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

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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 as input data. A 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 three years. The results show that the stochastic mean of the majority of WA+ parameters and performance indicators are within 5 % deviation from the original values. Stochastic simulation can be used as part of a standard procedure for WA+ water accounting because it provides the error bandwidth for every WA+ output, which is essential information for sound decision making. The majority of WA+ parameters and performance indicators have a Coefficient of Variation (CV) of less than 20 % which implies that they are reliable. The results 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 it is recommended that they are not used to formulate important policy decisions.

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). WA+ has the ability to accommodate satellite measurements to quantify land use and hydrological variables. WA+ is a successor of the International water Management institute (IWMI) WA that was introduced by Molden (1997) and Molden and Sakthivadivel (1999) for

describing the depletion of water resources in river basins. Whereas 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 designed to use remote sensing data. Remote sensing information can replace hydro-meteorological data sets measured in situ, especially when administrations are reluctant to share data, and 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 agro-ecological 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, 1996). A recent literature review by Karimi et al. (2013b) showed that the average error in land use, precipitation and evapotranspiration mapping on the basis of multi-spectral remote sensing data was 14.5, 18.5, and 5.4 % respectively. Such errors are not worse than classical ground-based observations. They are thus suitable for application in WA+ for any river basin, including ungauged basins. Bastiaanssen and Chandrapala (2003), Karimi et al. (2012), Droogers et al. (2010), Shilpakar et al. (2012), Karimi et al. (2013b) and Dost et al. (2012) used remote sensing data for the water accounts of un-gauged 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. While field devices are considered reliable measurement instruments, the radiometer onboard a satellite is often interpreted as futuristic, and not having accurate measurement capabilities.

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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; river and canal discharge is often based on water levels or the sound of water flow, rather than direct measurements; Leaf Area Index is based on intercepted solar radiation, and is not a direct measurement of 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 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, some critical scientists only trust their own devices and measurements obtained on a particular location, preferably by themselves. It is already known for quite some time that the quantification of water stocks 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 km^2 cannot be predicted accurately even if 15 advanced flux towers are installed. Hence, in situ measurements are not the ultimate for determining water flows at river basin scale. 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 degree of inaccuracy in remote sensing data are based on the comprehensive review of Karimi and Bastiaanssen (2014). The objective of the current paper is to study the impact of these errors on two WA+ sheets.

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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 north east 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 km^2 (Fig. 1). Lake Abbe is located in the downstream end of the basin and has an average size of 34 000 ha open water, surrounded by 11 000 ha 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. Groundwater flows are of key importance in the Awash basin both as a major water supply for people and its impact on surface water flows. The highland's fractured volcanic cover is favorable for groundwater recharge processes (Ayenew et al., 2008). Thus, groundwater recharge from the highlands is substantial and it flows in a relatively shallow depth. Groundwater gradually percolates into the lower aquifers through large marginal faults before it reaches the rift floor (Ayenew, 2001). In the Upper and Middle 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. In the Middle valley groundwater levels are considerably lower than the Awash River, with consequent recharge from the river to the aquifers. The major and deeper aquifers in this region are fractured basalts 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 sand- stones 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, 1997). Agriculture, providing livelihood for 85 % of the population, contributes to 45 % of GDP. According to the FAO's Aquastat country fact sheet for Ethiopia, the country has an estimated 2.7 million hectares of irrigable land, yet only about 289 000 ha (11 %) is 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 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 floes at the downstream end of the system are also suffering from water shortage, and there is a threat of salt storms when these floes dry up. It is therefore necessary to understand the hydrological processes better, and summarize the management options. WA+ is an ideal framework for such a situation and has been applied to three consecutive years with rainfall varying from an average (510 $\text{mm}\,\text{yr}^{-1}$) in 2009, a high (862 $\text{mm}\,\text{yr}^{-1}$) in 2010, and a low (364 $\text{mm}\,\text{yr}^{-1}$) in 2011. Table 1 shows long term average rainfall and potential ET (PET) in the Awash basin.

2.1.1 Remote sensing input data used

Actual evapotranspiration (ET) for the Awash basin was computed by means of the ETLook model, using input data from MODIS (albedo, vegetation index), AMSR-E (top soil moisture) and Meteosat Second Generation (cloud cover). ETLook is 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

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and open water are also computed. An interval of eight days was applied, and the accumulated value for the three-yearly cycle is presented in Fig. 2.

Daily rainfall maps were acquired from the US Agency for International Development (USAID) Famine Early Warning Systems Network (FEWSNET). FEWSNET 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. FEWSNET provides daily rainfall with a spatial resolution of 8 km × 8 km. The FEWS RFE 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).

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 data set, containing monthly maps of growing areas and crop calendars of 26 irrigated and rainfed crops (Portmann et al., 2010). 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 FAO and the university of Kassel (Döll and Siebert, 2000). Since these datasets 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

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alluvial soils and flat topography are suitable for irrigation, the unreliability of water resources is the constraint for further development.

2.2 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 water 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 define. These are “Conserved Land Use” (CLU), “Utilized Land Use” (ULU), “Modified Land Use” (MLU), and “Managed Water Use” (MWU). CLU are 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 infrastructure (diversion dams, canals, ditches, pumping stations, gates, weirs, pipes, etc.). This is also known as blue water usage (Falkenmark and Rockström, 2006).

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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 ground water from adjacent basins. Net inflow is the gross inflow after correction for 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 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. It represents the water that is available for allocation. 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: exploitable water fraction, storage change fraction, available water fraction, basin closure fraction, 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. Basin closure fraction describes to what extent available water is already depleted in a basin or domain. Reserved outflows

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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 use. The sheet provides a breakdown of ET into its components interception evaporation, and transpiration. Knowing the proportion that each of these components contribute 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.

Non-beneficial ET occurs through physical processes such as evaporation (from soil, water), interception evaporation from wet leaves and canopies (Rutter et al., 1971; Savenije, 2004) and wet surfaces (e.g. buildings, roads), and transpiration from weed infestations in cropland or in degraded landscapes, or when there are non-desirable plants

The evapotranspiration sheet indicators, summarized in Table 3, include: transpiration fraction, beneficial ET fraction, managed fraction, agricultural ET fraction, and irrigated ET fraction. The transpiration fraction is the proportion of ET that is transpired by plants and which has an impact on the bio-physical process in water scarce basins. 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 could be manipulated by land use, cultivation practices and water withdrawals. Agricultural ET fraction is the part of ET attributable to the agricultural production. Lastly, Irrigated ET fraction describes the portion of agricultural ET that is related to irrigated agriculture.

2.3 Methodology to express the reliability of the WA+ framework

The Monte Carlo (MC) technique was used to validate the WA+ outputs. The MC involves selecting numbers randomly from a pre-defined probabilistic distribution and applying it for stochastic simulation. MC computes the variability of the WA+ output

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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 MC study is defined by a skewed normal distribution as explained by Karimi and Bastiaanssen (2014). The statistical input data are specified in Table 4. A program was developed that 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):

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

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 ϖ and δ as:

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

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

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

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

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and land use. Care has been taken that the total basin area is conserved and that the mass balance of water flows applies. A constant correction factor was applied to all land use classes to match the total basin area of 116 449 km^2. 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 FEWSNET for the three years investigated is 582 $m\,yr^{-1}$, and the standard deviation is 256 mm (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 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 could be ascribed 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 as well, and these two phenomena compensate each other yielding temporal stable ET rates. Dry years also cause water stored in the unsaturated zone and carried over from a previous wetter year to be accessed.

Another interesting observation is that soil and water evaporation (304 mm) exceed transpiration (182 mm). The relative low values of transpiration and interception is probably 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 part 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. In

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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.

Many national and international sources report a mean annual surface runoff of 4.6–4.9 $km^3 yr^{-1}$ for the Awash basin (e.g. Behailu, 2004; Edossa et al., 2010). Reported annual runoff data is based on measured discharge rates. The surface water resources are internally re-distributed among 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 $km^3 yr^{-1}$. 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, which was the average rainfall year of this study, total evaporation from all natural lakes amounted to 622 $Mm^3 yr^{-1}$, while the rainfall over these lakes was only 278 Mm3 yr^{-1}. This difference of 344 $Mm^3 yr^{-1}$ must be from inflow to the lakes from the Awash River, which matches with the flow near Awash station. This finding shows that all Awash basin surface water resources are consumed, and 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. The evaporation of 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 $km^3 yr^{-1}$ 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 $km^3 yr^{-1}$, while EVDSA (1989) estimated 4.1 $km^3 yr^{-1}$. Ayenew et al. (2008) reported a basin wide average recharge of 30 mm, which is equivalent to 3.5 $km^3 yr^{-1}$. These estimates are mutually close, and the average number is 3.8 $km^3 yr^{-1}$. Groundwater flows towards the downstream end of the basin at Lake Abbe, where the elevation is only 240 m. Ayenew et al. (2008) confirms a regional groundwater flow in the direction of the Afar Depression. While detailed groundwater studies were not available, a regional flow of 3.8 $km^3 yr^{-1}$ is likely. This assumes that all groundwater recharge will flow across the

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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 inter-basin transfer process. It is assumed – without any scientific underpinning computations – that the basin outflow should not fluctuate more than 50 %, allowing a range between 2.5 and 5.7 $km^3 yr^{-1}$. This is a basis to compute the storage changes for the three different rainfall years analyzed (see Table 6).

There is an unexplained difference between the 8.7 $km^3 yr^{-1}$ basin rainfall surplus and a groundwater recharge of 3.8 $km^3 yr^{-1}$ 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 km^2 and wetlands cover 1078 km^2. If we assume that one-third of rainfall surplus water is stored in the aquifer and unsaturated zone, then two-thirds of the large storage change in 2010 of 29.7 km^3 had to be stored as surface water. Two-thirds is equivalent to 19.8 $km^3 yr^{-1}$ which at 1832 km^2 (754 + 1078 km^2) signifies a rise in surface water level of 10.8 m. Reported changes in water levels are 5 m, meaning that the area of open water bodies and wetlands expands with a factor 2 during a wet year. Expansion and level changes do happen, which together with some unknown deep seepage of groundwater explains 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. 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

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inundation water must come from the upstream areas. The evaporation from water bodies is lower than for wetlands because the saline sinks of the Afar depression are also included in this dataset, 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 with 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 is thus included already in the class Utilized Land Use. 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 $622 \times 10^6\,m^3\,yr^{-1}$, being the river flow that evaporates from natural lakes. The calculation is based on the assumption that this much of 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. Theses flows recharge the aquifers and leave the basin through underground inter-basin transfers. This outflow could be utilized by installing deep pumping stations and we thus assumed this portion of water to be utilizable. The resulting resource base sheet is presented in Fig. 7.

The results show that the class Utilized Land Use is with $37.7\,km^3\,yr^{-1}$ depleting the majority of the net inflow of $60.2\,km^3\,yr^{-1}$. This contributes to ecosystem services and grazing. The benefits and value from these depletion processes are moderate, especially considering that the majority is from bare soil evaporation. The largest value is related to the biodiversity of flora and fauna. The class Modified Land Use depletes $15.5\,km^3\,yr^{-1}$, and this contributes to a better food security of 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 withdrawals to irrigated land, industry and domestic water users is with $1\,km^3\,yr^{-1}$ minimal. While the depletion of this water provides many benefits in terms of energy, economy and domestic services, the amount of water being depleted

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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 agro-forestry systems and short duration low water consuming crops especially, could generate more benefits (e.g. Baudron et al., 2013). An amount of 3.2 km^3 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 (2014). For this purpose the average rainfall year 2009 has been analyzed. The variability of the input parameters, randomly generated through the Monte Carlo technique, is demonstrated in Fig. 8.

While precipitation and ET follow a similar uni-modal normal distribution, area of each land use class follows a bi-modal distribution. This different result for area 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 concentration between 0 to 4 % which is the median. Therefore the generated input data are concentrated around one peak maximum between −4 and +4 %. For 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 error PDF for each parameter (see Karimi and Bastiaanssen, 2014).

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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 $km^3 yr^{-1}$ (see Table 6). The reserved flow variability was taken as equal to the 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 the 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 difference is 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. Since the storage change is the residual of the water balance, it will also have 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 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 parameters in a standardized way; it will allow comparison of 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.

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The interim conclusion is that MC simulations provide a slightly different result to standard modeling, which for certain parameters can exceed 5 %. Since 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 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 error in the MC results. A CV of 10 % and less is generally considered as 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 value implies that the frequency distribution for a given year has a relatively minor variability, meaning that the results are accurate. The range of the average CV for multiple years is indicated by the height of the bar, and it reflects how vulnerable a decision is on the time frame considered for the water accounting. The results indicate that CVs for some

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of the parameters including "available water", "exploitable water", "utilized flow", and the "outflow", vary from year to year. 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 CV's less than, or close to 10 % in all the three years. Another two indictors, "exploitable water fraction" and "irrigated ET fraction", have average CVs close to 20 % which fall in the acceptable range. All the parameters and indictors that have CVs less than 20 % are deemed to be reliable and can be used in policy formulation processes. On the other hand, some of the indictors such as "basin closure fraction" have a high average CV and a high temporal variability. The same accounts for "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. Hence, extra allocation of water and exploitation of utilizable flows are highly unreliable, and should not be done without some cross examination.

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 use to quantify hydrological variables and water accounts. This makes WA+ framework application to a large extent independent from conventional hydrological measurements. This independence makes it feasible 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

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the ground. To address this concern this paper examined the impact of the errors in satellite based input data to WA+ on the confidence 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 three years which included 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 Famine Early Warning Systems Network (FEWS NET) and a land use map, customized by Dost et al. (2013) for 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 (2014). The Monte Carlo technique that is based on selecting numbers randomly from a pre-defined probabilistic distribution was used for stochastic simulation of WA+ outputs. The simulation was repeated 1000 times for all three years.

The results of this exercise show that the stochastic mean of the majority of WA+ parameters and performance indicators (13 out of 25) are within 1 % deviation from the original value. Nineteen out of 25 are within 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 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 those that have low reliability. In such a way, outputs with a high error margin,

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

Results of the multi-year 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 on average is about 3.4 $km^3 yr^{-1}$, this figure is not reliable. The same applies for the figures related to “basin closure fraction” and “utilized flow”. In another word, 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 mean 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.

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Table 1. Long term average rainfall and potential ET (PET) in the Awash basin.

Month	Rainfall ($mm\,month^{-1}$)	PET ($mm\,day^{-1}$)
Jan	5.2	4.82
Feb	15.1	5.23
Mar	38.4	5.57
Apr	56.3	5.4
May	40.5	5.44
Jun	30.2	5.82
Jul	117.6	5.53
Aug	142.1	5.33
Sep	65.3	5.18
Oct	13.7	4.73
Nov	4	4.41
Dec	1.5	4.36

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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 inter-basin transfer, navigation and environmental purposes

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Table 3. Key performance indicators of the evapotranspiration sheet.

Indicator	Definition	What does it indicate ?
Transpiration fraction	$\frac{T}{\text{ET}}$	the part of ET that is transpired by plants and it reflects a bio-physical process
Beneficial ET fraction	$\frac{E\_\text{beneficial}+T\_\text{beneficial}}{\text{ET}}$	relates beneficial E and T to the total ET in a basin
Managed ET fraction	$\frac{\text{ET managed}}{\text{ET}}$	the ET processes in a basin that could be manipulated by land use, cultivation practices and water withdrawals
Agricultural ET fraction	$\frac{\text{Agricultural ET}}{\text{ET}}$	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

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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 ϖ	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

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Table 5. Annual total precipitation and ET in the Awash basin averaged over the three years 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

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Table 6. Annual water balance of Awash basin for the selected hydrological years. The basin area is 116 449 km^2.

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

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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	Precipitation (mm)			ET (mm)		
		km^2	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	30 579	387	728	255	340	382	343
Closed to open grassland	ULU	16 132	413	740	266	347	388	345
Closed to open shrubland	ULU	12 936	557	935	399	489	551	484
Mosaic Forest-Shrubland/Grassland	ULU	24 414	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 semi-deciduous forest	ULU	102	637	960	524	969	945	889
Water bodies	ULU	746	373	681	340	833	878	953
Rainfed croplands	MLU	22 546	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

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Table 8. Difference between standard and stochastic modeling of the WA+ outputs for 2009.

Parameter	Reference computation (km^3)	Stochastic Mean (km^3)	Conf. 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 %
T Total	18.00	18.00	±3.42	0.0 %
E Total	36.31	36.30	±5.03	0.0 %
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*				
T 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 %
Irri. ET fraction	0.10	0.11	±0.05	5.4 %

* Indicators are dimensionless.

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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 %
T Total	18.00	10 %	25.95	9 %	20.76	9.3 %
E Total	36.30	7.3 %	36.25	7 %	34.61	6.8 %
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 %
T 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 %
Irri. ET fraction	0.11	21 %	0.10	21 %	0.11	20 %

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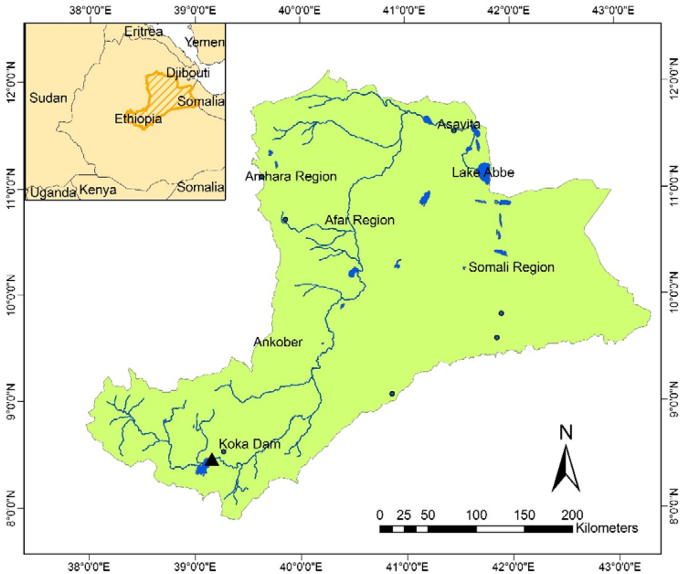

Fig. 1. Location of the Awash River basin in the Central Rift Valley of Ethiopia.

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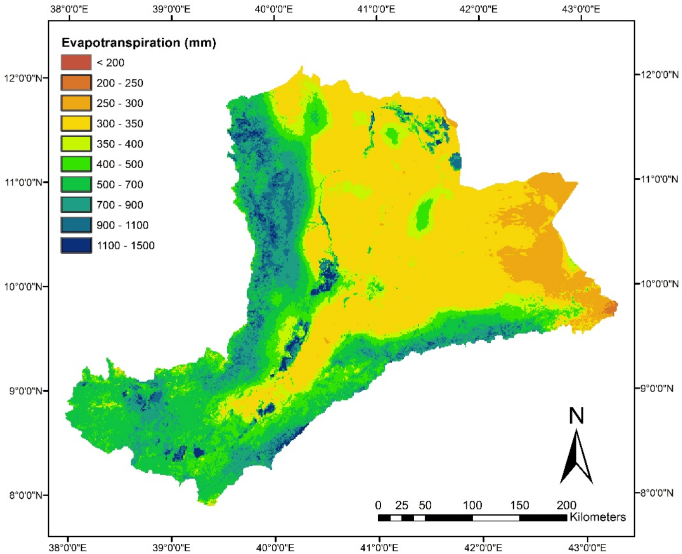

Fig. 2. Spatial distribution of the annual ET of the Awash basin for 2009 computed with the ETLook model (after Dost et al., 2013).

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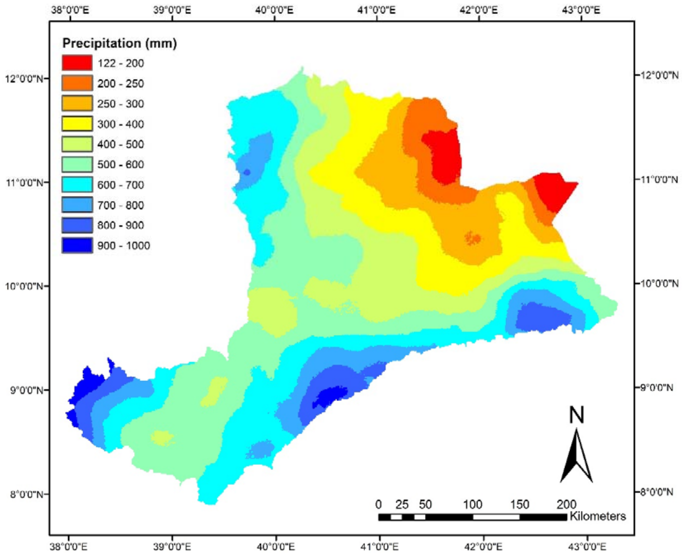

Fig. 3. Spatial distribution of annual rainfall of the Awash basin for the average rainfall year 2009 taken from FewsNet (after Dost et al., 2013).

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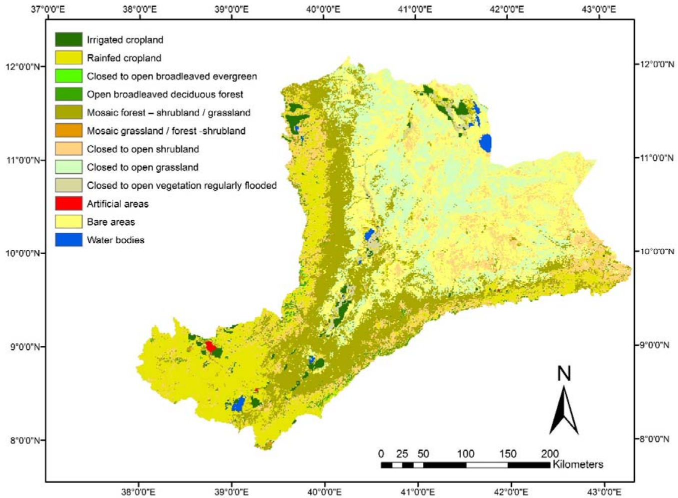

Fig. 4. Updated spatial distribution of land use in the Awash basin (after Dost et al., 2013).

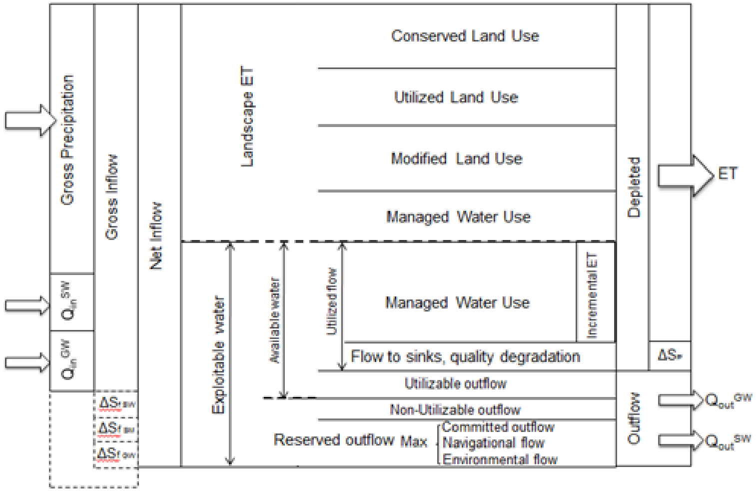

Fig. 5. Resources base sheet for WA+ (after Karimi et al., 2013a).

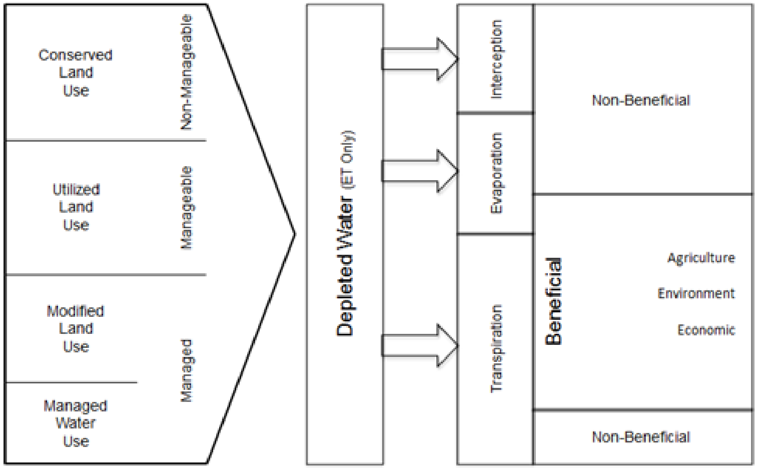

Fig. 6. Schematic representation of the evapotranspiration sheet (after Karimi et al., 2013a).

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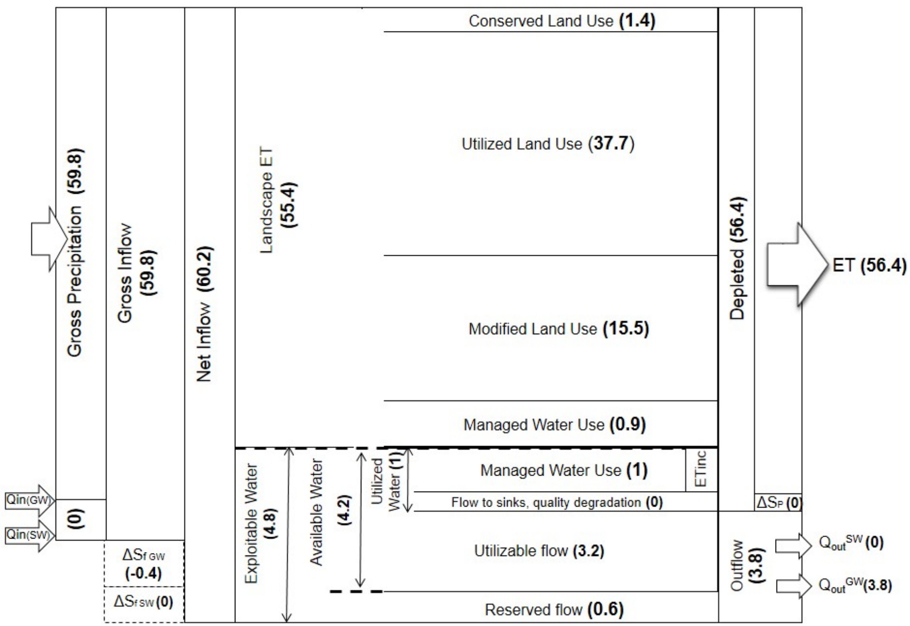

Fig. 7. Resource base sheet of WA+ for the Awash basin during 2009. All units are km^3 (adjusted after Dost et al., 2013).

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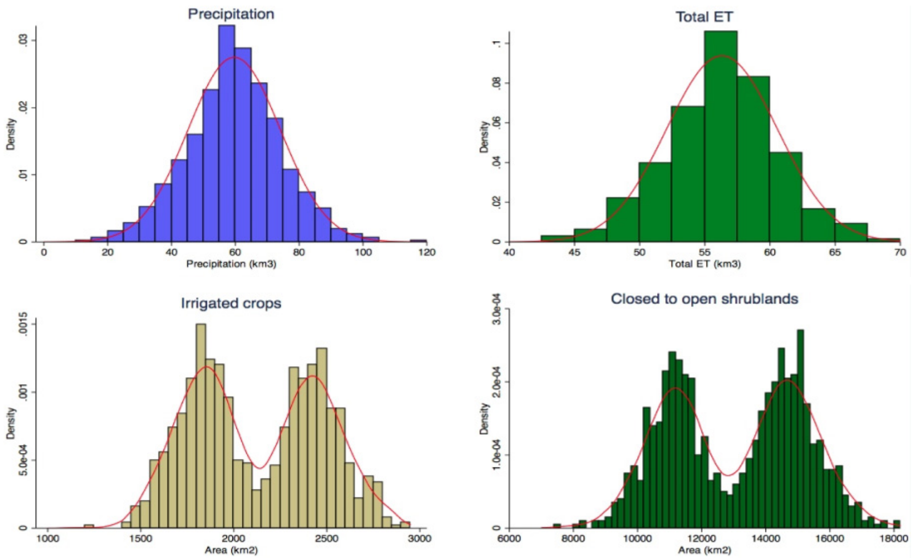

Fig. 8. Example of the variability of the 2009 input parameters ET, rainfall and land use (two classes; e.g. irrigated crops and closed to open shrublands into the Monte Carlo simulations).

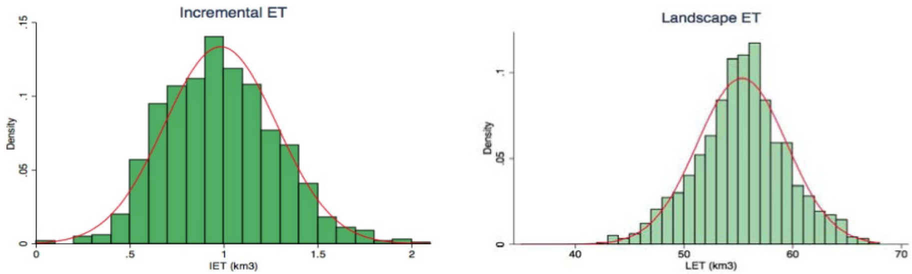

Fig. 9. Variability of two selected output parameters for 2009 i.e. incremental ET and landscape ET following from the Monte Carlo simulation of 1000 runs.

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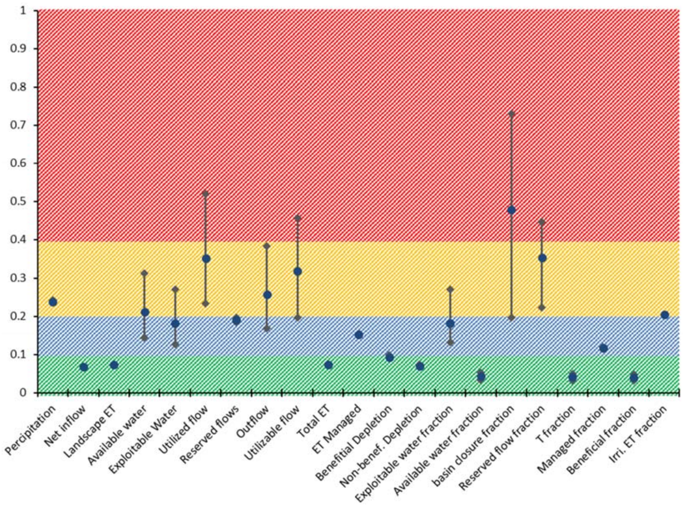

Fig. 10. The level of inaccuracy expressed as a Coefficient of Variation for a dry, wet and average rainfall year. The height of the bars expresses temporal variability. The background colors indicates where a certain parameter should be considered in the water management decision process.