical groundwater flow model confirms the lateral transport of water.

6.2.2 Evapotranspiration Sheet, 2009

The Evapotranspiration Sheet provides an overview of what happens with the total amount of water consumed. If we take the hydrological year 2009 again as an example, then it becomes apparent that 31% of the total consumption is managed (i.e. Modified Land Use or Managed Water Use) and the majority is not (69%). Rainfed agriculture water can be managed by means of crop selection, sowing dates, mulching, weed control, etc. This is however a minor part of the water cycle in the Awash basin. Pastures on rangeland is common and is considered as Utilized Land Use, because the human interference on the vegetation is limited to grazing: soils are not ploughed. Every reduction of consumptive use of rainfed crops, will enhance stream flow, and by doing so convert landscape ET into Total water (or green water into blue water).

The Evapotranspiration 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 (67 %) is used non-beneficially by vast volumes of soil evaporation. Soil evaporation in the Awash basin (36.3 km^3/yr) exceeds transpiration (18.0 km^3/yr). It was decided that open water evaporation is considered as being beneficial, as wetlands provide environmental services. Similar, soil evaporation from Conserved Land Use can be considered as beneficial, because the landscape is protected because of its rich biodiversity.

From the Evapotranspiration Sheet it is clear that most beneficial use of water in the Awash Basin is related to agriculture, followed by environmental use. Further developments of the basin should take this aspect into consideration. Please note that pastoralism is not included in the agricultural production. This is rather doubtful, and next versions of WA+ should explicitly describe pastoralism as a form of agriculture and living.

6.2.3 Production Sheet, 2009

The last sheet of WA+ is the Production Sheet. It provides a summary on whether scarce water resources are consumed productively. The 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. The biomass production of Conserved Land Use is very low due to wet soils in the inundation areas surrounded by esert surfaces that occur in these protected areas. The carbon sequestration in Utilized Land Use is very high: an amount of 36.5 Mton is sequestered from the atmosphere. This is 6 times the values found for Modified Land Use.

The biomass production of the Managed Land Use (13,790 kg/ha) is higher than found for Modified Water Use (11,263 kg/ha). Upon checking with the other years, the same observation was found. This apparent contradiction can be an error in the irrigated area map, or related to different crop types. Intensive cropping is only possible if water resources are safeguarded, and farmers will then invest in protection measures of their sugarcane and cotton crops. Perhaps the irrigation supply is highly irregular, and farmers do not risk these investments.

Finally, the Production Sheet gives also water productivity values for harvested yield. The water productivity for Managed Water Use is lower than for Modified Land Use, indicating that the agricultural performance of irrigation systems is beyond expectations. This suggests that more crops could be produced from the same water resources in Awash basin, and that this management needs more attention.

6.2.4 Three years period

Analyses were performed for three years and the results are presented in Appendix A and in table 6. The Resource Base Sheets for the three years confirm that the year 2009 is normal, the year 2010 is wet and the year 2011 is dry in climate conditions. This is clearly reflected in changes in groundwater storage between these three years. It is likely that surface water storage changes occurred simultaneously, but this was disregarded by the lack of water level fluctuation data of open water surfaces. It is interesting to note that water level fluctuations can be acquired from lidar and radar altimeters aboard satellites. The spatial resolution of radar altimeters is, however, at this moment too large for operational implementations. Lidar instruments on satellites are preferred.

The Evapotranspiration Sheets for the three years indicate that the overall water consumption varies between 56.4 to 65.1 km^3/yr. The main reason for this quasi-constant behavior is the quite large surface and groundwater buffer capacity of the basin. The overall distribution of consumptive use between the various uses is more or less constant between the three years investigated.

6.2.5 WA+ Indicators

Further to default WA+ Sheets, WA+ provides key performance parameters describing the entire system by a few indicators. The indicators are presented in table 6, and the discussion will focus on the year 2009. An ET Fraction of 94.2% in 2009 indicates that not all rainfall is consumed so that surplus of rainfall is used to increase storage and/or generate non-utilized outflow from the basin. The representative value for ET Fraction across the three year period is 88.1 %. Especially wet rainfall years will increase the intra-annual storage considerably, mainly because the outflow from Awash is and remains small. Managing storage is thus an issue that needs to get attention by the Ethiopian authorities. Groundwater flow models need to be developed and explored for making strategic plans for safe water withdrawals in future Awash. The Stationarity Index indicator describes which percentage of the consumption that is originating from changes in the surface and groundwater storage. An average positive indicator of 6.7% means that groundwater is not over-exploited. The Basin Closure percentage indicates that some limited outflow occurs. The outflow data is based on existing geo-hydrological reports, and not on remote sensing data.

The second set of indicators in table 6 focuses on the actual amount of water that is currently managed, or is available to be managed. The total amount of Available Water is 9,263 km^3/yr. From this, a total amount of 2,458 km^3/yr is withdrawn, or 26.5%. This is essentially all the surface water flow that can be extracted from the stream network of Awash, although return flows via drainage networks are not incorporated. Any future development should be focused on groundwater abstractions.

The third set of indicators shows for which purpose water is used in the Awash Basin. This result depend very strongly on the opinion of the policy maker. In this particular case of Awash, it changes significantly with the value of bare soil evaporation. The Evapotranspiration Sheet has indicated that the soil evaporation exceeds transpiration, and the value assessment of the evaporation process will have a significant impact. The bare soil evaporation from Conserved Land Use has been considered 100% beneficial, and so it is from water bodies as they provide habitats and resources for irrigation. Soil evaporation from pastures and savannah has been accounted as non-beneficial. For this reason, the total beneficial consumption is 39.6 % only. It is also clear that agricultural benefits are most important (77.5%). While environmental water consumption is significant in the basin, the benefits from grasslands, bushland and wasteland is rather soft.

The last set of WA+ indicators compares the current year with the long-term averages. The vulnerability to environmental and economic benefits seems to be higher than for the agricultural benefits. This can be be explained by the relative low long term average value for these classes. Deviations to a low long term average value will yield into larger numbers.

Table 6 Water Accounting Indicators for the entire Awash Basin.

	2009	2010	2011	*Numerical average*	*Integrated average*
ET fraction (%)	94.2	64.8	134.8	*97.9*	*88.1*
Stationarity Index (%)	-0.8	45.6	-15.3	*9.8*	*6.7*
Basin Closure (%)	93.6	94.3	94.0	*94.0*	*94.1*
Available Water (MCM)	5,230	36,070	-13,510	*9,263*	*9,263*
Managed Water (MCM)	2,450	1,800	3,125	*2,458*	*2,458*
Managed Fraction (%)	46.8	5.0	-23.1	*9.6*	*26.5*
Beneficial Consumption (%)	35.6	43.0	39.8	*39.5*	*39.6*
Agricultural Consumption (%)	86.2	71.3	77.5	*78.3*	*77.5*
Environmental Consumption (%)	12.4	25.8	20.3	*19.5*	*19.5*
Economic Consumption (%)	1.4	2.9	2.3	*2.2*	*3.0*
Deviation Beneficial Consumption (%)	14.9	-18.6	3.7	*0*	*0*
Deviation Agricultural Consumption (%)	5.5	-9.2	+3.8	*0*	*0*
Deviation Environmental Consumption (%)	37.4	-44.7	7.6	*0*	*0*
Deviation Economic Consumption (%)	38.8	-42.8	6.1	*0*	*0*

7 Conclusions

Water Accounting is considered by an increasing group of water managers, policy makers and donors as a supporting tool to facilitate the understanding and management of scarce water resources in relation to land use. This study showed for the Awash basin what the situation and options for water management are.

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 Awash basin, no standard existing dataset has proven sufficient accuracy. The area of irrigated croplands is 216,900 ha and the area of rainfed croplands is 2,258,500 ha. Twelve different LULC classes have been prepared, and they are clumped together into 4 types of land/water management groups: (i) Conserved Land Use: no changes in land and/or water management are possible due to legal restrictions, (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 is withdrawn from surface water and/or groundwater resources. The class of Utilized Land Use is dominant in Awash and this defines that 69% of the water resources are unmanageable. Many grasslands and savannah ecosystems occur in this land use group, especially in the drier downstream part of the basin. Modified Land Use with rainfed cereals occur essentially in the higher elevated areas with more rainfall. Irrigated areas are rather restricted, mainly because of the limited renewable surface water resources. Irrigation with groundwater resources is less common. Certain areas of Utilized Land Use with more than 1000 mm of annual rainfall (e.g. open broadleaved deciduous forest, mosaic Grassland/Forest-Shrubland) could be converted into Modified Land Use, without affecting stream flow. There is however a risk of inundation, and river embankments need to be constructed.

This pilot study for the Awash basin has shown that the selection of three years (wet, dry and average) is a relevant approach for performing WA+. The Resource Base Sheet is rather different between rainfall years, and due to the limited basin outflow, storage management is a relevant issue for Awash. From the selected years, average yearly precipitation is quantified as 581 mm/yr and the ET is 507 mm. The surplus of 75 mm is recharging the aquifer. A distinct lateral groundwater flow towards the lowland salt lakes, and sinks in Djibouti are likely to occur. It is recommended to set up a detailed groundwater flow model (if not already done so) and estimate the safe amounts of groundwater that could be exploited. Probably this groundwater gets gradually saline, and interception of good quality fresh groundwater in the Upper Awash basin could increase the total benefits of the basin. 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 flags particular issues relevant for the basin for a specific time frame.

The surface runoff is basically consumed when it transects from the source to saline depressions at the downstream end of the basin. Most water is extracted to irrigation systems and evaporated from wetlands, inundation areas and open water bodies, although certain return flows are likely to occur. Stream flow enhancement could be introduced by land use changes. The surface runoff should not be confused with the outflow of the basin: the runoff into the salt lakes is not basin outflow but a redistribution of water within the basin physical boundaries, that is evaporated at the end of the system.

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 C 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

Awash 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. For this reason, the form is kept blank.

The limitation of this study is that the uncertainty in the surplus (P-ET) is equal to the uncertainty in the rainfall data, and to a lesser extent in the ET data. It is recommended for future WA+ studies to provide more attention to the collection of matching rain gauge data, and develop calibration procedures of the FEWS-NET rainfall product.

Recommendations:

- Calibrate FEWS-Net distributed rainfall data
- Verify hydraulic heads and their response to rainfall for understanding storage mechanisms better
- Set up a detailed groundwater flow model for Awash
- Exploit groundwater for urban and irrigation systems users
- Convert Utilized Land Use into Modified Land Use by introducing rainfed crops in flat areas (with less erosion) and sufficient rainfall
- Create flood protection measures in the Central Rift Valley so that farmers can migrate to the plane areas
- Convert wetlands and other wet ecosystems in the class Utilized Land Use into Conserved Land Use for conserving biodiversity
- Encourage eco-tourism to areas with Conserved Land Use
- Improve crop water productivity for establishing a larger food security
- Pastoralism should get more recognition in the WA+ sheets

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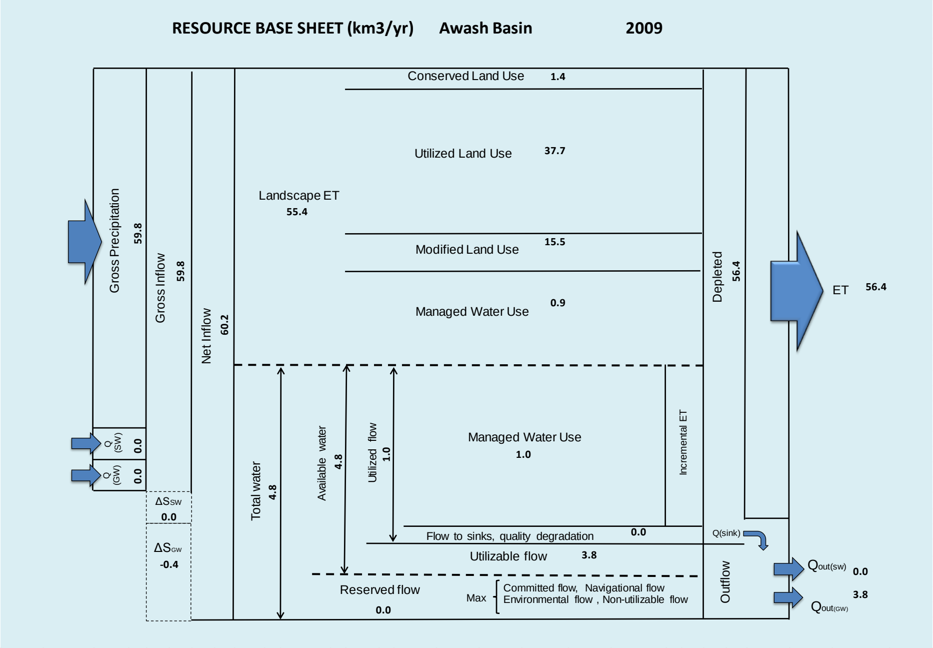
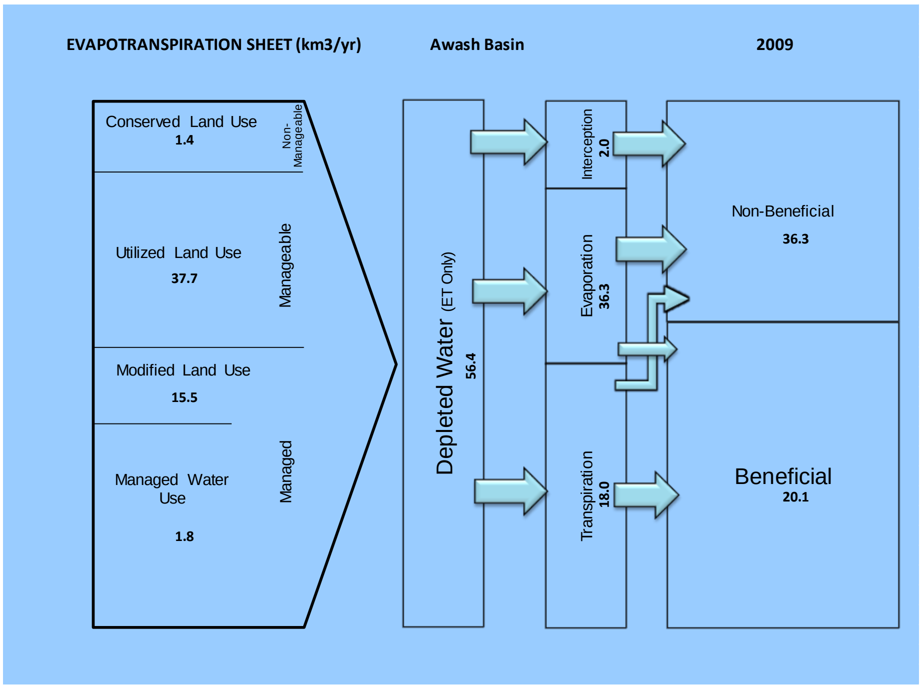
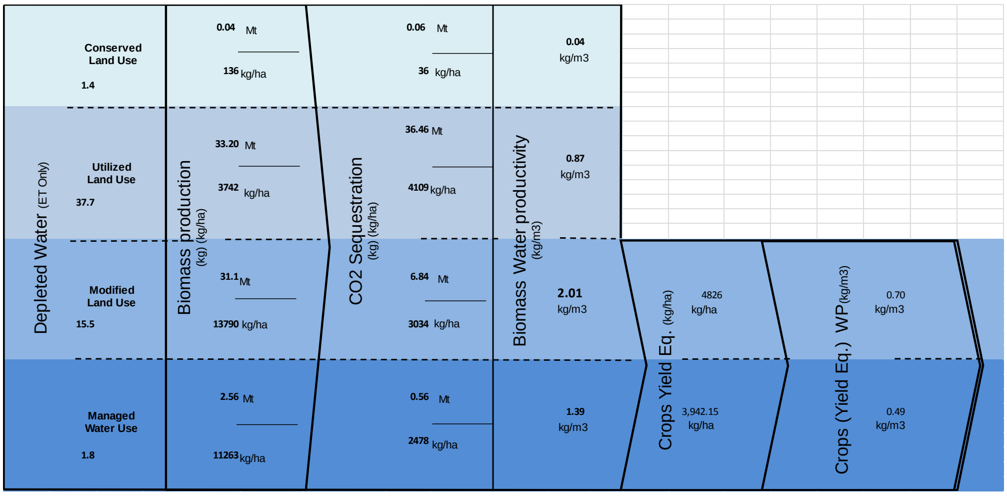
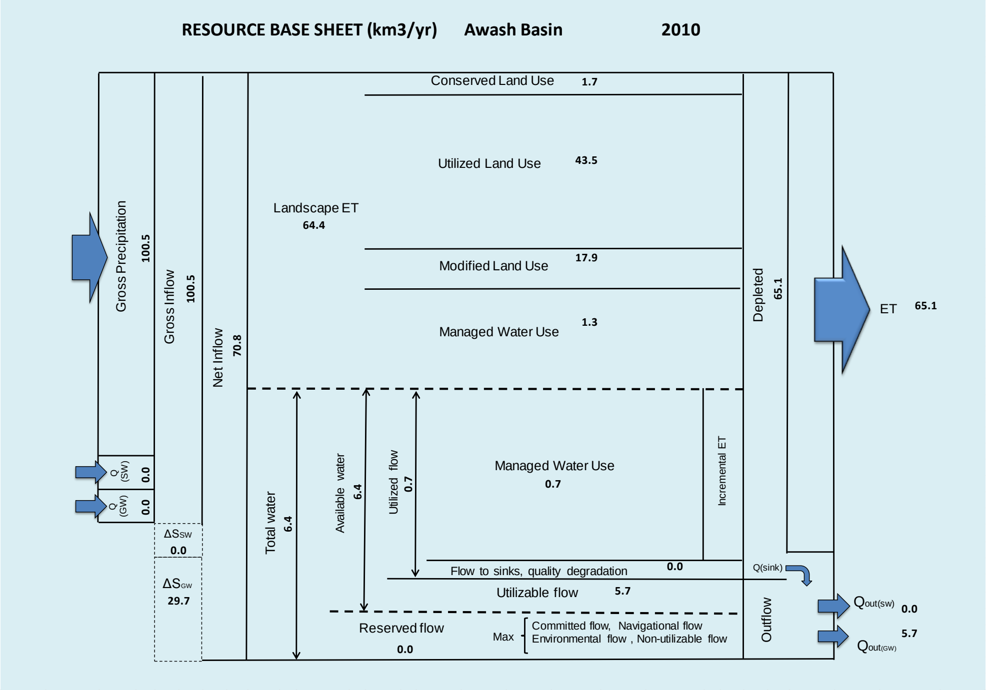
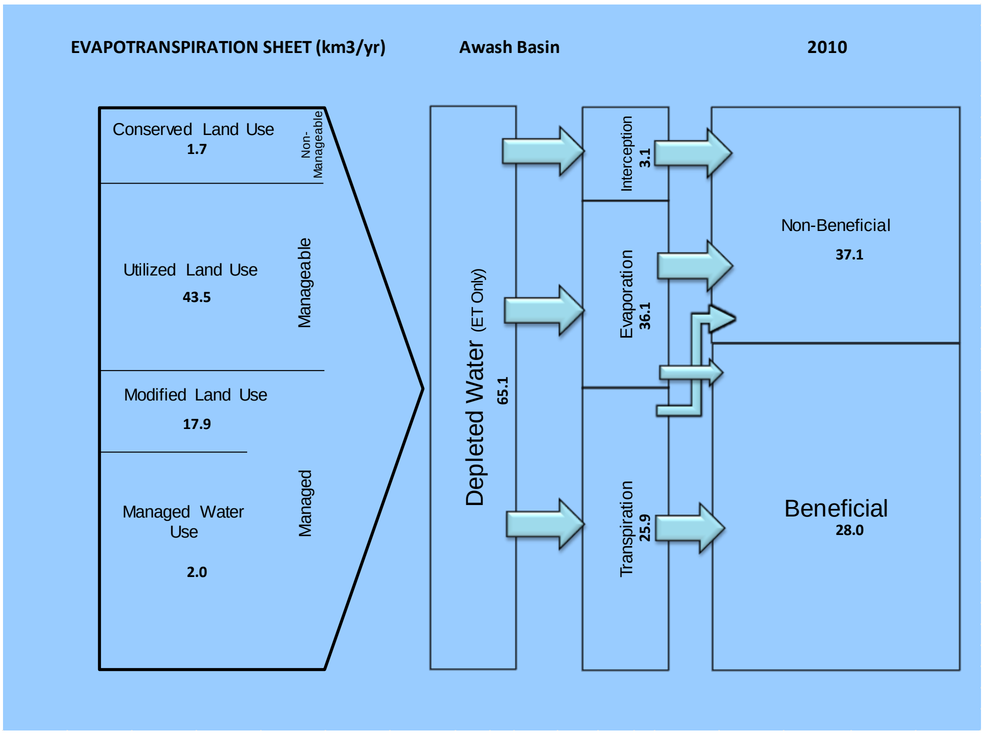
Appendix A: Water Accounting Plus (WA+) Sheets

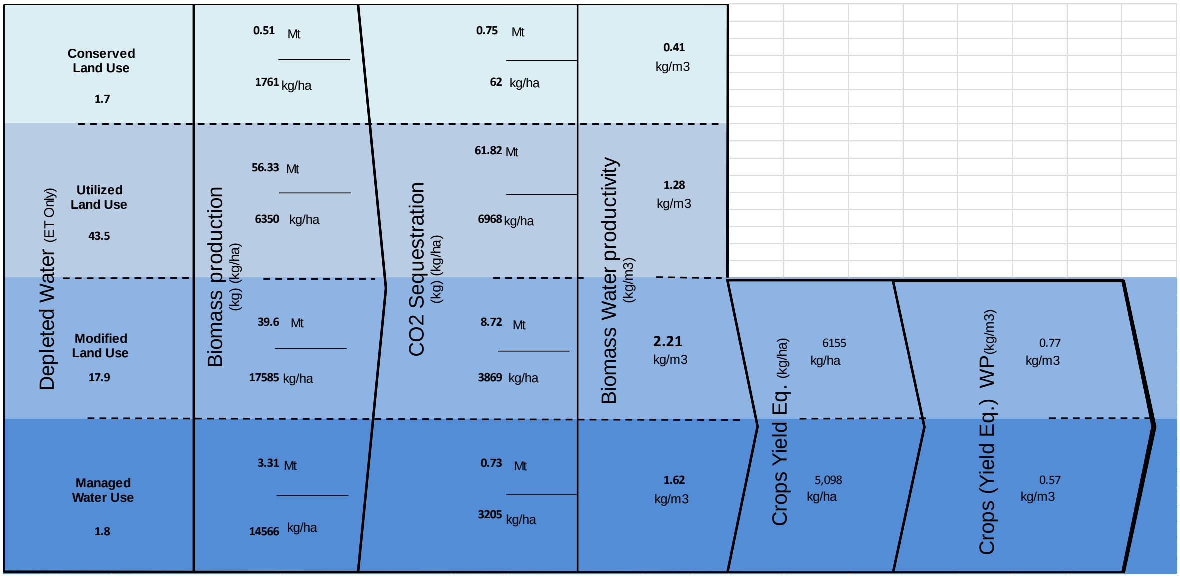


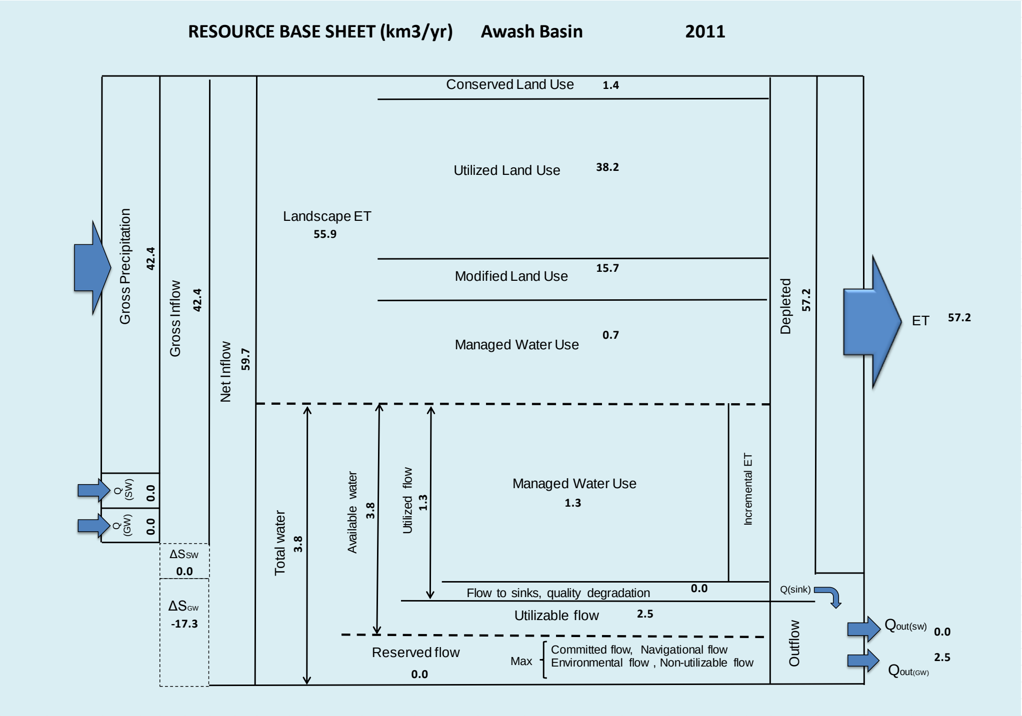


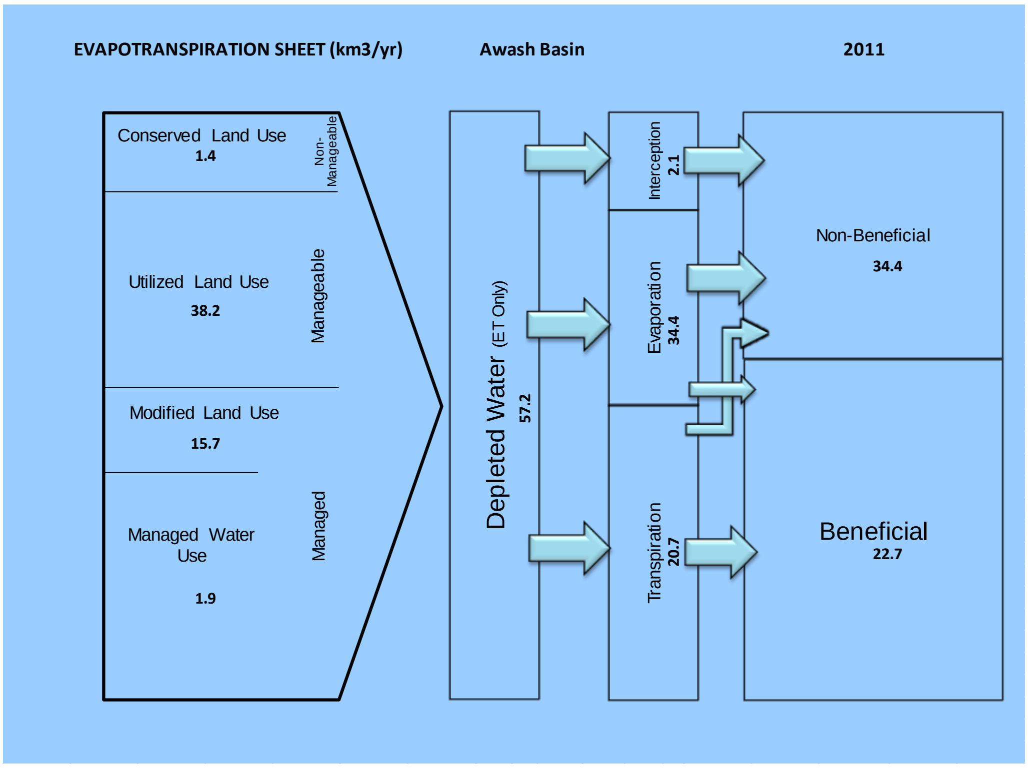

Depleted Water (ET Only)
Conserved Land Use
1.4
Utilized Land Use
37.7
Modified Land Use
15.5
Managed Water Use
1.8
Biomass production (kg) (kg/ha)
0.04 Mt
136 kg/ha
33.20 Mt
3742 kg/ha
31.1 Mt
13790 kg/ha
2.56 Mt
11263 kg/ha
CO2 Sequestration (kg) (kg/ha)
0.06 Mt
36 kg/ha
36.46 Mt
4109 kg/ha
6.84 Mt
3034 kg/ha
0.56 Mt
2478 kg/ha
Biomass Water productivity (kg/m3)
0.04 kg/m3
0.87 kg/m3
2.01 kg/m3
1.39 kg/m3
Crops Yield Eq. (kg/ha)
4826 kg/ha
3,942.15 kg/ha
Crops (Yield Eq.) WP(kg/m3)
0.70 kg/m3
0.49 kg/m3

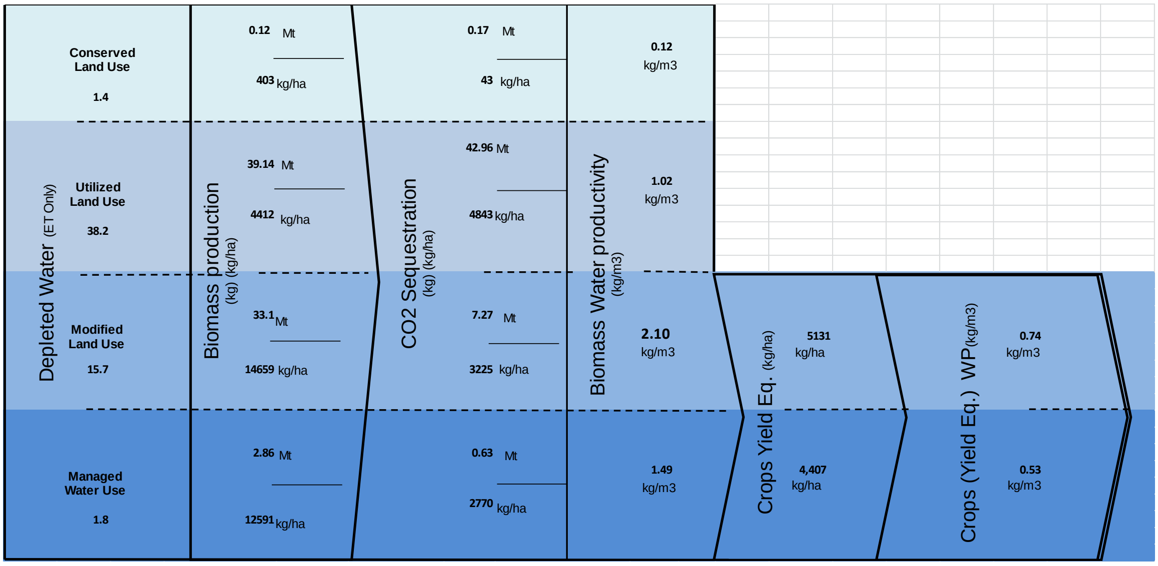

RESOURCE BASE SHEET (km3/yr)
Awash Basin
2010
Gross Precipitation
100.5
Gross Inflow
100.5
Net Inflow
70.8
Q (SW)
0.0
Q (GW)
0.0
ΔSsw
0.0
ΔSGW
29.7
Landscape ET
64.4
Conserved Land Use
1.7
Utilized Land Use
43.5
Modified Land Use
17.9
Managed Water Use
1.3
Depleted
65.1
ET
65.1
Total water
6.4
Available water
6.4
Utilized flow
0.7
Managed Water Use
0.7
Incremental ET
Flow to sinks, quality degradation
0.0
Q(sink)
Utilizable flow
5.7
Reserved flow
0.0
Max
Committed flow, Navigational flow
Environmental flow , Non-utilizable flow
Outflow
Qout(sw)
0.0
Qout(GW)
5.7


EVAPOTRANSPIRATION SHEET (km3/yr)
Awash Basin
2010
Conserved Land Use
1.7
Non-Manageable
Utilized Land Use
43.5
Manageable
Modified Land Use
17.9
Managed Water Use
2.0
Managed
Depleted Water (ET Only)
65.1
Interception
3.1
Evaporation
36.1
Transpiration
25.9
Non-Beneficial
37.1
Beneficial
28.0

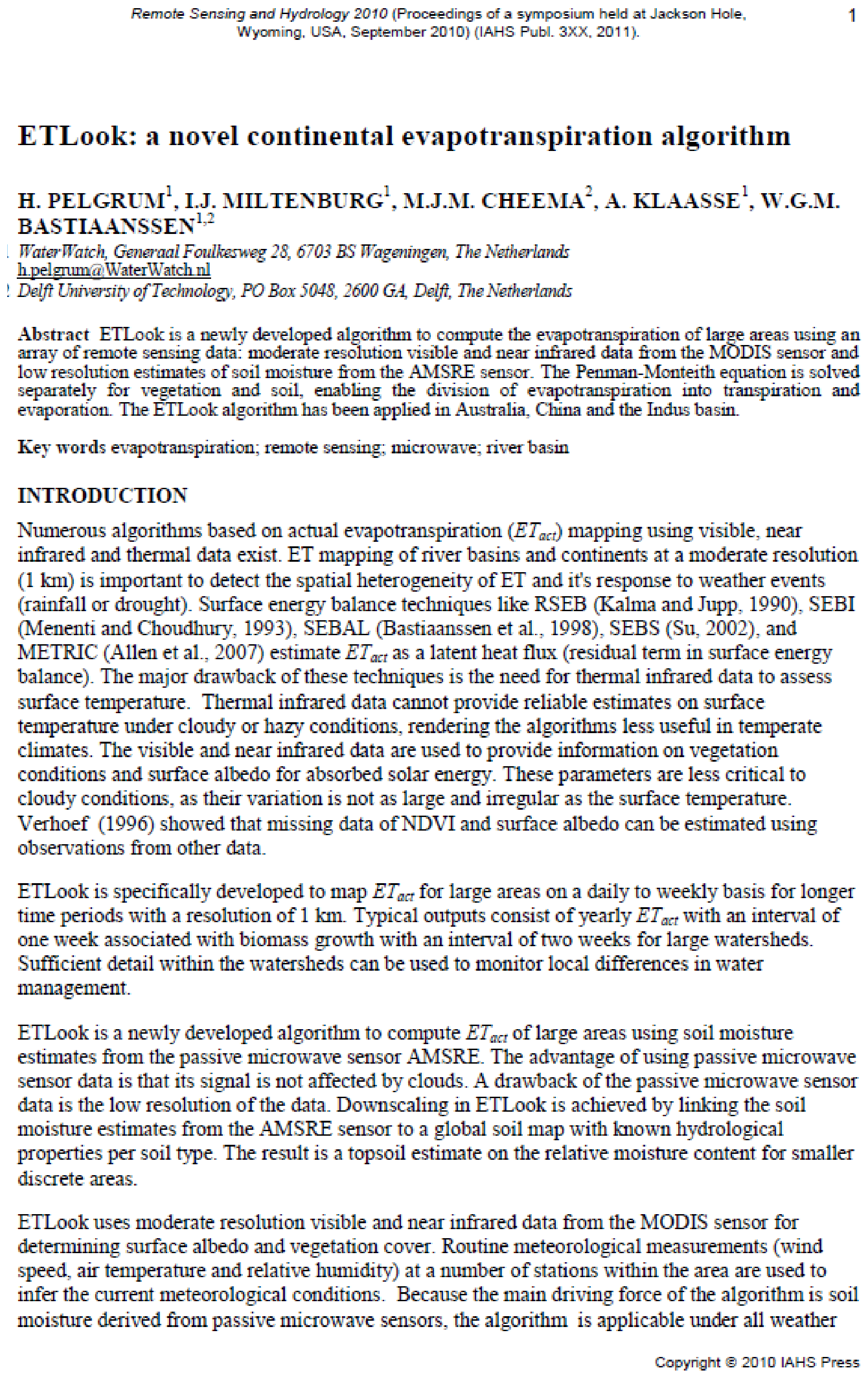

Depleted Water (ET Only)
Conserved Land Use
1.7
Utilized Land Use
43.5
Modified Land Use
17.9
Managed Water Use
1.8
Biomass production (kg) (kg/ha)
0.51 Mt
1761 kg/ha
56.33 Mt
6350 kg/ha
39.6 Mt
17585 kg/ha
3.31 Mt
14566 kg/ha
CO2 Sequestration (kg) (kg/ha)
0.75 Mt
62 kg/ha
61.82 Mt
6968 kg/ha
8.72 Mt
3869 kg/ha
0.73 Mt
3205 kg/ha
Biomass Water productivity (kg/m3)
0.41
kg/m3
1.28
kg/m3
2.21
kg/m3
1.62
kg/m3
Crops Yield Eq. (kg/ha)
6155
kg/ha
5,098
kg/ha
Crops (Yield Eq.) WP(kg/m3)
0.77
kg/m3
0.57
kg/m3


RESOURCE BASE SHEET (km3/yr) Awash Basin 2011
Gross Precipitation 42.4
Gross Inflow 42.4
Net Inflow 59.7
Q (SW) 0.0
Q (GW) 0.0
ΔSsw 0.0
ΔSgw -17.3
Landscape ET 55.9
Conserved Land Use 1.4
Utilized Land Use 38.2
Modified Land Use 15.7
Managed Water Use 0.7
Total water 3.8
Available water 3.8
Utilized flow 1.3
Managed Water Use 1.3
Incremental ET
Flow to sinks, quality degradation 0.0
Utilizable flow 2.5
Reserved flow 0.0
Max Committed flow, Navigational flow Environmental flow, Non-utilizable flow
Depleted 57.2
ET 57.2
Q(sink)
Outflow
Qout(sw) 0.0
Qout(GW) 2.5


EVAPOTRANSPIRATION SHEET (km3/yr) Awash Basin 2011
Conserved Land Use 1.4
Non-Manageable
Utilized Land Use 38.2
Manageable
Modified Land Use 15.7
Managed Water Use 1.9
Managed
Depleted Water (ET Only) 57.2
Interception 2.1
Evaporation 34.4
Transpiration 20.7
Non-Beneficial 34.4
Beneficial 22.7


Depleted Water (ET Only)
Conserved Land Use
1.4
Utilized Land Use
38.2
Modified Land Use
15.7
Managed Water Use
1.8
Biomass production (kg) (kg/ha)
0.12 Mt
403 kg/ha
39.14 Mt
4412 kg/ha
33.1 Mt
14659 kg/ha
2.86 Mt
12591 kg/ha
CO2 Sequestration (kg) (kg/ha)
0.17 Mt
43 kg/ha
42.96 Mt
4843 kg/ha
7.27 Mt
3225 kg/ha
0.63 Mt
2770 kg/ha
Biomass Water productivity (kg/m3)
0.12 kg/m3
1.02 kg/m3
2.10 kg/m3
1.49 kg/m3
Crops Yield Eq. (kg/ha)
5131 kg/ha
4,407 kg/ha
Crops (Yield Eq.) WP (kg/m3)
0.74 kg/m3
0.53 kg/m3

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).

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.

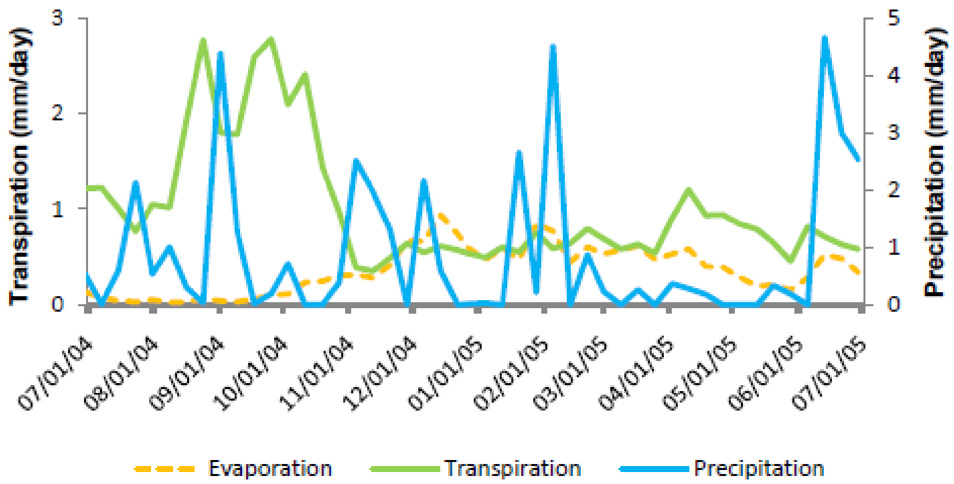

Fig. 1 Time series of ETLook evaporation, transpiration and measured precipitation for a cropland near Griffith NSW, Australia.

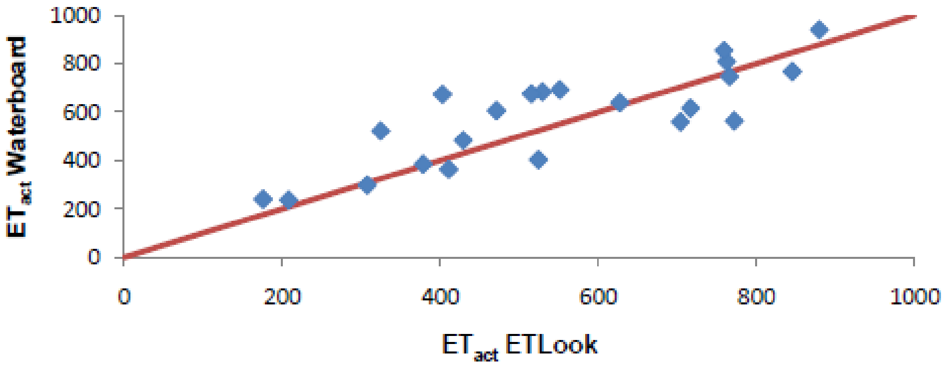

Fig. 2. Comparison of mean actual evapotranspiration as reported by Australian Water Resources Study 2005 and ETLook for 22 priority water balance areas

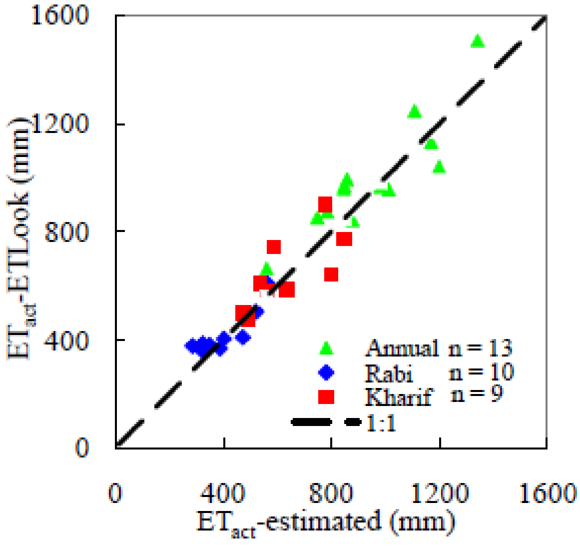

Fig. 3. Comparison of evapotranspiration estimated by previous studies and ETLook for different seasons measured at different locations in the Indus Basin.

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.

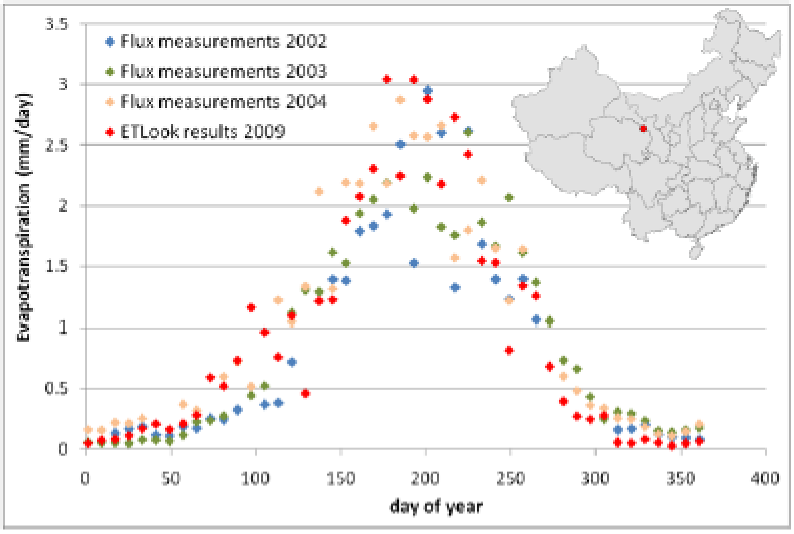

Fig. 4. Comparison of 10-day actual evapotranspiration estimated by an Eddy correlation station in Haibei (data courtesy of Fluxnet) and uncalibrated ETLook for different years.

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: 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 occurrence				• 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