



Spatial evapotranspiration, rainfall and land use data in water accounting – Part 2: Reliability of water accounting results for policy decisions in the Awash Basin

P. Karimi¹, W. G. M. Bastiaanssen^{1,2,3}, A. Sood², J. Hoogeveen⁴, L. Peiser⁴, E. Bastidas-Obando⁵, and R. J. Dost⁵

¹UNESCO-IHE Institute for Water Education, Delft, the Netherlands

²International Water Management Institute, Battaramulla, Sri Lanka

³Faculty of Civil Engineering and Geosciences, Water Management Department, Delft University of Technology, Delft, the Netherlands

⁴Land and Water Division, FAO, Rome, Italy

⁵eLEAF Competence Centre, Wageningen, the Netherlands

Correspondence to: P. Karimi (p.karimi@unesco-ihe.org)

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Abstract. Water Accounting Plus (WA+) is a framework that summarizes complex hydrological processes and water management issues in river basins. The framework is designed to use satellite-based measurements of land and water variables and processes as input data. A general concern associated with the use of satellite measurements is their accuracy. This study focuses on the impact of the error in remote sensing measurements on water accounting and information provided to policy makers. The Awash Basin in the central Rift Valley in Ethiopia is used as a case study to explore the reliability of WA+ outputs, in the light of input data errors. The Monte Carlo technique was used for stochastic simulation of WA+ outputs over a period of 3 yr. The results show that the stochastic mean of the majority of WA+ parameters and performance indicators are within 5% deviation from the original WA+ values based on one single calculation. Stochastic computation is proposed as a standard procedure for WA+ water accounting because it provides the uncertainty bandwidth for every WA+ output, which is essential information for sound decision-making processes. The majority of WA+ parameters and performance indicators have a coefficient of variation (CV) of less than 20%, which implies that they are reliable and provide consistent information on the functioning of the basin. The results of the Awash Basin also indicate that the utilized flow and basin closure fraction (the degree to which available water in a basin is

utilized) have a high margin of error and thus a low reliability. As such, the usefulness of them in formulating important policy decisions for the Awash Basin is limited. Other river basins will usually have a more accurate assessment of the discharge in the river mouth.

1 Introduction

Water Accounting Plus (WA+) is a novel analytical framework that summarizes complex hydrological processes and water management issues in vast river basins by means of four simple sheets (Bastiaanssen, 2009; Karimi et al., 2013a), although the accounting system is expanded continuously. WA+ has the ability to accommodate satellite measurements to quantify land use and hydrological variables. WA+ is a successor of the water accounting (WA) system initiated by the International Water Management Institute (IWMI) that was introduced by Molden (1997) and Molden and Sakthivadivel (1999) for describing the depletion of water resources in river basins. Whereas the IWMI WA is based on piezometers, water levels, discharge measurement, rain gauges and reference evapotranspiration to assess water stocks, water usage, and depletion in river basins, WA+ is also designed to allow for the use of remote sensing data. Remote sensing information can replace hydrometeo-

rological data sets measured in situ, especially when administrations are reluctant to share data, and also where the data quality from field observatories is questionable.

WA+ facilitates the understanding of the water resource situation and the use of water by riparian administrations. The number of river basins under water stress is rapidly growing (Vörösmarty et al., 2010; Wolf et al., 2003), and there is a growing need for transparent and independent water-related data (CA, 2007; FAO, 2003; UN-Water, 2013). WA+ meets this need by quantifying the resources and their depletion by all the agroecological land use units in the river basin. WA+ provides policy makers with data for water (re-) allocation, withdrawal permits, flows to sustain ecosystems, and for soil and water conservation, among others.

The art of using remote sensing to derive hydrological variables is well established (e.g., Neale et al., 2012; Stewart et al., 1996). A recent literature review by Karimi and Bastiaanssen (2015) showed that the average errors in land use mapping, and annual or seasonal precipitation and evapotranspiration estimates on the basis of multispectral remote sensing data were 14.5, 18.5, and 5.4%, respectively. These figures are based on a comprehensive literature review in which for each variable several numbers of post-2000 peer-reviewed publications were consulted for reported differences of satellite-based estimates from conventional ground measurements. Results of the study show that errors in satellite-based estimates are within an acceptable range and comparable to errors reported in conventional ground-based observations. They are thus suitable for application in WA+ for any river basin, including ungauged basins. Bastiaanssen and Chandrapala (2003), Bastiaanssen et al. (2014), Karimi et al. (2012, 2013b), Drooger et al. (2010), Shilpakar et al. (2012) and Dost et al. (2012) used remote sensing data for the water accounts of ungauged river basins in Sri Lanka, and for the Nile, Okavango, East Rapti, Indus, and Awash Basins, respectively. While this is great for basin planning, arbiters may raise concerns on the reliability of the accounts if they have not been verified on the ground, especially if the water accounts are not favorable for the water manager that is responsible for the operational distribution of water resources. While field devices are considered reliable measurement instruments, the radiometer onboard a satellite is often interpreted as futuristic, and not having accurate measurement capabilities. This is not correct, as many in situ devices also measure variables indirectly. In situ soil moisture sensors for instance measure the soil dielectric properties, and not soil moisture; measured river and canal discharge are sometimes based on the sound of water flow, rather than being direct measurements; leaf area index is based on intercepted solar radiation, and not a direct measurement of total leaf area.

By demonstrating the accuracy of satellite measurements they will become more acceptable for use in water accounting. Water-resources-related court cases in the USA and Spain have already used remote sensing data in dealing

with conflicts between competing water users (e.g., Allen et al., 2007). This created a precedent for more frequent usage of satellite measurements to alleviate international water conflicts. However, certain critical scientists only trust their own devices and measurements obtained in a particular location, preferably operated by themselves and not by their colleagues. It is already known for quite some time that the quantification of water stocks, fluxes and flows in river basins will not necessarily be better if conventional point measurements are used. Pelgrum and Bastiaanssen (1996) demonstrated for instance that the regional scale actual evapotranspiration (ET) for an area of 10 000 km² cannot be predicted accurately even if 15 advanced flux towers are installed. Hence, in situ measurements are not the ultimate solution for determining water flows at river basin scale, although they are needed to verify local model predictions. The core issue is to determine the reliability of WA+ accounts if remote sensing input data is used.

This paper investigates the impact of the errors in remote sensing measurements on water accounting and the information provided to policy makers. The water accounting exercise in this study has been done at an annual scale because the monthly storage changes were not known with sufficient accuracy. Future studies will focus on monthly water accounts though. The degree of inaccuracies in remote sensing data is based on the comprehensive review of Karimi and Bastiaanssen (2015). The objective of the current paper is to study the impact of these errors on the water resources of two WA+ reporting sheets.

2 Background information

2.1 Awash Basin

The Awash River is located in the central Rift Valley in Ethiopia. The river emerges from the central highlands 150 km west of Addis Ababa and flows via the central Rift Valley to Lake Abbe on the border with Djibouti (Edossa et al., 2010). The mean annual rainfall is 530 mm and varies from about 1600 mm yr⁻¹ at Ankober, in the highlands northeast of Addis Ababa to 160 mm yr⁻¹ at Asayita on the northern border of the basin. The drainage area of the Awash River basin is 116 449 km² (Fig. 1). Lake Abbe is located in the downstream end of the basin and has an average size of 340 km² open water, surrounded by 110 km² of salt flats. The lake surface area and water depth fluctuates with rainfall and runoff. The water level can drop as much as 5 m. The maximum depth of the lake is 36 m.

The Awash Basin is located in the tectonically active East African Rift System and it has a complex geology. The complexity of geology of the basin has a direct impact on its hydrogeological characteristics and geohydrological flows. Groundwater flow is of key importance in the Awash Basin both as a major source of water supply for people and be-

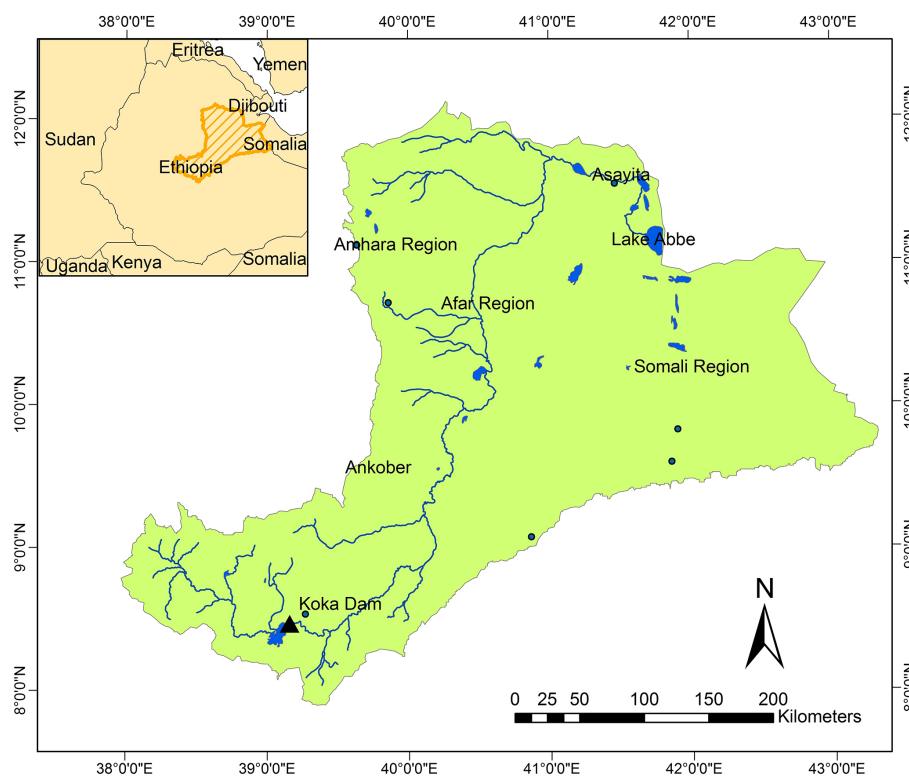


Figure 1. Location of the Awash River basin in the central Rift Valley of Ethiopia.

cause of its impact on hydrographs, especially during the dry period. The highland's fractured volcanic cover is favorable for groundwater recharge processes (Ayenew et al., 2008). Thus, groundwater recharge from the highlands is substantial. Groundwater gradually percolates into the lower aquifers through large marginal faults before it reaches the rift floor (Ayenew, 2001). In the upper and middle parts of the valley, the groundwater levels range between 30 and 70 m. The levels drop to lower than 200 m in some areas in the southern corner of the Awash Valley. In the upper basin, upstream of the Koka dam, the Awash River is hydraulically linked to the aquifers. However, this link weakens downstream of the dam. The major and deeper aquifers in this region are fractured basalt and ignimbrites. The axial faults together with the thickness and the extent of Quaternary deposits control groundwater occurrence below the pediment slopes. In the southern Afar plains the thick alluvio-colluvial deposits and the underlying Mesozoic limestones, dolomites and sandstones form highly productive aquifers. These aquifers are recharged by seasonal floods in wadis and wide river beds that are often highly permeable Quaternary deposits (Ayenew et al., 2008; Meskale, 1982). These aquifers are recharged by the streams that originate from the eastern highlands and seasonal floods that occur in summer.

The Awash Basin has an irrigation potential of 205 400 ha (FAO, 2003). Agriculture, providing livelihood for 85 % of the population, contributes to 45 % of Ethiopia's GDP. Ac-

ording to the FAO's AQUASTAT country fact sheet for Ethiopia, the country has an estimated 2.7×10^6 ha of irrigable land, yet only about 289 000 ha (11 %) are presently irrigated and only provides approximately 3 % of the country's food crop requirements. Most of the irrigation developed to date in Ethiopia is located in the Awash Basin.

The basin has been selected by the FAO as a case study for testing its approach in coping with water scarcity (FAO, 2012). Awash is experiencing water shortage for irrigated agriculture and for the wetlands and natural lakes along the riparian corridor of the river. The salt flows at the downstream end of the system are also suffering from water shortage, and there is a threat of salt storms when these flows dry up. It is therefore necessary to understand the hydrological processes and ecosystem services better, and summarize the management options. WA+ is an ideal framework for such a situation and has been applied to 3 consecutive years with rainfall varying from an average (510 mm yr^{-1}) in 2009, a high (862 mm yr^{-1}) in 2010, and a low (364 mm yr^{-1}) in 2011. Table 1 shows long-term average rainfall and potential ET (PET) in the Awash Basin.

2.2 Remote sensing input data used

Annual actual ET for the Awash Basin was computed by means of the two-layer ETLook surface energy balance model, using input data from MODIS (Moderate-

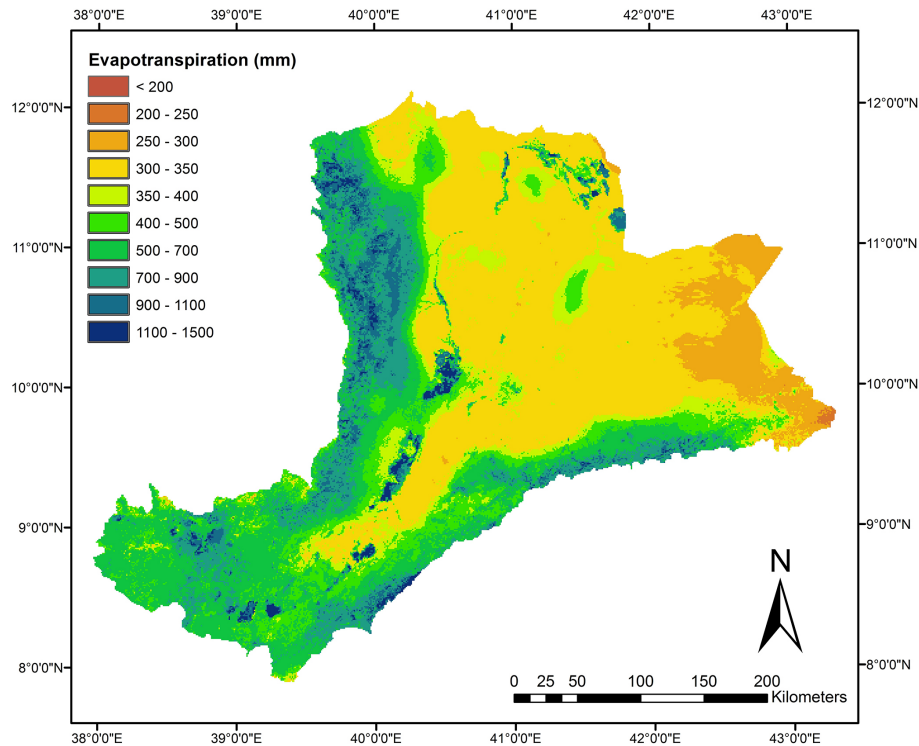


Figure 2. Spatial distribution of the annual ET of the Awash Basin for 2009 computed with the ETLook model (after Dost et al., 2013).

Table 1. Long-term average (1961–1990) rainfall and PET in the Awash Basin.

Month	Rainfall (mm month ⁻¹)	PET (mm day ⁻¹)
Jan	5.2	4.8
Feb	15.1	5.2
Mar	38.4	5.6
Apr	56.3	5.4
May	40.5	5.4
Jun	30.2	5.8
Jul	117.6	5.5
Aug	142.1	5.3
Sep	65.3	5.2
Oct	13.7	4.7
Nov	4	4.4
Dec	1.5	4.4

resolution Imaging Spectroradiometer; albedo, vegetation index), AMSR-E (Advanced Microwave Scanning Radiometer for EOS; top soil moisture) and Meteosat Second Generation (cloud cover). ETLook is based on a two-layer Penman–Monteith equation that describes soil evaporation and plant transpiration as separated physical processes (Bastiaanssen et al., 2012). Evaporation from wet leaves (i.e., interception) and open water is also computed. An interval of 8 days was

applied based on recurrent MODIS measurements, and the accumulated ET value for 2009 is presented in Fig. 2.

Daily rainfall maps were acquired from the US Agency for International Development (USAID) Famine Early Warning Systems Network (FEWS NET). FEWS NET is an information system designed to identify problems in the food supply system that can potentially lead to famine or other food-insecure conditions in the Horn of Africa, amongst other regions. FEWS NET provides daily rainfall with a spatial resolution of 8 km × 8 km. The FEWS RFE (rainfall estimate) 2.0 algorithm is implemented by NOAA's Climate Prediction Center and uses an interpolation method to combine Meteosat and global telecommunication system (GTS) data. More background information on the FEWS rainfall algorithm can be found in Herman et al. (1997). Figure 3 shows the spatial distribution of annual rainfall in 2009.

A new land use map customized for application of water accounting in the Awash Basin was generated by Dost et al. (2013). The basis for the new land use map is the existing GlobCover map (Bicheron et al., 2008). The new additions are related to the separation of rainfed and irrigated agriculture, and the temporal changes in the size of the open water body. The institute of Physical Geography of the Goethe University of Frankfurt developed the MIRCA (Monthly Irrigated and Rainfed Crop Areas) data set, containing monthly maps of growing areas and crop calendars of 26 irrigated and rainfed

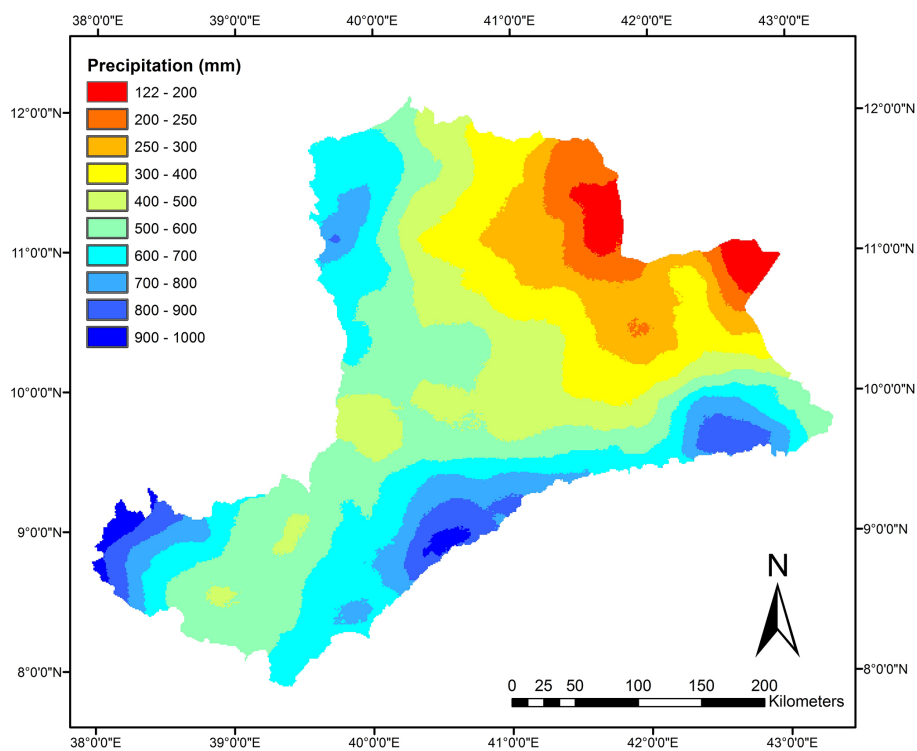


Figure 3. Spatial distribution of annual rainfall of the Awash Basin for the average rainfall year 2009 taken from FEWS Net (after Dost et al., 2013).

crops (documented at <http://www.geo.uni-frankfurt.de/jpg/ag/dl/forschun/MIRCA/index.html>). MIRCA contains data for 1999–2002 and has a spatial resolution of 5 arcmin (± 10 km). The cropped area is based on the period with maximum rainfed crop acreage. Areas equipped for irrigation are extracted from the irrigated area map of the FAO and the university of Kassel (Döll and Siebert, 2000). Since these data sets are to some extent outdated, a time series of the normalized difference vegetation index (NDVI) during 2009 was used to verify the crop phenology. Fallow land was identified and reclassified. Figure 4 shows the resulting locations of irrigated and rainfed cropland 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 for irrigation is exploited already. While the alluvial soils and flat topography are suitable for irrigation, the unreliability of water resources due to the overall water scarcity is the constraint for further land reclamation.

2.3 Water Accounting (WA+)

The latest version of the WA+ framework provides four sheets including (i) a resource base sheet, (ii) an evapotranspiration sheet, (iii) a productivity sheet, and (iv) a withdrawal sheet (Karimi et al., 2013a). The resource base sheet deals with water volumes and provides information on wa-

ter availability, water depletion and outflow processes. The evapotranspiration sheet distinguishes beneficial water depletion from non-beneficial depletion by partitioning total evapotranspiration (ET) into evaporation (E), transpiration (T), and interception (I). The productivity sheet links water depletion with benefits gained through biomass production. It extends to carbon sequestration, crop production and water productivity. The withdrawal sheet presents information on water withdrawals, depletions, and returns.

Each sheet has a set of indicators that are used to summarize the overall water resources situation. WA+ explicitly recognizes the influence of land use on the water cycle. To provide the link between land use and water use, land use classes with common management characteristics were defined. These are conserved land use (CLU), utilized land use (ULU), modified land use (MLU), and managed water use (MWU). CLU comprises environmentally sensitive land uses and natural ecosystems which are set aside for environmental protection. ULU represents a low to moderate resource utilization, such as savannah, woodland and mixed pastures which provide ecosystem services. MLU represents areas where the original vegetation was replaced for increased utilization of land resources or treatment of the soil. Rainfed crop land, plantations and biofuel crops are examples of replacement cover. The soil treatment can for instance be plowing, mulching and tilling. MWU represents landscapes that receive withdrawals by means of man-made

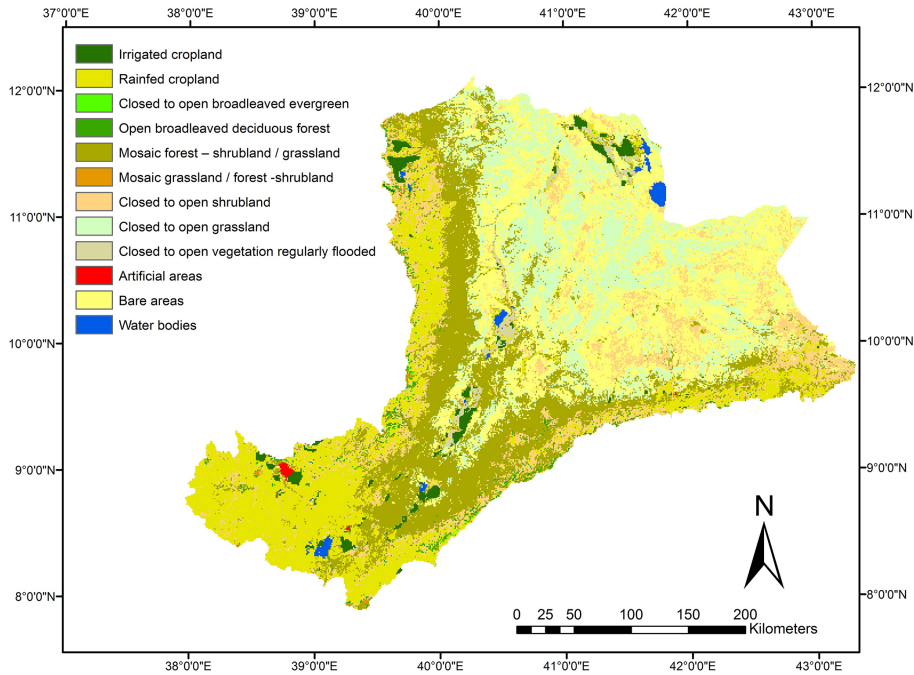


Figure 4. Updated spatial distribution of land use in the Awash Basin (after Dost et al., 2013).

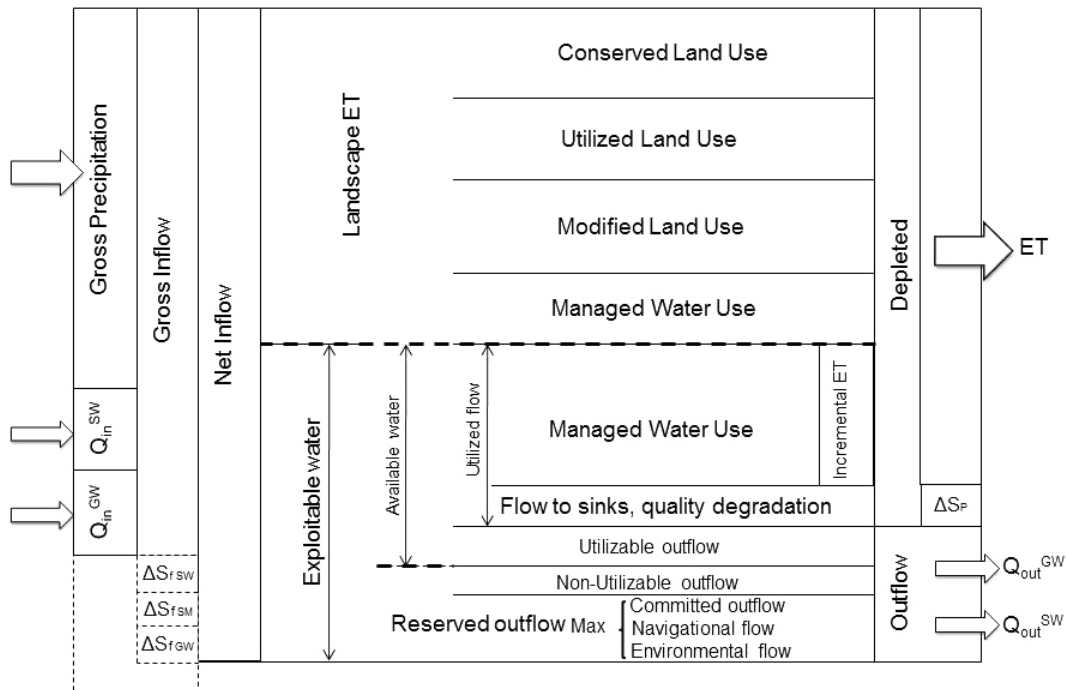


Figure 5. Resources base sheet for WA+ (after Karimi et al., 2013a).

infrastructure (diversion dams, canals, ditches, pumping stations, gates, weirs, pipes, etc.). This is also known as blue water usage (Falkenmark and Rockström, 2006).

The resource base sheet’s main components are gross inflow, storage change, net inflow, landscape ET, exploitable

water, available water, utilized flow, utilizable outflow, incremental ET, reserved outflow, non-utilizable outflow, and surface and groundwater outflows (see Fig. 5). Gross inflow is the total amount of water that flows into the domain, including precipitation and any inflow of surface or groundwater

Table 2. Key performance indicators of the resource base sheet.

Indicator	Definition	What does it indicate?
Exploitable water fraction	$\frac{\text{Exploitable water}}{\text{Net inflow}}$	The part of the net inflow that is not depleted by landscape ET, and thus exploitable
Storage change fraction	$\frac{\Delta S_{fw}}{\text{Exploitable water}}$	The dependency of exploitable water on fresh water storage change
Available water fraction	$\frac{\text{Available water}}{\text{Exploitable water}}$	The portion of exploitable water that is actually available for withdrawals
Basin closure fraction	$\frac{\text{Utilized water}}{\text{Available water}}$	The extent to which available water is depleted in a basin
Reserved outflow fraction	$\frac{\text{Reserved outflow}}{\text{Outflow}}$	The degree of meeting the flows set aside for interbasin transfer, navigation and environmental purposes

from adjacent basins. Net inflow is the gross inflow after correction for annual storage change (ΔS) and represents water available for landscape ET, and exploitable water. Landscape ET is the water that evaporates directly from the soil surface and water intercepted by the vegetation cover, as well as water taken up by plant roots and transpired into the atmosphere. Exploitable water represents water in reservoirs, rivers, lakes and groundwater that can be partitioned further into utilized, utilizable, non-utilizable and reserved outflows. Available water, the part of water that can be allocated to various water use sectors, would be a good definition for the often used term “renewable water resources”. Reserved outflow is the water that has to be reserved to meet the committed outflow, navigational flows, and environmental flow. Available water is the exploitable water minus reserved outflows and non-utilizable outflow. The latter is the part of water that cannot be utilized due to the lack of required infrastructure; e.g., a flash flood in utilized flow is the part of available water that is depleted by uses and hence is no longer available for downstream usage. Utilized flow is the difference between the withdrawals and the return flow from these withdrawals. Utilizable outflow is the available water for resources development and defined as the difference between available and utilized flow (see Fig. 5).

The resource base sheet indicators include the exploitable water fraction, storage change fraction, available water fraction, basin closure fraction, and the reserved outflows fraction. Exploitable water fraction is the part of the net inflow that is not depleted by landscape ET processes. Storage change fraction defines the degree of dependency of exploitable water on fresh storage change (ΔS_{fw}). Available water fraction relates available water to exploitable water. It describes the portion of exploitable water that is actually available for withdrawals within a basin because certain water resources have to be committed to sustain minimal environmental flows, navigation or should be allocated to users

outside the basin. Basin closure fraction describes to what extent available water is already depleted in a basin or domain. Reserved outflows fraction relates the reserved outflows to outflow via streams and aquifers. It indicates whether the committed outflows are being met. A summary is provided in Table 2.

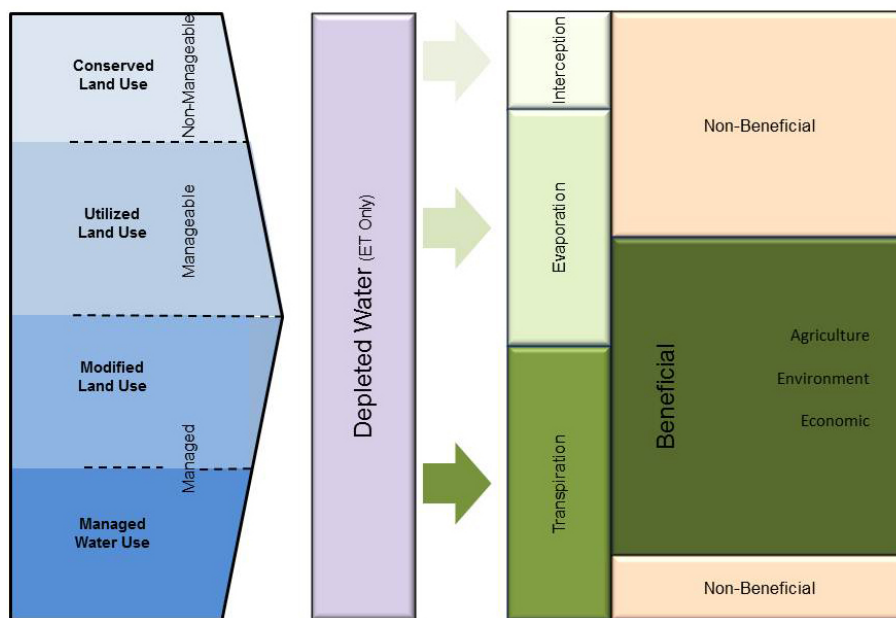
The WA+ evapotranspiration sheet (Fig. 6) relates ET to the generated benefits. ET processes are classed as managed, manageable, and non-manageable, which indicate the level of human influence on water consumption. The sheet provides a breakdown of ET into its components: interception evaporation, and transpiration. Knowing the proportion that each of these components contributes to total ET of each land use class makes it possible to determine the proportion of ET that has beneficial use, called *beneficial* ET, and the portion that does not have a beneficial use, called *non-beneficial* ET.

Beneficial ET comprises beneficial *T* and beneficial evaporation *E*. *T* is generally considered as beneficial. However, it can be considered non-beneficial in some cases such as for weed infestations in cropland or in degraded landscapes, or when it originates from non-desirable plants. *E* is usually considered as non-beneficial. However, the *E* in some cases such as evaporation from natural water surfaces is considered beneficial as these water bodies serve their purpose for fishing, aquatic birds, buffering floods, water sports, leisure, etc. In short, beneficial ET would be transpiration by usable vegetation cover (crops for example), and also evaporation from natural water surfaces and from cooling towers. Non-beneficial ET would be transpiration and evaporation from unwanted vegetation such as weeds and invasive species and evaporation from wet surfaces such as bare soil, buildings, and roads.

The evapotranspiration sheet indicators, summarized in Table 3, include a transpiration fraction, beneficial ET fraction, managed fraction, agricultural ET fraction, and irrigated ET fraction. The transpiration fraction is the proportion of ET

Table 3. Key performance indicators of the evapotranspiration sheet.

Indicator	Definition	What does it indicate?
Transpiration fraction	$\frac{T}{ET}$	The part of ET that is transpired by plants and it reflects a biophysical process.
Beneficial ET fraction	$\frac{E_{\text{beneficial}}+T_{\text{beneficial}}}{ET}$	Relates beneficial E and T to the total ET in a basin.
Managed ET fraction	$\frac{ET_{\text{managed}}}{ET}$	The ET processes in a basin that is manipulated by land use change, cultivation practices and water withdrawals.
Agricultural ET fraction	$\frac{\text{Agricultural ET}}{ET}$	The part of ET that is from agricultural activities.
Irrigated ET fraction	$\frac{\text{Irrigated agricultural ET}}{\text{Agricultural ET}}$	Irrigated ET fraction describes the portion of agricultural ET that is related to irrigated agriculture

**Figure 6.** Schematic representation of the evapotranspiration sheet.

that is transpired by plants and relates to net carbon assimilation of vegetation. The beneficial ET fraction relates beneficial E and T to the total ET in a basin. Managed ET fraction indicates the ET processes in a basin that are manipulated by land use change, soil treatment, cultivation practices and water withdrawals. This includes ET from managed water use, e.g., irrigated areas and urban parks, and ET from modified land use, e.g., rainfed areas. Agricultural ET fraction is the part of ET attributable to the agricultural production from rainfed and irrigated crops. Lastly, irrigated ET fraction describes the portion of agricultural ET that is related to irrigated agriculture.

2.4 Methodology to express the reliability of the WA+ framework

The Monte Carlo (MC) technique was used to validate the WA+ outputs. The MC technique involves selecting numbers randomly from a predefined probabilistic distribution and applying them in stochastic simulation. MC computes the variability of the WA+ output parameters by defining the variability of the input parameters. The variability in this case expresses the accuracy and thus confidence that can be attached to the outputs, because the variability of the input parameter space expresses error in the remotely sensed hydrological variables. The space of input parameters in this

Table 4. Statistics of the probability density function of variation for each remote sensing input parameter into WA+.

Remote sensing parameter	Shape α	Shape Δ	Skewness γ (-)	Scale ω	Variance (%)	Standard deviation error (%)	Location ζ	Mean (%)
ET	25	1.000	1.18	2.444	2.17	4.7	3.5	5.4
Rainfall	6.4	0.988	0.90	3.218	3.92	15.4	16.0	18.5
Land use	1.66	0.856	0.35	2.258	2.72	7.4	13.1	14.6

Table 5. Annual total precipitation and ET in the Awash Basin averaged over the 3 yr: 2009, 2010 and 2011. Rainfall and ET data are based on remote sensing. The actual evapotranspiration is partitioned into evaporation, transpiration and interception following ETLook principles.

Year	Rainfall (mm)	ET (mm)	Interception (mm)	Evaporation (mm)	Transpiration (mm)	Biomass production (kg ha ⁻¹)
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

MC study is defined by a skewed normal distribution as explained by Karimi and Bastiaanssen (2015). The statistical input data are specified in Table 4. A program was developed to generate random numbers from a positively skewed normal distribution based on mean, variance and skewness. This code handled only skewness smaller or equal to 1.0 and hence this number has been modified accordingly. The skewness γ is defined as the third standardized moment (γ_3):

$$\gamma_3 = \frac{4 - \pi}{2} \frac{(\delta \sqrt{2/\pi})^3}{(1 - \frac{2\delta^2}{\pi})^{3/2}}, \tag{1}$$

where δ and α are shape parameters:

$$\delta = \frac{\alpha}{\sqrt{1 + \alpha^2}}. \tag{2}$$

The variance is described by means of the scale ω and δ as

$$\text{variance} = \omega^2 \left(1 - \frac{2\delta^2}{\pi}\right). \tag{3}$$

The means value of the population can be computed from the location ζ :

$$\text{mean} = \varepsilon + \omega \delta \sqrt{\frac{2}{\pi}}. \tag{4}$$

The results of this exercise is a set of 1000 WA+ resource base sheets and evapotranspiration sheets, each of them based on a unique combination of ET, rainfall and land use. Care has been taken that the total basin area is conserved and that the mass balance of water flows applies. While in

simulations the distribution of different land use classes was flexible and a function of randomly chosen error, a constant correction factor was applied to all land use classes to match the total basin area of 116449 km² and hence keep the total physical area constant. The 1000 WA indicators were then analyzed to determine their accuracy and thus reliability.

3 Awash Basin results

3.1 Baseline hydrology and water accounting

Rainfall and ET are the two most important hydrological variables for WA+. The average rainfall from FEWS NET for the 3 yr investigated is 582 m yr⁻¹ (see Table 5). The average ET computed with ETLook is 507 mm yr⁻¹, which compares well with the average rainfall. Note that ETLook is based on an energy balance and is computed independent from rainfall. The magnitude of the annual ET for the different years is apparently dampened, which could be ascribed to compensating effects of atmospheric demand and soil moisture availability: dry years have a high potential ET but the ET reduction due to soil moisture stress is high as well, yielding an ET value similar to lower potential ET but lower reductions due to soil moisture stress. This behavior is also observed for ET from other surface energy balance models in the Nile Basin (e.g., Yilmaz et al., 2014). Dry years also partially compensate the lack of infiltrated water by consuming moisture from the unsaturated zone that is carried over from a previous wetter year.

Another interesting observation is that soil and water evaporation (304 mm) exceed transpiration (182 mm). The rela-

tively low values of transpiration and interception are due to the reduced fractional vegetation cover in the Awash Basin, especially during the dry season. A large portion of the basin has barren land and the vegetation is senescent during elongated dry periods. The ETLook results show that transpiration from the vegetation (rainfed crops and hillslope forests) in the western and southern parts of the basin and the irrigated croplands are the major contributing factors to evapotranspiration in the river basin during the dry winters. During the rainy season, transpiration is higher due to the increased photosynthesis and biomass production of natural vegetation. In the eastern plains, evaporation values rise as the soil is saturated with water during the wet summer period, while the transpiration remains low due to the low vegetation cover.

Many national and international sources report a mean annual surface runoff of 4.6–4.9 km³ yr⁻¹ for the Awash Basin (e.g., Behailu, 2004; Edossa et al., 2010). This annual runoff data is based on measured discharge rates. This surface water flow is withdrawn by irrigation systems, wetlands, inundation areas and lakes. The long-term average annual flow at the Awash station in the middle of the basin is 1.7 km³ yr⁻¹, revealing that a substantial part is withdrawn in the upstream part of the basin (approximately 3 km³ yr⁻¹). The non-utilized water from Awash River flows into the saline depressions of Afar at the downstream end of the basin, where it is exposed to evaporation. In 2009, the average rainfall year of this study, total evaporation from all natural lakes amounted to 622 × 10⁶ m³ yr⁻¹, while the rainfall over these lakes was only 278 Mm³ yr⁻¹. This difference of 344 × 10⁶ m³ yr⁻¹ must be the inflow to the lakes from the Awash River, which matches the flow measured near the Awash station. This finding shows that all Awash Basin surface water resources are consumed and that no surface water outflow takes place. Awash is an example of a basin in which the available water is depleted (Molden, 1997).

Hence, all river flow that is not recharging the aquifer evaporates inside the basin either as a result of withdrawals or due to evaporation from the sink at the downstream end of the system. The evaporation from terminal lakes is included in the total ET value of 507 mm yr⁻¹ (see Table 5). Hence, the rainfall surplus of 75 mm (582–507 mm) or 8.7 km³ yr⁻¹ is not related to surface runoff and has to go somewhere else. The only possible outlet is underground basin discharge. Taddese et al. (2003) refer to a study of UNDP (1973) that estimates the total groundwater recharge in Awash to be 3.8 km³ yr⁻¹, while EVDSA (1989) estimated 4.1 km³ yr⁻¹. Ayenew et al. (2008) reported a basin-wide average recharge of 30 mm, which is equivalent to 3.5 km³ yr⁻¹. These estimates are mutually close, and the average number is 3.8 km³ yr⁻¹. Groundwater flows towards the downstream end of the basin at Lake Abbe, where the elevation is only 240 m. Ayenew et al. (2008) describe a regional groundwater flow in the direction of the Afar Depression. While detailed groundwater studies were not available, a regional flow of 3.8 km³ yr⁻¹ is likely. This assumes that

Table 6. Annual water balance of the Awash Basin for the selected hydrological years. The basin area is 116 449 km².

Year	Rainfall (km ³)	ET (km ³)	Basin outflow (km ³)	Storage change (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

all groundwater recharge will flow across the basin boundaries into deep depressions in the Horn of Africa. Since deep regional groundwater flow is usually rather stationary, variability of rainfall will have a limited impact on this interbasin transfer process. As such, in the absence of data and information on groundwater flows in the basin, it is assumed – without any scientific underpinning computations – that the basin outflow should not fluctuate more than 50%. This assumption is used to define lower and upper boundaries for changes in annual groundwater outflow, allowing for a range of between 2.5 and 5.7 km³ yr⁻¹. This is a basis for computing the storage changes for the 3 different rainfall years analyzed (see Table 6), which must have significantly more dynamics than a deep quasi-stationary groundwater flow. Since the storage change is calculated as a residual term for *P* minus ET minus the underground recharge, it is important to note that it collects the errors of all three parameters including the error that assumed underground recharge might have. Thus, to have better and more accurate estimates of these flows, further research is needed to understand groundwater flows and outflows from the Awash Basin. A large uncertainty will be associated with groundwater outflow in the stochastic analysis described in the next section.

There is an unexplained difference between the 8.7 km³ yr⁻¹ basin rainfall surplus and a groundwater recharge of 3.8 km³ yr⁻¹ that requires more detailed discussion. It is possible that some groundwater seeps to deeper levels via faults and tectonic plates. Another possible explanation is the change in storage. The storage changes among years must be significant and this is confirmed by reported changes in water levels of lakes and reservoirs. These storage changes occur in lakes and reservoirs, as well as in the deep aquifers of the Awash Basin. The average area of water bodies is 754 km² and wetlands cover 1078 km². If we assume that one-third of the 2010 storage (29.7 km³ yr⁻¹) takes place in the aquifer and unsaturated zone (i.e., 9.9 km³ yr⁻¹), then two-thirds of the storage change had to be stored as surface water (19.8 km³ yr⁻¹), which over 1832 km² (754 + 1078 km²) signifies a rise in surface water level of 10.8 m. Reported changes in water levels are of 5 m, meaning that the area of open water bodies and wetlands expands with a factor of 2 during a wet year

Table 7. Rainfall and ET by land use class for 2009, 2010 and 2011. CLU is conserved land use, ULU is utilized land use, MLU is modified land use, and MWU is managed water use.

Land use class	Area km ²	Precipitation (mm)			ET (mm)			
		2009	2010	2011	2009	2010	2011	
Bare areas	CLU	1270	352	757	222	340	433	340
Closed to open grassland	CLU	1639	362	779	217	336	425	335
Closed/open vegetation regularly flooded	CLU	17	356	745	238	392	447	372
Rainfed croplands	CLU	39	520	727	340	364	407	376
Closed to open shrubland	CLU	173	343	698	225	326	342	308
Mosaic forest–shrubland/grassland	CLU	778	631	818	418	370	418	382
Irrigated cropland	CLU	24	674	718	425	795	864	810
Bare areas	ULU	30579	387	728	255	340	382	343
Closed to open grassland	ULU	16132	413	740	266	347	388	345
Closed to open shrubland	ULU	12936	557	935	399	489	551	484
Mosaic forest–shrubland/grassland	ULU	24414	608	930	420	507	618	525
Open broadleaved deciduous forest	ULU	1376	678	1017	505	705	771	686
Mosaic grassland/forest–shrubland	ULU	327	690	1026	528	841	883	797
Closed/open vegetation regularly flooded	ULU	1078	426	784	309	931	1142	963
Closed to open broadleaved evergreen or semideciduous forest	ULU	102	637	960	524	969	945	889
Water bodies	ULU	746	373	681	340	833	878	953
Rainfed croplands	MLU	22546	638	1034	504	687	796	697
Water bodies	MWU	8	667	691	415	499	533	414
Irrigated cropland	MWU	2145	550	854	428	826	924	867
Artificial areas	MWU	120	703	1130	587	533	520	493

for hosting a storage of $19.8 \text{ km}^3 \text{ yr}^{-1}$. Expansion and level changes do happen and, together with some unknown deep seepage of groundwater, explain the total water balance.

A basic component of water accounting is the distribution of the rainfall and ET across all land use classes. Table 7 shows that the classes open broadleaved deciduous forests, mosaic forest shrubland/grassland and rainfed cropland receive more rainfall than the other land use classes, which indeed is the source of the existence of these types of vegetation. The highest ET is found in the land use class of ‘regularly flooded closed and open vegetation. These are the wetlands in the riparian corridor of Awash River system. ET is highest in the wet year when a larger contiguous layer of water is ponded in these wetlands. The average ET for this particular land use class in 2010 is 1142 mm, and the rainfall is 784 mm. Hence, this inundation water must come from upstream drainage areas. The evaporation from water bodies is lower than for wetlands because the saline sinks of the Afar depression are also included in this data set, and these brines evaporate significantly less than wetlands.

The WA+ framework was applied for the average rainfall year, 2009, using Table 7 as input and the basin outflows as specified in Table 6. The flow to sink has been assigned a zero value because all surface flow is assumed to be depleted by evaporation and it thus included already in the ULU class. Reserved flow, which is the required flow to maintain a specific constant river flow, was fixed in accordance with

the general guidelines for environmental flow requirements (Smakhtin and Eriyagama, 2008). Environmental flows were estimated to be $622 \times 10^6 \text{ m}^3 \text{ yr}^{-1}$, being the river flow required to meet the evaporation from natural lakes. The calculation is based on the assumption that this volume water is necessary to maintain the lakes and consequent conservation of aquatic ecosystems. The basin has no surface outflow and, since evaporation from the lakes is already accounted for, the outflow from the basin is through underground flows. These flows recharge the aquifers and leave the basin through underground interbasin transfers as outlined in the previous section. This outflow could be utilized by installing deep pumping stations that withdraw from this water before it flows away. We thus assume this portion of water to be utilizable, although in reality the abstraction should be an economic discussion. The resulting resource base sheet is presented in Fig. 7.

The results show that the ULU class is with $37.7 \text{ km}^3 \text{ yr}^{-1}$ depleting the majority of the net inflow of $60.2 \text{ km}^3 \text{ yr}^{-1}$. This contributes to ecosystem services and grazing. The benefits and value of these depletion processes are moderate to low, especially considering that the majority is bare soil evaporation. The largest value is related to the biodiversity of flora and fauna. The MLU class depletes $15.5 \text{ km}^3 \text{ yr}^{-1}$, and this contributes to a better food security in the basin. MLU consists of rainfed crops such as wheat and teff that occupy an area of 2 254 600 ha. Depletion from surface water with-

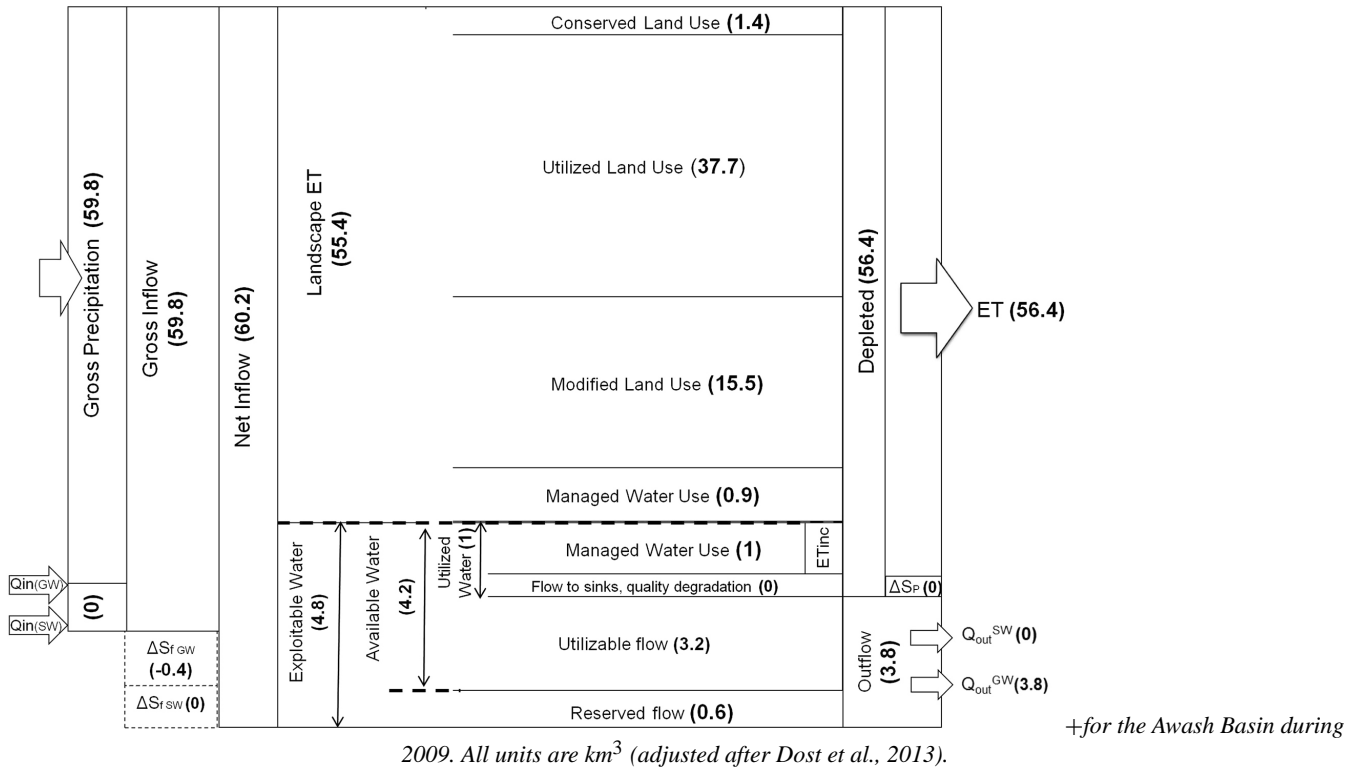


Figure 7. Resource base sheet of WA

drawals to irrigated land, industry and domestic water use is with 1 km³ yr⁻¹ minimal. While the depletion of this water provides many benefits in terms of energy, the economy and domestic services, the amount of water being depleted is very low compared to the significant amount of water depleted by utilized land use. Land use planning is thus crucial for improving the benefits from water depletion in the Awash Basin. The introduction of agroforestry systems and short-duration low-water consuming crops could generate more benefits (e.g., Baudron et al., 2014). A volume of 3.2 km³ is utilizable flow. This is groundwater that is not utilized. Options for groundwater abstraction and expansion of irrigated areas could be appraised.

3.2 Probability distribution of WA+ for 2009

The goal of this paper is to investigate the difference between the reference data of Table 7 and the results if the remote sensing input data is made variable according to the errors identified by Karimi and Bastiaanssen (2015). For this purpose the average rainfall year 2009 has been analyzed. The frequency distribution of the input parameters, randomly generated through the Monte Carlo technique based on their levels of uncertainty, is demonstrated in Fig. 8.

While precipitation and ET follow a similar unimodal normal distribution, the area of each land use class follows a bimodal distribution. This different result for land use is related

to two factors: firstly, the error is an absolute error and, secondly, the skewness of error probability distribution is low. The error probability distribution function (PDF) of both precipitation and ET are highly skewed to the right (see Table 4). The implication is that the majority of cases have an error that is less than the mean value. As such, randomly generated inputs tend to be more concentrated. For example, the mean absolute error for ET is 5.4 % with a high positive skewness of 1.18. This implies that the majority of randomly generated error levels are less than 5.4 %, with a higher proportion between 0 and 4 % which is the median. Therefore, the generated input data are concentrated around one peak maximum between -4 and +4 %, which creates a unimodal distribution. For land use area, the low skewness of the error probability distribution function would imply that the randomly generated inputs are concentrated around the absolute mean of 14.5 %, which generates two peaks of -14.5 and +14.5 %. Because the error is absolute, the observed distribution in the randomly generated input follows a mirrored shaped of the error PDF for each parameter (see Karimi and Bastiaanssen, 2015).

In addition to variability of remote sensing input data, outflow and reserved flow have also been made variable. Outflow was allowed to vary between 2.5 and 5.7 km³ yr⁻¹ (see Table 6). The reserved flow variability was taken as equal to the observed variability of lake evaporation. The water balance of the Awash Basin was closed by mass conservation

on the storage change. An example of the variability of two output parameters is demonstrated in Fig. 9.

The results are 1000 versions of the WA+ sheets. Table 8 shows the mean value of all 1000 different versions, referred to as the stochastic mean. The differences between the original results – using the reference values – and the stochastic mean are often within a few percent, except for a few interesting cases where the differences are 10.6 % (storage change), 6.3 % (utilizable flow), 7.6 % (beneficial ET fraction), 9.4 % (basin closure fraction) and 10.6% (reserved flow fraction). These differences are mainly a result of the larger variability that each of these parameters have. A few numerical outliers in the population of the output data distribution of a given parameter can yield a different mean value of the 1000 water accounts. The large uncertainty of (groundwater) outflow and its translation into utilizable flow (outflow is utilizable plus reserved flow) is the root cause of these differences and is in agreement with the general difficulty of estimating the groundwater flow of hydrological systems. Since the storage change is the residual of the water balance, it will automatically also get a large variability. The resource base performance indicators follow the same trend as the absolute values. Hence, the absence of reliable outflow data has, in this specific case study, impacts on the uncertainty of utilizable flow and storage change and thus also on the basin closure fraction.

The stochastically generated data sets of error ranges can be described by an interval around the mean value. This gives an indication of the error probability and accuracy of each of the parameters in a standardized way; it will allow comparing the variability of different parameters. The band widths surrounding the mean value at 95 % confidence intervals for the main input and output parameters of WA+ resource base and evapotranspiration sheets are presented in Table 8.

The interim conclusion is that MC simulations provide a slightly different result to standard modeling which, for certain parameters, can exceed 5 %. Since the consideration of larger variability of certain terms is realistic, it is recommended to run the WA+ sheets always in the MC mode.

3.3 Temporal variability and error probabilities for multiple years

To understand the temporal variability of the error band width in WA+, the MC analysis was extended to multiple years. The covered period was 2009–2011. As explained earlier, the period includes an average rainfall year, 2009, a wet year, 2010, and a dry year, 2011. For every year the MC model was run 1000 times and a stochastic mean for each WA+ parameter was calculated. To normalize the variability of the error component, their CVs (coefficients of variation) were calculated for all the parameters. Table 9 summarizes the results of this exercise.

The CV is an indication of the variability of the population of output values of one particular parameter. In this case, a

larger variability can be attributed to a larger uncertainty of the MC results. A CV of 10 % or less is generally considered indicative of a very good accuracy because the variability is within an acceptable value range of a particular variable. CV values in the range of 10–20 % are deemed acceptable and are close to the accuracy that is generally achieved through field measurements. Estimates with CVs of more than 20 % require caution and those with CVs of 40 % are unreliable. However, in all the cases the mean value must also be considered because a low mean value with a high CV may represent a smaller variation range compared to a high mean with a low CV.

Figure 10 illustrates the temporal variability of CVs for all the WA+ parameters and performance indicators in the study period. A low average CV value implies that the frequency distribution of a single WA parameter for a given year has a relatively minor variability, meaning that the results are stable and accurate. The CV for multiple years of the CV of the stochastic distribution of a single parameter is indicated by the height of the bar. The latter reflects how vulnerable a decision is on the time frame considered for the water accounting. A certain WA+ parameter can be more accurate in a low rainfall year than during a high rainfall year. The results indicate that CVs for available water, exploitable water, utilized flow, and the outflow, vary from year to year, which is a mere consequence of the combination of the temporal variable rainfall and temporal constant ET values. Consequently, the performance indicators that are related to these parameters have varying CVs. These include exploitable water fraction, basin closure fraction, and the reserved flow fraction. In general, more temporal variability implies lower accuracy.

An important observation is that the majority of the performance indicators show low sensitivity to the input data. Four out of eight indicators, i.e., available water fraction, T fraction, managed fraction, and beneficial fraction, have CVs of less than, or close to, 10 % in all 3 yr. Another two indicators, exploitable water fraction and irrigated ET fraction, have average CVs of close to 20 % which fall in the acceptable range. All the parameters and indicators that have CVs of less than 20 % are deemed to be reliable and can be used in policy formulation processes. However, some of the indicators such as basin closure fraction have a high average CV and a high temporal variability. The same applies to utilized flow, utilizable flows, and the reserved flow fraction. This shows that these parameter and indicators should be treated with caution and should not be used to formulate policy decisions. Most inaccurate indicators are related to the outflows and their low reliability is directly linked to the lack of accurate information on groundwater outflows. The uncertainty of groundwater flows is a general problem in ungauged basins (Hrachowitz et al., 2013) and should not be interpreted as being typical for the Awash Basin. Hence, extra allocation of water and exploitation of utilizable flows are highly unreliable, and should not be done without some cross-examination and execution of advanced groundwater studies. First priority should

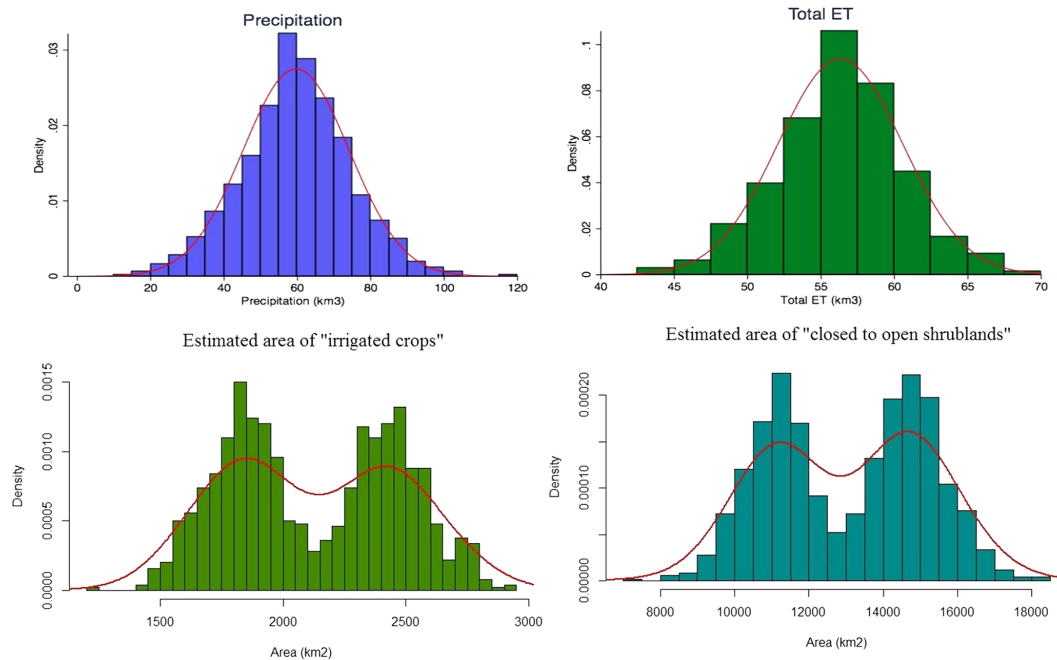


Figure 8. Example of the frequency distribution of the randomly simulated input parameters ET, rainfall and land use into the Monte Carlo simulations for 2009 (for land use estimated area of two classes, i.e., irrigated crops and closed to open shrublands, are demonstrated).

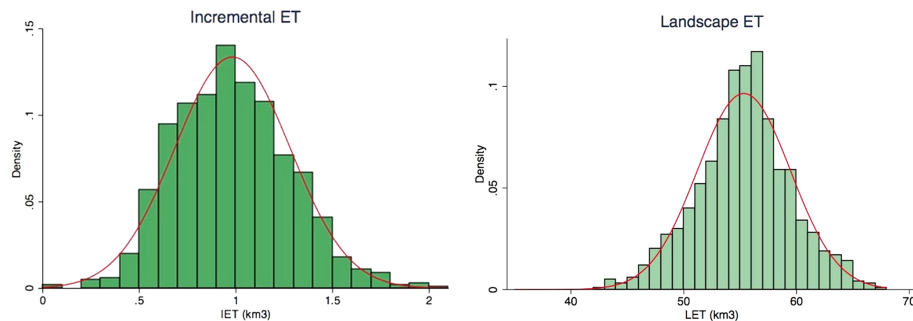


Figure 9. Variability of two selected output parameters for 2009, i.e., incremental ET and landscape ET, following from the Monte Carlo simulation of 1000 runs.

be given to understanding spatial and temporal variability of the less-known flows in any basin. In other basins, however, outflow could be measured or modeled with a much more comfortable accuracy, which will make it feasible to make decisions on re-allocation of available water resources. Hence, the uncertain outflow is specific for the Awash Basin.

4 Summary and conclusions

WA+ is a novel analytical framework that summarizes complex hydrological processes and water management issues in river basins. The framework uses state of the art satellite-based measurements of land and water consumption to quantify hydrological variables and water accounts. This makes WA+ to a large extent independent from conventional hy-

drological measurements. Such independence is necessary to apply WA+ on any river basin, including poorly gauged and ungauged basins. However, the use of satellite-based measurements for water accounting may raise concerns about the reliability of the accounts if they have not been verified on the ground. To address this concern, this paper examined the impact of the errors in satellite-based input data to WA+ on the confidence that policy makers can have in the outputs and information provided.

The focus of the study was on the WA+ resource base sheet and evapotranspiration sheet. ET, precipitation, and land use are the three main satellite-based spatial data sets used for these two sheets. The Awash Basin in the central Rift Valley in Ethiopia was used to demonstrate the influence that errors in the input data could have on the confidence in the outputs. The analysis covered a period of 3 yr which included

Table 8. Difference between standard and stochastic modeling of the WA+ outputs for 2009 (RB – resource base).

Parameter	Reference computation (km ³)	Stochastic mean (km ³)	Confidence interval (0.95) (km ³)	Difference between standard and stochastic mean
Resource base sheet				
Precipitation	59.80	59.96	±28.55	0.3 %
Storage change	−0.40	−0.45	±26.98	10.6 %
Net inflow	60.20	60.41	±7.76	0.3 %
Landscape ET	55.37	55.36	±7.74	0.0 %
Exploitable water	4.83	5.05	±2.77	4.4 %
Available water	4.21	4.42	±2.80	4.9 %
Utilized flow	0.98	0.98	±0.59	0.0 %
Reserved flows	0.62	0.62	±0.24	0.5 %
Outflow	3.84	4.07	±3.10	5.4 %
Utilizable flow	3.22	3.44	±3.14	6.3 %
Evapotranspiration sheet				
Total ET	56.36	56.35	±7.98	0.0 %
ET managed	17.34	17.33	±5.14	0.0 %
<i>T</i> total	18.00	18.00	±3.42	0.0 %
<i>E</i> total	36.31	36.30	±5.03	0.0 %
<i>I</i> total	2.05	2.05	±0.37	0.0 %
Beneficial depletion	20.08	18.66	±3.50	7.6 %
Non-benef. depletion	36.28	37.69	±5.20	3.7 %
RB sheet indicators*				
Exploitable water fraction	0.08	0.08	±0.05	4.1 %
Available water fraction	0.87	0.87	±0.09	0.6 %
Basin closure fraction	0.23	0.26	±0.26	9.4 %
Reserved flow fraction	0.16	0.18	±0.16	10.6 %
Evapotranspiration sheet indicators*				
<i>T</i> fraction	0.32	0.32	±0.03	0.1 %
Managed fraction	0.31	0.31	±0.07	0.2 %
Beneficial fraction	0.36	0.33	±0.03	7.7 %
Irrigated ET fraction	0.10	0.11	±0.05	5.4 %

* Indicators are dimensionless.

an average rainfall year (510 mm yr^{−1}) 2009, a wet year (862 mm yr^{−1}) 2010, and a dry year (364 mm yr^{−1}) 2011. Spatial ET data for the Awash Basin was computed by means of the ETLook model. Daily rainfall maps were acquired from the FEWS NET, and a land use map, customized by Dost et al. (2013) was also used for the application of water accounting in the Awash Basin. The errors in these satellite-based land and water use measurements are based on a comprehensive review by Karimi and Bastiaanssen (2015). The Monte Carlo technique that is based on selecting numbers randomly from a predefined probabilistic distribution was used for stochastic simulation of WA+ outputs. The simulation was repeated 1000 times for all 3 yr.

The results of this exercise show that the stochastic mean of the majority of WA+ parameters and performance indi-

cators (13 out of 25) are within a 1 % deviation from the original value. Out of 25, 19 are within a 5 % deviation. The maximum deviation of 10 % was observed for the storage change and reserved flow fraction. This shows that stochastic simulation can be used as part of a standard procedure to produce water accounts with WA+. There are two main advantages related to the MC technique. Firstly, it allows for the incorporation and acknowledgement of input data errors in producing water accounts. Secondly, it provides the possibility to estimate and report on the error bandwidth that surrounds every WA+ output. The latter is of essential value to informed decision making, as it enables users to better understand the error margin that is associated with the generated information. The goal is to separate reliable information from that with low reliability. In such a way, outputs with a

Table 9. Temporal variability of WA+ across a longer period with low and high rainfall years.

Parameter	2009		2010		2011	
	Mean	CV	Mean	CV	Mean	CV
Resource base sheet						
Precipitation	59.96	24 %	101.51	23 %	42.84	24 %
Storage change	−0.45	–	30.81	77 %	−17.25	61 %
Net inflow	60.41	6.8 %	70.70	6.7 %	60.09	6.8 %
Landscape ET	55.36	7.4 %	64.60	7.2 %	56.20	7.2 %
Exploitable water	5.05	27 %	6.10	12 %	3.89	15 %
Utilized flow	0.98	30 %	0.71	52 %	1.26	23 %
Available water	4.42	5.3 %	5.44	14 %	3.17	18 %
Reserved flows	0.62	18 %	0.66	19 %	0.71	20 %
Outflow	4.07	38 %	5.40	17 %	2.62	22 %
Utilizable flow	3.44	45 %	4.74	20 %	1.91	30 %
Evapotranspiration sheet						
Total ET	56.35	7.5 %	65.30	7.3 %	57.46	7 %
ET managed	17.33	15 %	20.01	15 %	17.65	15 %
<i>T</i> total	18.00	10 %	25.95	9 %	20.76	9.3 %
<i>E</i> total	36.30	7.3 %	36.25	7 %	34.61	6.8 %
<i>I</i> total	2.05	9.6 %	3.11	8.8 %	2.10	9 %
Beneficial depletion	18.66	9.8 %	26.64	8.9 %	21.49	9.2 %
Non-benef. depletion	37.69	7.3 %	38.66	6.9 %	35.97	6.8 %
Indicators						
Exploitable water fraction	0.08	27 %	0.09	13 %	0.06	15 %
Available water fraction	0.87	5 %	0.89	3 %	0.81	5 %
Basin closure fraction	0.26	51 %	0.14	73 %	0.40	20 %
Reserved flow fraction	0.18	45 %	0.13	39 %	0.28	22 %
<i>T</i> fraction	0.32	5 %	0.40	3 %	0.36	4 %
Managed fraction	0.31	12 %	0.31	12 %	0.31	12 %
Beneficial fraction	0.33	5 %	0.41	3 %	0.37	4 %
Irrigated ET fraction	0.11	21 %	0.10	21 %	0.11	20 %

high error margin and low reliability will be identified and it is recommended that they should not be used to formulate policy decisions. This reliability can be normalized and quantified by calculating coefficients of variation for all the WA+ parameters.

Results of the multiyear analysis for the Awash Basin, after incorporating input data error, showed that the majority of WA+ parameters and performance indicators have CVs of less than 20 % which implies that they are reliable. The results also indicate that parameters and indicators such as utilized flow, utilizable flow, and basin closure fraction have a high margin of error and thus have low reliability. This implies, for instance, that despite the fact that accounting results show that the utilizable flow is on average about $3.4 \text{ km}^3 \text{ yr}^{-1}$, this estimate has low reliability. The same applies for the figures related to basin closure fraction and utilized flow. In other words, although the accounting outputs, i.e., utilized flow, utilizable flow, and basin closure fraction, suggest that more water can be utilized in the basin, the high

margin of error associated with these outputs means they are not reliable enough to be used for formulating policy decisions. As such, more research with more accurate input data is required to verify and endorse such possibilities which, in this case, are related to uncertain groundwater flows in deeper geological layers. This finding applies to the Awash Basin and cannot be generalized because for many basins, the discharge at the river mouth is not properly measured or modeled.

Every measurement, regardless of the method used, has some level of uncertainty. In many instances, hydrologists and engineers know the uncertainty associated with in situ measurements such as runoff, canal water levels, etc., yet these estimates are used in studies and in policy decision making. It is a fact that compared to ground measurements, our knowledge on the accuracy of remote-sensing-based estimates of hydrological parameters is less complete. The review conducted by Karimi and Bastiaanssen (2015) provides essential information in this regard for annual and seasonal

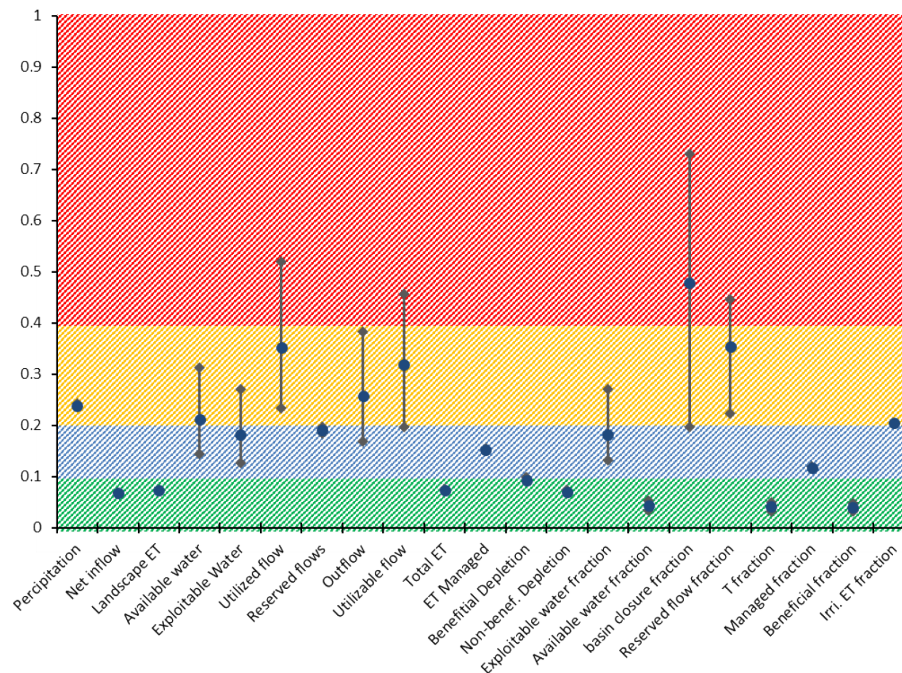


Figure 10. The level of inaccuracy expressed as a coefficient of variation for a dry, a wet and an average rainfall year. The height of the bars expresses temporal variability. The background colors indicate where a certain parameter should be considered in the water management decision process.

estimates. At this timescale, remote-sensing-based model performance outweighs monthly, weekly, and daily scale estimates that are known to have larger uncertainties. The important point is to acknowledge these uncertainties while processing information and inform the users accordingly. Nevertheless, remote-sensing-based information can be very valuable in data-scarce areas of the world and can contribute to bridging spatial scales in hydrology (Stewart et al., 1996).

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References

- Allen, R. G., Tasumi, M., Morse, A., Trezza, R., Wright, J. L., Bastiaanssen, W., Kramber, W., Lorite, I., and Robison, C. W.: Satellite-Based Energy Balance for Mapping Evapotranspiration with Internalized Calibration (METRIC) – Applications, *J. Irrig. Drain. Eng.*, 133, 395–406, 2007.
- Ayew, T.: Numerical groundwater flow modelling of the Central Main Ethiopian Rift lakes basin, *SINET Ethiop. J. Sci.*, 24, 167–184, 2001.
- Ayew, T., Kebede, S., and Alemyahu, T.: Environmental isotopes and hydrochemical study applied to surface water and groundwater interaction in the Awash, *Hydrol. Process.*, 22, 1548–1563, doi:10.1002/hyp.6716, 2008.
- Bastiaanssen, W. G. M.: Water accountants: de nieuwe generatie waterbeheercontroleurs, *intreerede*, in: Inaugural Address, Delft University of Technology, Delft, the Netherlands, p. 16, 2009.
- Bastiaanssen, W. G. M. and Chandrapala, L.: Water balance variability across Sri Lanka for assessing agricultural and environmental water use, *Agr. Water Manage.*, 58, 171–192, 2003.
- Bastiaanssen, W. G. M., Cheema, M. J. M., Immerzeel, W. W., Miltenburg, I., and Pelgrum, H.: The surface energy balance and actual evapotranspiration of the transboundary Indus Basin estimated from satellite measurements and the ETLook model, *Water Resour. Res.*, 48, W11512, doi:10.1029/2011WR010482, 2012.
- Bastiaanssen, W. G. M., Karimi, P., Rebelo, L.-M., Duan, Z., Senay, G., Mutuwatte, L., and Smakhtin, V.: Earth observation-based assessment of the water production and water consumption of Nile Basin Agro-Ecosystems, *Remote Sensing*, 6, 10306–10334, 2014.
- Baudron, F., Jaleta, M., Okitoi, O., and Tegegn, A.: Conservation agriculture in African mixed crop-livestock systems: Expanding the niche, *Agr. Ecosyst. Environ.*, 187, 171–182, 2014.
- Behailu, S.: Stream flow simulation for the Upper Awash Basin, MSc Thesis, Addis Ababa University, Addis Ababa, 2004.
- Bicheron, P., Defourny, P., Brockmann, C., Schouten, L., Vancutsem, C., Huc, M., Bontemps, S., Leroy, M., Achard, F., Herold, M. F., Ranera, F., and Arino, O.: GLOBCOVER Products Report Description and Products Description and Validation Report, MEDIAS, Toulouse, France, 2008.
- CA: Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture, Earthscan, London and International Water Management Institute, Colombo, 2007.

- Döll, P. and Siebert, S.: A digital global map of irrigated areas, *ICID J.*, 49, 55–66, 2000.
- Dost, R., Obando, E. B., Bastiaanssen, W., and Hoogeveen, J.: Background report: Water accounting+ in the Awash River Basin, eLEAF Report, Wageningen, the Netherlands, 56 pp., 2013.
- Drooger, P., Simons, G. W. H. G., Bastiaanssen, W. G. M., and Hoogeveen, J.: Water accounting Okavango; Coping with water scarcity – developing national water audits Africa, WaterWatch, Wageningen, the Netherlands, 58 pp., 2010.
- Edossa, D. C., Babel, M. S., and Das Gupta, A.: Drought Analysis in the Awash River Basin, Ethiopia, *Water Resour. Manage.*, 24, 1441–1460, doi:10.1007/s11269-009-9508-0, 2010.
- EVDSA – Ethiopian Valleys Development Studies Authority: Master plan for the development of Surface water resources in the Awash Basin, Addis Ababa, Ethiopia, 1989.
- Falkenmark, M. and Rockström, J.: The new Blue and Green water paradigm: Breaking new ground for water resources planning and management, *J. Water Resour. Pl. Manage.*, 132, 129–132, 2006.
- FAO: Review of world water resources by country, Water Report No. 23, Rome, Italy, 2003.
- FAO: Coping with water scarcity; an action framework for agriculture and food security, Water Reports No. 38, FAO, Rome, Italy, 78 pp., 2012.
- Herman, A., Kumar, V. B., Arkin, P. A., and Kousky, J. V.: Objectively determined 10-day African rainfall estimates created for famine early warning systems, *Int. J. Remote Sens.*, 18, 2147–2159, doi:10.1080/014311697217800, 1997.
- Hrachowitz, M., Savenije, H. H., Bloschl, G., McDonnell, J. J., Sivapalan, M., Pomeroy, J., Arheimer, B., Blume, T., Clark, M. P., Ehret, U., Fenicia, F., Freer, J. E., Gelfan, A., Gupta, H. V., Hughes, D. A., Hut, R., Montanari, A., Pande, S., Tetzlaff, D., Troch, P. A., Uhlenbrook, S., Wagener, T., Winsemius, H., Woods, R. A., Zehe, E., and Cudennec, C.: A decade of Predictions in Ungauged Basins (PUB) – a review, *Hydrolog. Sci. J.*, 58, 1198–1255, 2013.
- Karimi, P., Molden, D., Bastiaanssen, W. G. M., and Cai, X.: Water accounting to assess use and productivity of water: evolution of a concept and new frontiers, in *Water accounting: International approaches to policy and decision-making*, edited by: Godfrey, J. M. and Chalmers, K., Edward Elgar Publishing, Cheltenham, UK, 76–88, 2012.
- Karimi, P., Bastiaanssen, W. G. M., and Molden, D.: Water Accounting Plus (WA+) – a water accounting procedure for complex river basins based on satellite measurements, *Hydrol. Earth Syst. Sci.*, 17, 2459–2472, doi:10.5194/hess-17-2459-2013, 2013a.
- Karimi, P., Bastiaanssen, W. G. M., Molden, D., and Cheema, M. J. M.: Basin-wide water accounting based on remote sensing data: an application for the Indus Basin, *Hydrol. Earth Syst. Sci.*, 17, 2473–2486, doi:10.5194/hess-17-2473-2013, 2013b.
- Karimi, P. and Bastiaanssen, W. G. M.: Spatial evapotranspiration, rainfall and land use data in water accounting – Part 1: Review of the accuracy of the remote sensing data, *Hydrol. Earth Syst. Sci.*, 19, 507–532, doi:10.5194/hess-19-507-2015, 2015.
- Meskale, M.: Hydrogeology of South Afar and adjacent areas, MSc Thesis, International Inst. for Aerial Survey and Earth Sciences, Enschede, the Netherlands, 1982.
- Molden, D.: Accounting for water use and productivity, SWIM paper 1, International Water Management Institute, Colombo, Sri Lanka, 1997.
- Molden, D. and Sakthivadivel, R.: Water Accounting to Assess Use and Productivity of Water, *Int. J. Water Resour. Dev.*, 15, 55–71, doi:10.1080/07900629948934, 1999.
- Neale, C. M. U., Geli, H. M. E., Kustas, W. P., Alfieri, J. G., Gowda, P. H., Evett, S. R., Prueger, J. H., Hipps, L. E., Dulaney, W. P., Chávez, J. L., French, A. N., and Howell, T. a.: Soil water content estimation using a remote sensing based hybrid evapotranspiration modeling approach, *Adv. Water Resour.*, 50, 152–161, doi:10.1016/j.advwatres.2012.10.008, 2012.
- Pelgrum, H. and Bastiaanssen, W. G. M.: An Intercomparison of Techniques to Determine the Area-Averaged Latent Heat Flux from Individual in Situ Observations: A remote Sensing Approach Using the European Field Experiment in a Desertification-Threatened Area Data, *Water Resour. Res.*, 32, 2775–2786, doi:10.1029/96WR01396, 1996.
- Shilpakar, R. L., Bastiaanssen, W. G. M., and Molden, D. J.: A remote sensing-based approach for water accounting in the East Rapti River Basin, Nepal, *Himal. J. Sci.*, 7, 15–30, 2012.
- Smakhtin, V. U. and Eriyagama, N.: Developing a software package for global desktop assessment of environmental flows, *Environ. Model. Softw.*, 23, 1396–1406, 2008.
- Stewart, J. B., Engman, E. T., Feddes, R. A., and Kerr, Y.: *Scaling up in hydrology using remote sensing*, Wiley, New York, 270 pp., 1996.
- Taddese, G., Sonder, K., and Peden, D.: The water of the Awash River basin a future challenge to Ethiopia, Addis Ababa, Ethiopia, 2003.
- UNDP: *Geology, geochemistry and hydrology of hot springs of the East African Rift system within Ethiopia*, New York, 1973.
- UN-Water: UN-Water country briefs project, Geneva, 2013.
- Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R., and Davies, P. M.: Global threats to human water security and river biodiversity, *Nature*, 467, 555–561, doi:10.1038/nature09440, 2010.
- Wolf, A. T., Yoffe, S. B., and Giordano, M.: International waters?: identifying basins at risk, *Water Policy*, 5, 29–60, 2003.
- Yilmaz, M. T., Anderson, M. C., Zaitchik, B., Hain, C. R., Crow, W. T., Ozdogan, M., Chun, J. A., and Evans, J.: Comparison of prognostic and diagnostic surface flux modeling approaches over the Nile River basin, *Water Resour. Res.*, 50, 386–408, doi:10.1002/2013WR014194, 2014.