Food and Agriculture Organization of the United Nations

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REMOTE SENSING FOR WATER PRODUCTIVITY

WATER ACCOUNTING SERIES

# Water accounting in the Awash River Basin

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# Acronyms and Abbreviations

| | |
|---|---|
| **$ET_a$** | Actual Evapotranspiration |
| **FAO** | Food and Agriculture Organization |
| **GRACE** | Gravity Recovery and Climate Experiment |
| **GSFC** | Goddard Space Flight Center |
| **GWF** | Grey Water Footprint |
| **IWMI** | International Water Management Institute |
| **L1_PCP_E** | Level 1 Precipitation (Daily) |
| **L1_PCP_M** | Level 1 Precipitation (Monthly) |
| **L1_RET_M** | Level 1 Reference Evapotranspiration (Monthly) |
| **L2_AETI_M** | Level 2 Actual Evapotranspiration and Interception (Monthly) |
| **L2_I_M** | Level 2 Interception (Monthly) |
| **L2_LCC_A** | Level 2 Land Cover Classification (Annual) |
| **MLU** | Managed Land Use |
| **MWU** | Managed Water Use |
| **NASA** | National Aeronautics and Space Administration |
| **P** | Precipitation |
| **PLU** | Protected Land Use |
| **$Q_{out}$** | Flow out of the basin |
| **TWSA** | Total Water Storage Anomalies |
| **ULU** | Utilized Land Use |
| **WA+** | Water Accounting Plus |
| **WaPOR** | Water Productivity |

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Water Accounting is an approach which is based on open access data sets and information. The validation of the water accounts for the Awash River Basin depends on observed data. We are therefore grateful for the following institutions providing this information. The Ministry of Water, Irrigation and Electricity and Awash River Basin office for sharing some meteorological and hydrological data and FAO Land and Water Division and Ethiopia country office for providing documents of previous studies on Awash Water Audit. We would like also to acknowledge the support we received from Water Accounting group at IHE Delft including Claire Michailovsky, Bert Coerver, Abebe Chukalla, Quan Pan and Elga Salvadore. We are especially very grateful to Prof Graham Jewitt for his guidance and valuable comments and for editing the report. We also appreciated all the institutions that publish their database openly, which are all valuable for this water accounts study. These institutions/ research groups include, but not limited to, the National Oceanic and Atmospheric Administration, the World Protected Area Database and NASA's Goddard Space Flight Center (GSFC).

# Executive summary

The Awash River Basin is the most utilized river basin in Ethiopia hosting most of the industrial activities in the country, a number of small to large scale irrigation schemes and the main population centres of the country with more than 18.6 million people (2017 estimate). The basin faces high water stress during the peak of the irrigation season and frequent flooding in rainy seasons. The average yearly precipitation is 560 mm/year and the average yearly evapotranspiration is 503 mm/year. With the population estimated in 2017 and with yearly average exploitable water resources of 8.7 $km^3$, the inhabitants are already facing severe water shortage (<500 $m^3$/cap/year).

As the duration, completeness and quality of the hydro-meteorological records obtained from the basin are insufficient to draw an appropriate picture of the water resources conditions, a rapid Water Accounting Plus (WA+) system designed by IHE Delft with its partners FAO and IWMI has been applied to gain insights into the state of the water resources in the basin. For this study, we used the FAO WaPOR database for the period 2009 to 2018. The WaPOR version 2.0 level 1 with 5km resolution data for precipitation and level 2 with 100m resolution data for actual evapotranspiration, interception and land cover classification layers were used for WA+ analyses. Additional open access data was used to assess changes in storage (the Gravity Recovery and Climate Experiment (GRACE) data). In addition, the WaPOR land cover classification layer was reclassified to WA+ classes using the World Database on Protected Areas and the Global Reservoir and Dam Database.

The results of the rapid Water Accounts showed a considerable amount of outflow from the basin according to the WaPOR-based water balance ($P - ET_a - \Delta S$). The basin, however, is considered a closed one with no surface water outflow. This outflow is attributed to groundwater outflow in the direction of the Afar depression, which is reported in literature to be about 3.8 $km^3$/year. However, the outflow estimated using WaPOR is almost double, similar to the outflow reported by Karimi (2015b). The water balance shows that the WaPOR database provides similar errors in the water balance at basin level as previous studies. The study however provides a longer time series of data (10 years) with high spatial resolution (100m). The detailed analysis shows that spatial patterns of $ET_a$ are consistent with expectations, however, in the highlands there are a few patches where $ET_a$ exceeds $P$ (identified as irrigated areas) where there is no known irrigation taking place. Similarly in the Afar depression, $P$ generally exceeds $ET_a$ indicating net generation of water, which is not consistent with observations. These discrepancies require further investigation.

Sustainable utilisation of the water resources in Awash River Basin is critical. Especially with the Ethiopian government's intention to increase sugar cane production, which is one of the main water consumers in the Awash River Basin. The results of the rapid WaPOR based Water Accounting study, shows that the water availability has large inter-annual variability. The overall managed water fraction is still low with 28% of the available water. To satisfy the growing demand of water in the basin, strategies focusing on increasing water productivity and storage capacity are the way forward to increase reliable availability of the much needed water resources.

# 1. Introduction

## 1.1. Case study description

The Awash River Basin is the fourth largest river basin out of the twelve River Basins of Ethiopia in terms of area, following Wabi- Shebele, Abbay (Blue Nile) and Genale-Dawa River Basins. The Awash River Basin covers a total area of about 119,000 km² and is bordered by Danakil, Abbay, Omo- Gibe, Rift-Valley lakes and Wabi-Shebele basins and Republic of Djibouti. The Awash River Basin hosts the main population centers of the country (e.g. Addis Ababa, Dire Dawa, Adama, Bishoftu, Dessie and Kombolacha) serving about 18.6 million people (2017 estimate). The Awash River emerges from the central highlands of Ethiopia near Ginchi and flows north east through the northern section of the Rift Valley to eventually discharging into the salty Lake Abbe near the Djibouti border, traveling a distance of about 1,200km (Figure 1; ARBA, 2017).

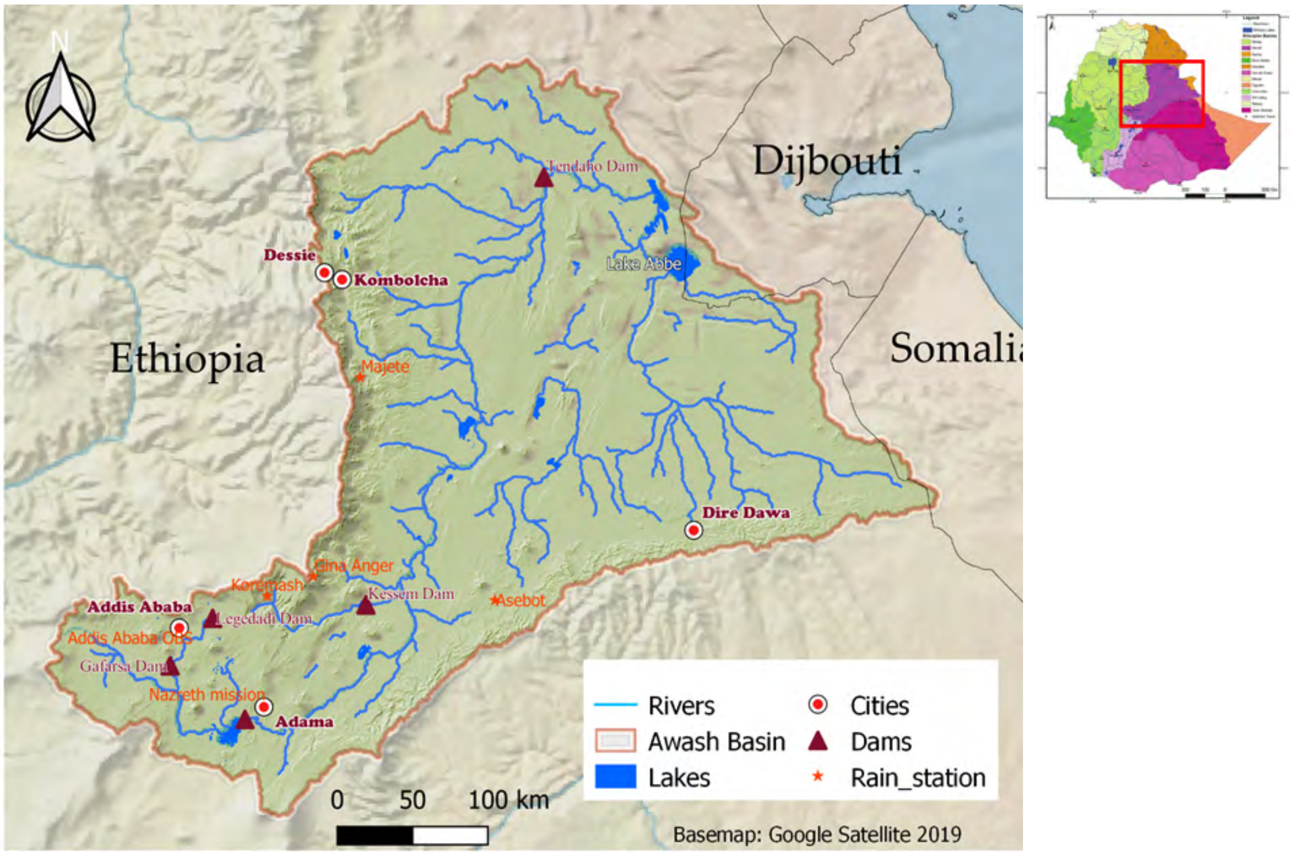



Figure 1. Location of the Awash River Basin in Ethiopia

The annual rainfall in the basin varies according to the elevation, with rainfall in the highlands amounting to 1,200 mm/year to around 200 mm/year in parts of the Afar depression. The rainfall distribution in the highland areas is bimodal, with a short rainy season in March and April and the main rains from June to September. The annual runoff within the basin was estimated at 4.6 km³/year based on the UNESCO Atlas of World Water Balance and compared with AQUASTAT data of annual renewable water resources (FAO, 1997). Some tributaries like Mojo, Akaki, Kassam, Borkena, Kebene and Mile rivers carry water the whole year, while many lowland rivers only function during the rainy seasons. Downstream of Dupti, no appreciable runoff from local rainfall reaches the river.

Lake Abbe is a terminal lake, where the Awash River ends, its surface area is on average 340 $km^2$ of open water, surrounded by 110 $km^2$ of salt flats. The lake surface area and water depth fluctuates depending on the inflow from the Awash River. The maximum depth of the lake is 36 m, which can drop as much as 5 m (Ayenew et al., 2008). The level of Lake Abbe thus rises and falls according to the balance between inflow and evaporation losses.

## 1.2. Water resources developments and challenges in Awash River Basin

Most of the industrial activity in Ethiopia (estimated 65%) is located in the Awash River Basin (ARBA, 2017) including two of the main industrial zones of the country (Dire Dawa and Kombolcha). Many of the big national industrial hotspots and corridors, big agro industries and highly populated cities and towns in the country are found inside the Awash River Basin (ARBA, 2017).

The Awash River Basin is the most utilized river basin in Ethiopia with a number of small, medium and large scale irrigation schemes (e.g. Ada'aBecho, Wonji-Shoa, Fental-Tibila, Metahara, Upper Awash Agro Industry, Kesem, Amibara, Gewane and Tendaho), totalling 200,000 ha of farmland (ARBA 2017). Other water users include (agro-) industries located along the river and urban and rural water supply schemes.

To accommodate these demands, four dams were constructed in the basin for irrigation and domestic and industrial water supply as well as hydropower (Aba Samuel (1932), Gefersa dam (1938) for domestic/industrial water supply, Koka dam (1960) for hydropower, Kessem and Tendaho for irrigation). Following the construction of Koka dam, downstream irrigation developments like Wonji and Metehara sugar plantations, upper, middle and, lower Awash state farms with fruits, vegetables and cotton plantations flourished. According to current estimates the irrigated land in the basin reach about 200,000ha (ARBA, 2017). Due to the intensive irrigation development in the basin particularly along the Awash River, there is high water stress during the peak of the irrigation season (April to June). On the other hand, flooding is frequently observed in the basin during the rainy season (July to September) (ARBA, 2017).

The irrigated agricultural water use is the largest water user in the basin, accounting to about 83% of the total water use (ARBA, 2017). A wide variety of crops are cultivated both commercially and for subsistence, for local and national markets as well as for export. The type of crops range from cereals, vegetables, flowers, cotton to perennial fruit orchards and sugarcane. From 2010, there was shift in crop preference following the Government's interest in sugar production. In the middle and lower valley areas, cotton cultivating areas have now been transformed to sugarcane production.

Other water uses include domestic, livestock and industrial uses. The basin provides annual water needs for 18.6 million people, 34.4 million livestock, 199,234 ha irrigated land and different commercial and industrial activities in the basin (ARBA, 2017). According to ARBA (2017) this amounts to 4.11 $km^3$/year, amounting to about 90% of the annual renewable water resources in the basin. With this high utilisation of the water resources, water allocation and water resources development require information about the current water resources availability and utilisation in the basin.

## 1.3. Objective of Water accounts

The purpose of this study is to get insights into the water availability, withdrawals, consumptive use, non-consumptive use and the benefits and services rendered from it in the Awash River Basin, using WaPOR data in conjunction with other data sources. In particular, the study seeks to investigate:

- What is the current water resources availability in the Awash River basin?
- How much water is being consumed by different land use classes and in particular by irrigation in the Awash River basin?
- What are the safe caps of water withdrawals for the agricultural sector in Awash?

A system referred to as Water Accounting Plus (WA+) has been designed by IHE Delft with its partners FAO and IWMI using spatial data from earth observations and various other open-access databases. It complements the lack of routine water resources data collection and incorporates spatially distributed water consumption. The WA+ framework is a reporting mechanism that summarizes the state of the water resources conditions by means of customized sheets (www.wateraccounting.org). While the WaPOR database does not contain all the input data required for fully implementing the WA+ framework, key data is provided, such as precipitation, actual evapotranspiration, the breakdown between transpiration, evaporation and interception, reference evapotranspiration, net primary production and total biomass production (FAO, 2018).

The present study, therefore, shows the results of the implementation of a rapid Water Accounting+ framework in the Awash River Basin for the period 2009 to 2018 using WaPOR v2.0 data. It identifies the current water challenges, the sustainable water withdrawals, and the key areas where future actions can have a profound impact. It focusses on the basin-wide analyses (WA+ Sheet 1) of the state of the water resources utilisation in a river basin.

Finally this report also reflects on the quality of the WaPOR v2.0 data for Water Accounting plus.

# 2. Methodology

## 2.1. WaPOR datasets

The WaPOR v2.0 database contains information at three different spatial resolutions. At continental level, data is available at 250m resolution (Level 1). For selected countries and basins, data is available at 100m resolution (Level 2). For detailed crop water productivity analyses for selected irrigation systems, 30m resolution data is available (Level 3). For this study, we used Level 2 (100m resolution) data. Before using the data for the Water Accounts, various checks of the data were performed such as 1) precipitation data was compared with observed rainfall data 2) water balance of the basin using WaPOR data and 3) identification of net water generating and consuming land cover classes.

### 2.1.1. Precipitation

WaPOR rainfall data is based on the CHIRPS database created by the United States Geological Survey (Funk et al., 2015; FAO, 2018). Figure 2 shows the spatial variability of the average annual WaPOR precipitation (P) in the Awash River Basin for the period 2009-2018. As it seen clearly in the precipitation map, most of the rainfall falls in the north-west and south-east highlands of the basin. There is little rainfall (<200 mm/year) in the central and north-eastern part of the basin.

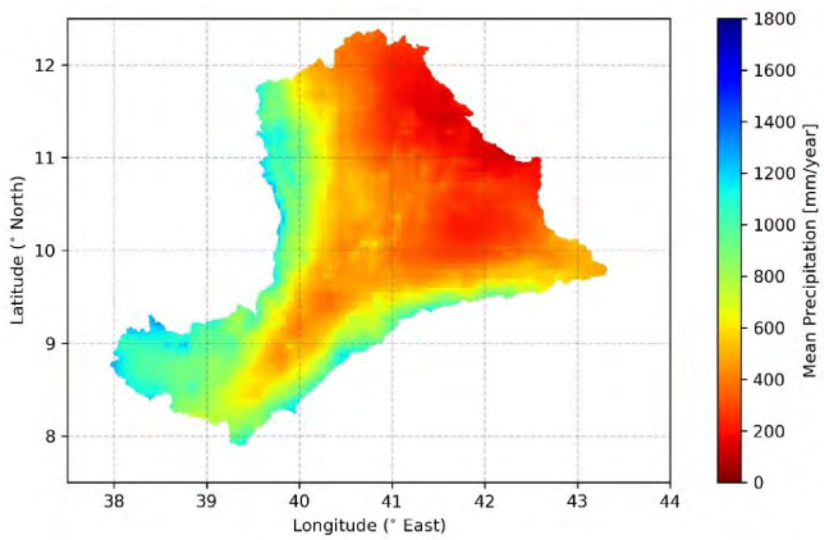
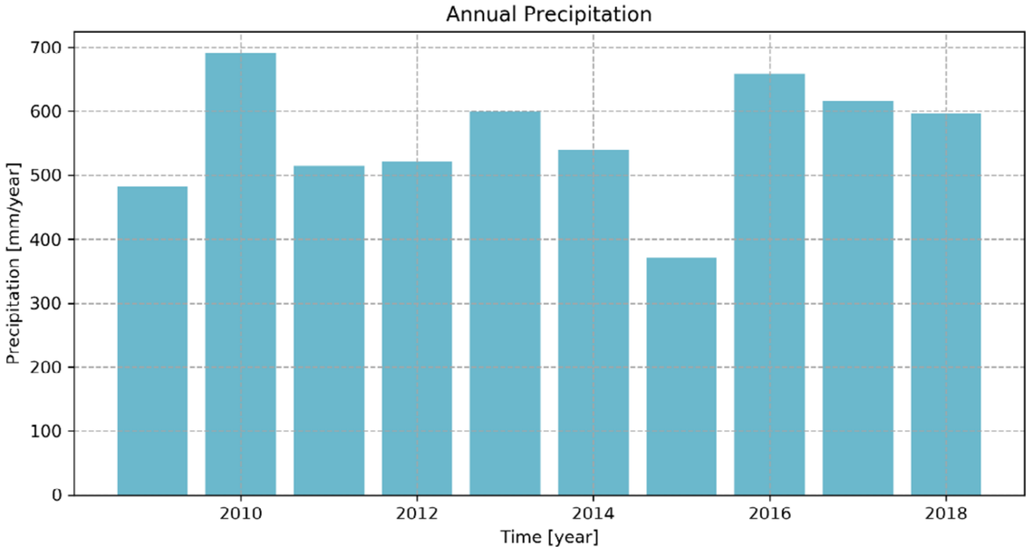



Figure 2. WaPOR annual precipitation (mm/year) for the Awash River basin averaged for 2009-2018. Maps for the individual years are provided in Annex 1.

The basin annual rainfall varied between 390 mm/year in 2015 to 690 mm/year in 2010 (Figure 3). The monthly-average precipitation shows a bimodal rainfall where a short rainy seasons last from March to May and a longer rainy season lasts from June to September where most of the rainfall happens (Figure 3).



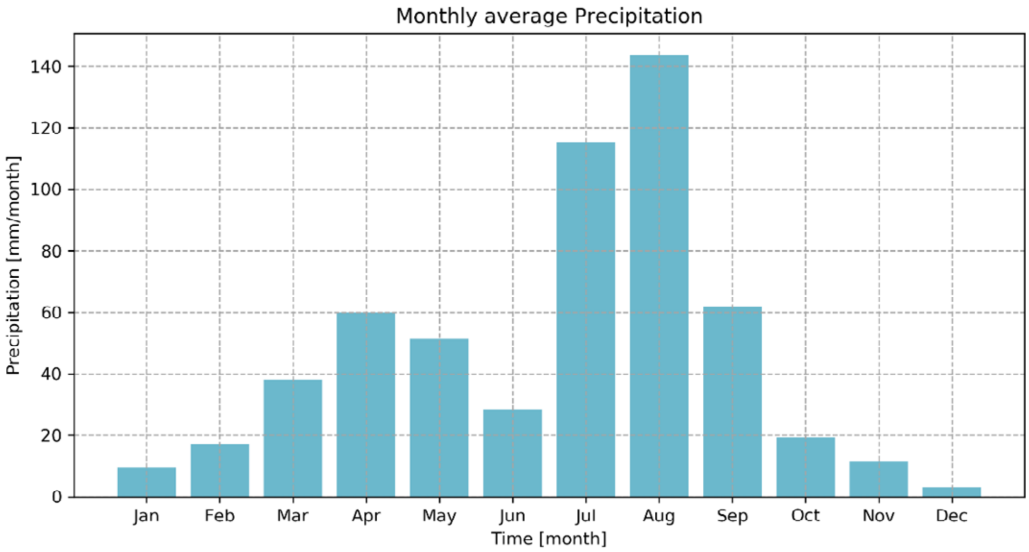




Figure 3. Average annual (top) and average monthly (below) WaPOR Precipitation in Awash River basin for a period of 10 years (2009 to 2018)

Additional local validation of the precipitation was done using observed rainfall data from the basin. We obtained rainfall records from various locations in the basin. Most of the rainfall gauging stations have a lot of missing data and we did not obtain data after 2015. We therefore selected the two stations with relatively long monthly precipitation records overlapping the WaPOR precipitation data. The results of the comparison are shown in Figure 4. For the short duration of the available precipitation records in the stations, it appears that WaPOR underestimates precipitation with a bias value of -0.575 and -0.021 mm/month at Gina Anger and Addis Ababa stations respectively.

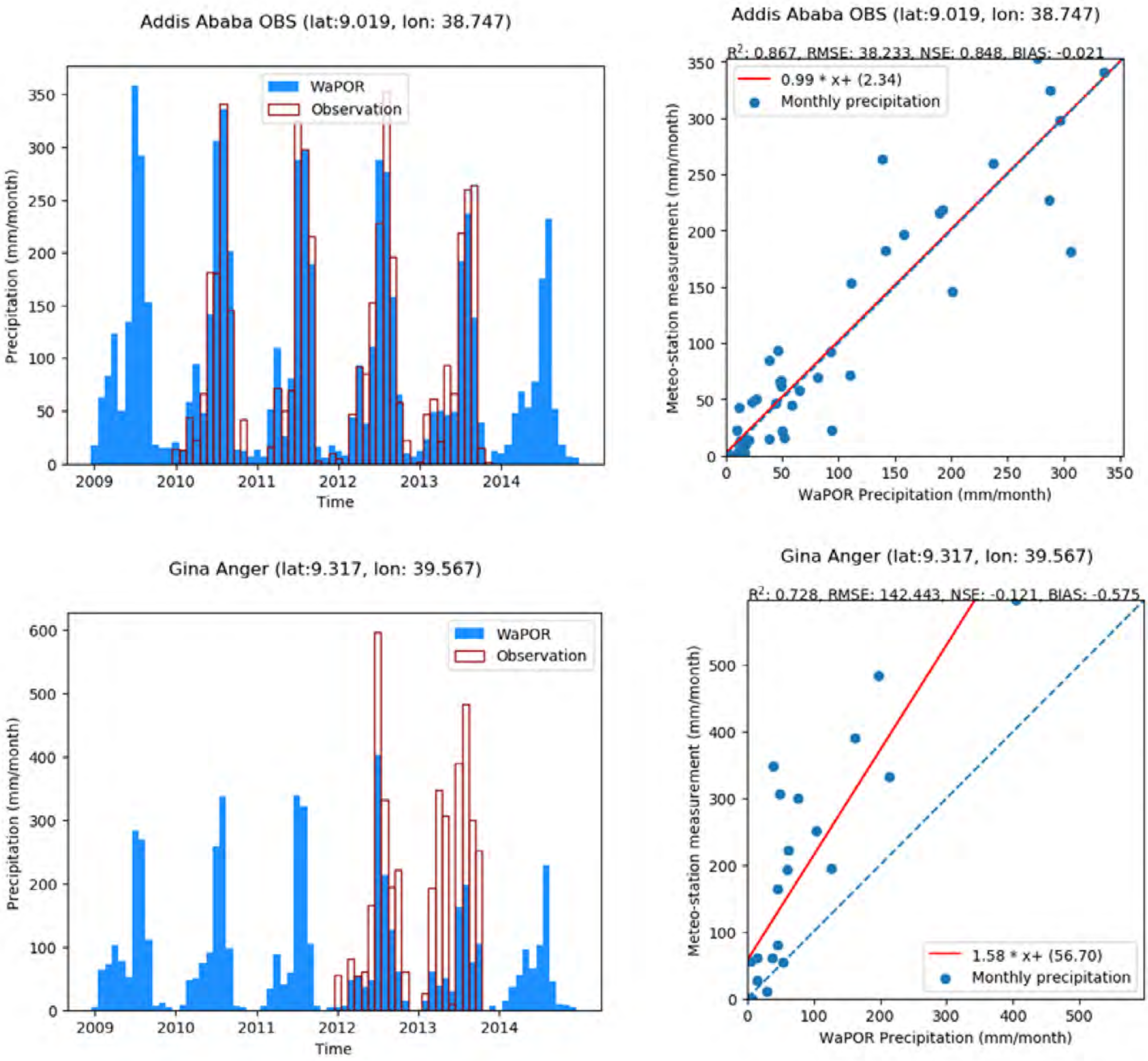



Figure 4. Monthly WaPOR precipitation compared with rain gauges in the Addis Ababa OBS for a period of 2011 and 2015 and Gina Anger station for the period 2013-2014

## 2.1.2. Actual Evapotranspiration and Interception

The WaPOR evapotranspiration ($ET_a$) layer estimates the total evapotranspiration, including interception. Figure 5 shows the spatial variation of $ET_a$ in the Awash River basin. $ET_a$ values follow more or less the patterns of the precipitation, indicating water (through precipitation) is the main limiting factor. The $ET_a$ in the Afar depression is up to 400 mm/year. The only areas in the lowland with high $ET_a$ values are in the irrigated areas and can be 1,200 to 1,400 mm/year depending on crop rotations and local water availability.

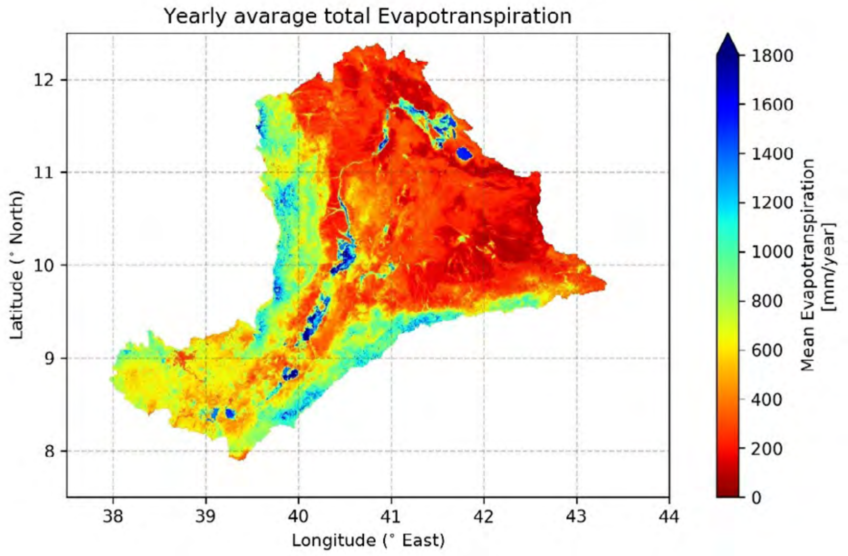



Figure 5. Average annual actual WaPOR evapotranspiration and interception (mm/year) for the Awash River basin averaged for 2009-2018. Maps for the individual years are provided in Annex 2.

### 2.1.3. Precipitation minus Evapotranspiration

To get a better sense of the basin scale water balance for each year the values are compared (Table 1). With the Awash being an internal drainage basin, no surface water outflow is observed, the difference between rainfall and evaporation therefore is due to a change in storage or a groundwater outflow. The long term imbalance between P and $ET_a$ is 57 mm/year (Table 1). Ayenew et al. (2008) indicated there is a groundwater flow towards the north east of the basin equivalent to 30 mm/year (3.5 $km^3$/year). In addition, Karimi et al. (2015) indicated a total imbalance of 3.8 $km^3$/year, after considering the groundwater outflow as reported by Ayenew et al. (2008) over the period of 2009 to 2011. The values obtained using WaPOR data are therefore in line with previous studies (Dost et al., 2013; Karimi, 2015).

Table 1. Comparison of annual WaPOR P and $ET_a$ values for the entire Awash River Basin

| Year | P (mm/year) | P ($km^3$/year) | $ET_a$ (mm/year) | $ET_a$ ($km^3$/year) | P – $ET_a$ (mm/year) | P – $ET_a$ ($km^3$/year) |
|---|---|---|---|---|---|---|
| v | 483 | 57.7 | 477 | 57.1 | 5 | 0.6 |
| 2010 | 690 | 82.6 | 546 | 65.3 | 145 | 17.3 |
| 2011 | 515 | 61.6 | 528 | 63.1 | -13 | -106 |
| 2012 | 521 | 62.3 | 498 | 59.5 | 23 | 208 |
| 2013 | 599 | 71.6 | 524 | 62.7 | 74 | 8.9 |
| 2014 | 541 | 64.6 | 494 | 59.0 | 47 | 5.6 |
| 2015 | 370 | 44.3 | 426 | 50.9 | -55 | -6.6 |
| 2016 | 658 | 78.7 | 515 | 61.6 | 143 | 17.1 |
| 2017 | 616 | 73.7 | 488 | 58.4 | 128 | 15.3 |
| 2018 | 596 | 71.3 | 530 | 63.3 | 67 | 8.0 |
| **Average** | 559 | 66.8 | 503 | 60.1 | 57 | 6.8 |

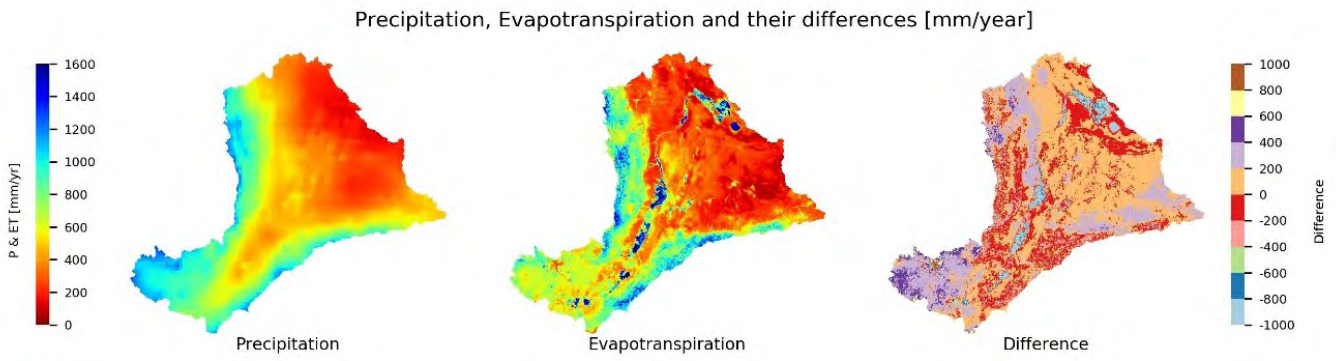



Figure 6. The average P, $ET_a$ and their difference for the period 2009-2018. Maps for the individual years are provided in Annex 3.

### 2.1.4. Land cover classification analysis

The WaPOR database provides a yearly land cover classification map for the Awash River Basin, which is based on the Copernicus land cover map (FAO, 2019). The land cover classification map of the year 2018 from the WaPOR database is presented in Figure 7. The map provides 22 land cover classes, with 10 different land cover classes for trees, for our purposes we grouped the 'tree cover open' and 'tree cover closed' classes to leave 11 different land cover classes.

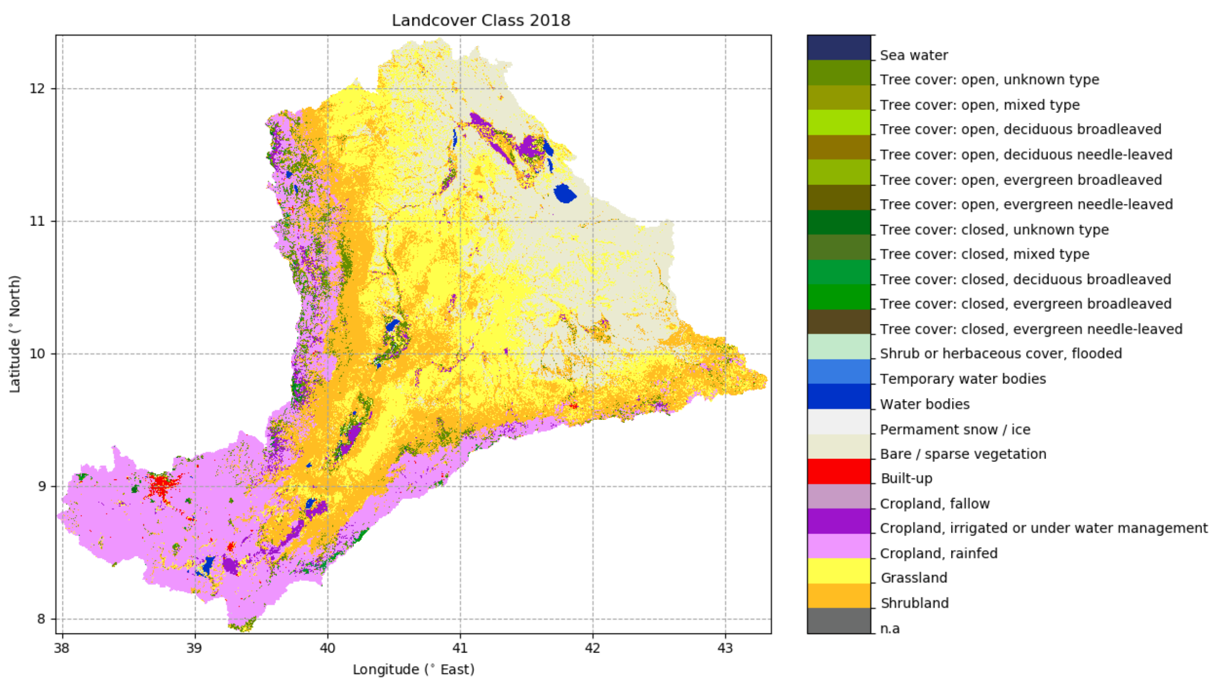



Figure 7. Land cover classification map of the Awash River Basin. Maps for the individual years are provided in Annex 4

Figure 8 shows the change in the land cover throughout the decade from 2009 to 2018. It shows that the land cover remains the same except change of small percentage of rainfed cropland to irrigated cropland in 2013 and which was changed back to rainfed cropland in 2014. The land cover class 'Cropland, Irrigated or under water management' is calculated from 'Cropland' by relating WaPOR Actual ET and Precipitation during the growing

season and therefore subject to the same uncertainty as the water balance. The irrigated crop land at 290,000 ha, is almost 50% higher than the literature values of 200,000 ha (ARBA, 2017). The classification of large areas in the highlands as irrigated land are suspicious and should be further investigated. In particular, some agricultural areas located in the highlands are classified as irrigated which is not consistent with observations.

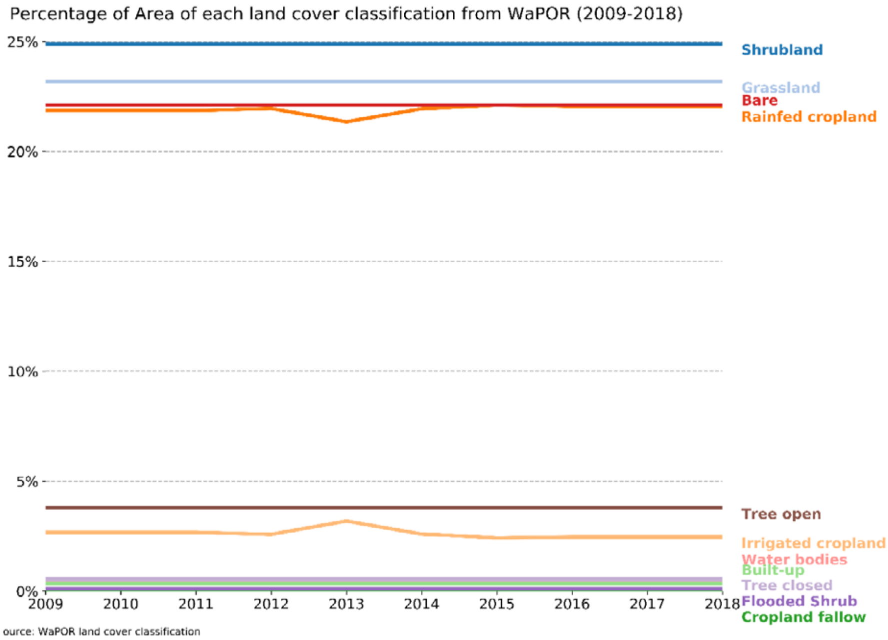



Figure 8. Percentage of area of each land cover classification from 2009 to 2018 for the Awash River Basin

Rainfed croplands and forests are located in high rainfall areas, whereas shrubland, grassland, bareland are located in dryer areas. Comparing the water balance per land cover class (Table 2 and Figure 9), it shows that $ET_a$ exceeds P in irrigated farmlands, water bodies and some farmlands in the highlands in the basin. In urban areas P exceeds $ET_a$ due to very low WaPOR $ET_a$ estimates (for example in and around Addis Ababa). Flooded shrub lands and irrigated croplands consume much water followed by forests or tree covers of different types. The arid character of the basin in the lowlands exhibited by the $ET_a$ exceeding P (water bodies). Surplus water is mostly generated from rainfed and fallow croplands, grassland, bare and built-up areas, or sparse vegetation lands covers. Mean values of P, $ET_a$ and their difference per each land cover class is provided in Table 2.

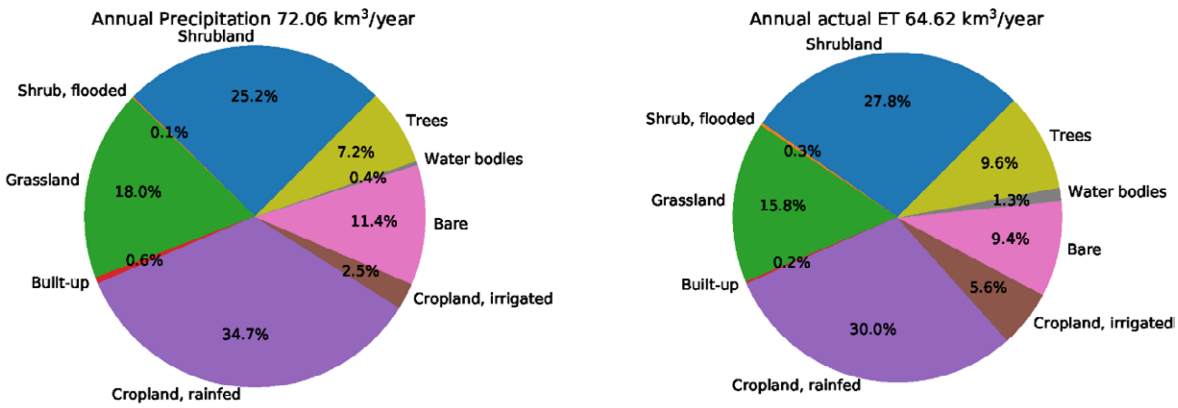



Figure 9. Contribution of the land cover classes to annual precipitation (P) and actual evapotranspiration ($ET_a$) of the Awash River Basin for the year 2018. The land cover classes that contribute less than 0.1% are not presented in the graphs.

Table 2. WaPOR P and $ET_a$ data presented by land cover class for the year 2018

| Code | Land Cover Class Description | Area (km²) | P (mm/year) | Actual ET (mm/year) | P – $ET_a$ (mm/year) | P (km³/year) | Actual ET (km³/year) |
|---|---|---|---|---|---|---|---|
| 20 | Shrublands | 29,753 | 610 | 604 | 6 | 18.1 | 18.0 |
| 30 | Grassland | 27,693 | 469 | 368 | 101 | 13.0 | 10.2 |
| 41 | Cropland, rainfed | 26,362 | 947 | 736 | 211 | 25.0 | 19.4 |
| 42 | Cropland, irrigated or under water management | 2,945 | 610 | 1,230 | - 620 | 1.8 | 3.6 |
| 43 | Cropland, fallow | 5 | 512 | 268 | 244 | 0.0 | 0.0 |
| 50 | Built-up | 408 | 1,025 | 320 | 705 | 0.4 | 0.1 |
| 60 | Bare / sparse vegetation | 26,412 | 310 | 229 | 81 | 8.2 | 6.1 |
| 80 | Water bodies | 612 | 418 | 1,380 | - 962 | 0.3 | 0.8 |
| 90 | Shrub or herbaceous cover, flooded | 130 | 612 | 1,421 | - 810 | 0.1 | 0.2 |
| 112 | Tree cover: closed, evergreen broadleaved | 80 | 1,079 | 1,240 | - 161 | 0.1 | 0.1 |
| 114 | Tree cover: closed, deciduous broadleaved | 345 | 1,070 | 1,130 | - 60 | 0.4 | 0.4 |
| 116 | Tree cover: closed, unknown type | 2,091 | 907 | 1,368 | - 461 | 0.2 | 0.3 |
| 122 | Tree cover: open, evergreen broadleaved | 0 | 1,087 | 1,506 | - 419 | 0.0 | 0.0 |
| 124 | Tree cover: open, deciduous broadleaved | 127 | 1,060 | 1,049 | 11 | 0.1 | 0.1 |
| 126 | Tree cover: open, unknown type | 4,402 | 835 | 908 | - 73 | 3.7 | 4.0 |

### 2.1.5. Conclusion

The analyses show that the WaPOR 2.0 Level 2 data provides reasonable estimates of WaPOR P, $ET_a$ at basin scale, general spatial distribution and analyses for different land cover classes were also consistent. However, in the highlands near the watershed, some areas in the highland (classified as irrigation) showed higher WaPOR $ET_a$ values compared to P. Upon further investigation, it is unlikely that these areas tap into blue water resources as 1) there is no irrigation taking place in those areas and 2) the land cover class is not covered with deep rooting vegetation. The likely reason for the discrepancy is the resolution of the rainfall data (5km for P vs 100m resolution for the $ET_a$) as well as the reported challenges in estimating rainfall in highland areas and areas with steep slopes (Dinku et al, 2018). Also our comparison between WaPOR P and observed rainfall in the highlands showed an underestimation of WaPOR P. As there was no enough observed data in the lowlands to compare with, we were not able to validate WaPOR P in the lowlands.

This discrepancy is also likely the reason behind the classification of irrigated land uses especially on the north-western and south-eastern highlands in the basin, which is based on P and $ET_a$ (FAO, 2018). The yearly land cover maps show a reduction of irrigated land cover in 2014 which may be due to the fact that after 2014 optical input data which is Proba V is used for $ET_a$ estimation. Ground truthing or some kind of verification of the areas where irrigated croplands observed in the highlands is therefore needed.

## 2.2. Other global data sets

### 2.2.1. GRACE

To assess how much of the difference between P and $ET_a$ is due to groundwater outflow and change in storage we use the Gravity Recovery and Climate Experiment (GRACE), a dual-satellite mission continuously monitoring and mapping Earth's changing gravity field to estimate the total water storage anomalies (TWSA). There are several GRACE solutions for TWSA estimation from gravity anomalies, which covers the whole globe from 2003 till end of 2015. The GSFC-v02.4-ICE6G solution (Luthcke et al., 2013) was used to validate the assumption that storage change over a longer time scale such as hydrological year should be zero or close to zero. Since GRACE solution provides mean monthly TWSA not the exact TWSA of the first and last day of the month, change of storage ($\Delta S/\Delta t$) in a time period was approximated using a second order central difference as proposed by Biancamaria et al. (2019). After that, P – $ET_a$ should be equal to the total outflow $Q_{out}$, after correction in change of storage ($\Delta S/\Delta t$) following the water balance equation:

$$\frac{\Delta S}{\Delta t} = P - ET_a - Q_{out}$$

The longer term trend in storage change ($\Delta S$) as observed by GRACE is positive (see Figure 10). The trend of water storage for a number of GRACE pixels that cover Awash River Basin from 2009 to 2016 is 0.78 mm/month, which is translated into 1.1 $km^3$/year. The increase in trend for change in storage may be a result of the filling of Tendaho reservoir in 2009 and Kesem in 2012.

Figure 11 shows the plot of cumulative storage in the Awash River Basin based on GRACE data compared to WaPOR P - $ET_a$. Both lines show a positive trend indicating storage in the basin is increasing. However the cumulative WaPOR P - $ET_a$ shows a significant increase compared to GRACE storage change. Without any other verification, we decided to attribute this difference to an ungauged outflow from the basin in the form of groundwater. This assumption is supported by Ayenew et al. (2008) who indicated that there is a groundwater outflow in the direction of the Afar depression, equivalent to 30 mm/year. According to our analyses (Figure 11), the outflow is in the range of 50 mm/year, which is significantly higher than the assumption by Ayenew et al. (2008). Karimi et al. (2014) showed a similar bias, which they attribute to change in storage.

Table 3 shows the bias of the WaPOR basin wide water balance, on average there is a bias of 5% (of the precipitation), which can either be attributed to unaccounted outflow of the basin or error in the estimations of P and $ET_a$ or GRACE. The biases are larger for the wet and dry years. For the wet year (2010), a positive bias of 11% and for the dry year (2015) a negative bias of 12% is observed.

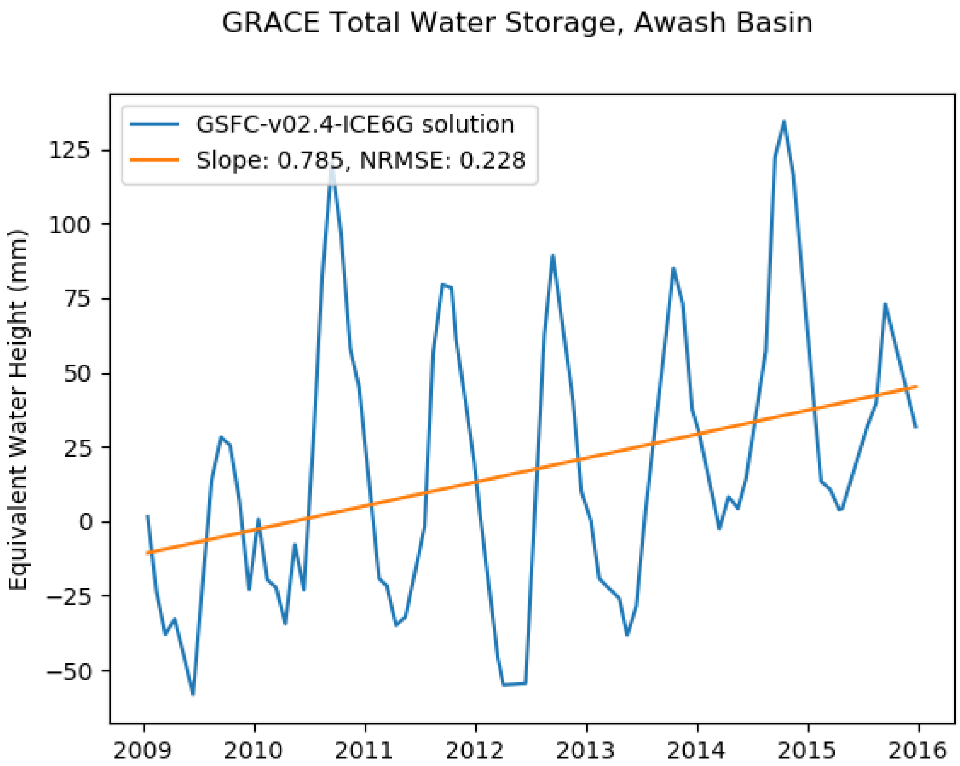



Figure 10. Longer term trend of increasing water storage in Awash River Basin on GRACE gravity measurements (source: https://ccar.colorado.edu/grace/gsfc.html)

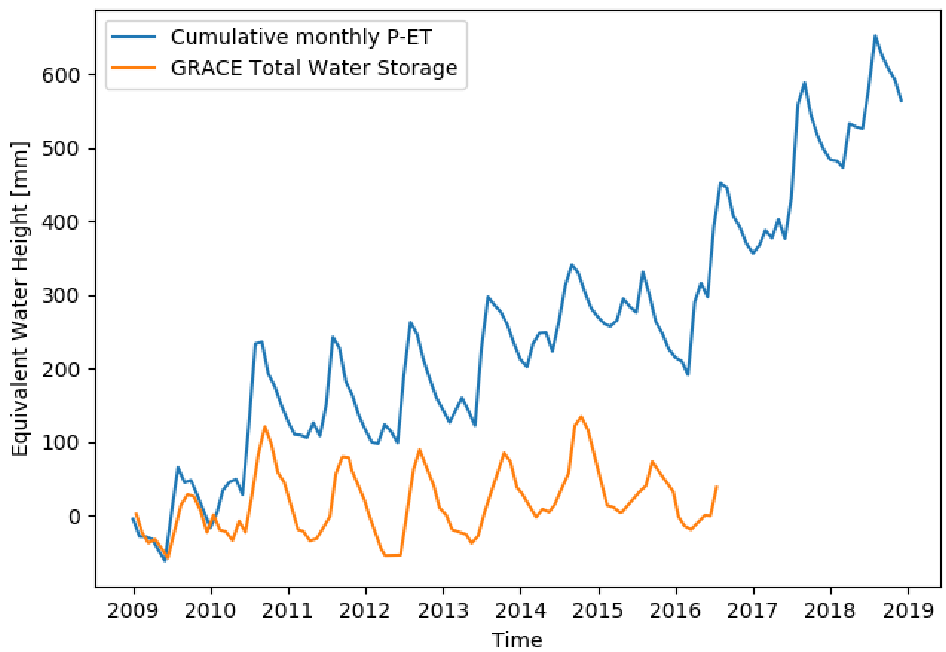



Figure 11. Cumulative monthly difference of WaPOR P - $ET_a$ and GRACE total water storage for Awash River Basin

Table 3. Estimation of Error in Water Balance of Awash River Basin based on GRACE Total Water Storage from 2010 to 2018

| Year | ΔS from GRACE (km³/year) | ΔS from WaPOR Water Balance (km³/year) | ΔS difference (km³/year) | Error percentage (% Precipitation) |
|---|---|---|---|---|
| 2009 | - 2.6 | - 3.2 | - 0.5 | - 0.9 |
| 2010 | 4.8 | 13.5 | 8.7 | 10.5 |
| 2011 | - 2.1 | - 5.4 | - 3.2 | - 5.3 |
| 2012 | - 0.8 | - 1.0 | - 0.3 | - 0.4 |
| 2013 | 3.4 | 5.1 | 1.7 | 2.4 |
| 2014 | 3.0 | 1.8 | - 1,2 | - 1.9 |
| 2015 | - 5.3 | - 10.4 | - 5.1 | - 11.6 |
| **Average** | 0.1 | 0.1 | 0.0 | - 1.0 |

### 2.2.2. Global maps to categorise land use classes

The land use map forms the basis for dividing the basin landscape into the four main categories (PLU, ULU, MLU, and MWU). Four main categories of land and water uses are distinguished:

- **Protected Land Use** (PLU); areas that have a special nature status and are protected by National Governments or Internationals NGO's
- **Utilized Land Use** (ULU); areas that have a light utilization with a minimum anthropogenic influence. The water flow is essentially natural
- **Modified Land Use** (MLU); areas where the land use has been modified. Water is not diverted but land use affects all unsaturated zone physical process such as infiltration, storage, percolation and water uptake by roots; this affects the vertical soil water balance
- **Managed Water Use** (MWU); areas where water flows are regulated by humans via irrigation canals, pumps, hydraulic structures, utilities, drainage systems, ponds etc.

The underlying reason for framing these four land use categories is that their management options widely differ from keeping them pristine to planning hourly water flows.

The land use categories map (Figure 12) is based on the land cover layer (LCC) from WaPOR database, but needed to be reclassified into the Water Accounting classes. Protected Land Use (PLU) class was updated using the protected area profile from the World Database on Protected Areas (UNEP-WCMC, 2019a, 2019b, 2019c, 2019d). The areas which are designated as IUCN categories I and II are reclassified as PLU. The Managed Water Use class was reclassified from the 'Cropland, irrigated or under water management' and 'Built-up' classes in WaPOR LCC layer and updated with the area of constructed reservoirs from the Global Reservoir and Dam Database (GRanD) (Lehner et al., 2011). The GRanD map from 2011 was also adjusted with the recently built Tendaho reservoir (from 2009). The Modified Land Use was reclassified from the class 'Cropland, fallow' and 'Cropland, rainfed' in WaPOR LCC layer. After that, the rest of the area was reclassified as Utilized Land Use class.

The map of the WA+ land use classes for the Awash River Basin used in the analyses is shown in Figure 12. The majority of the area in the Awash River basin is covered by utilised land use.

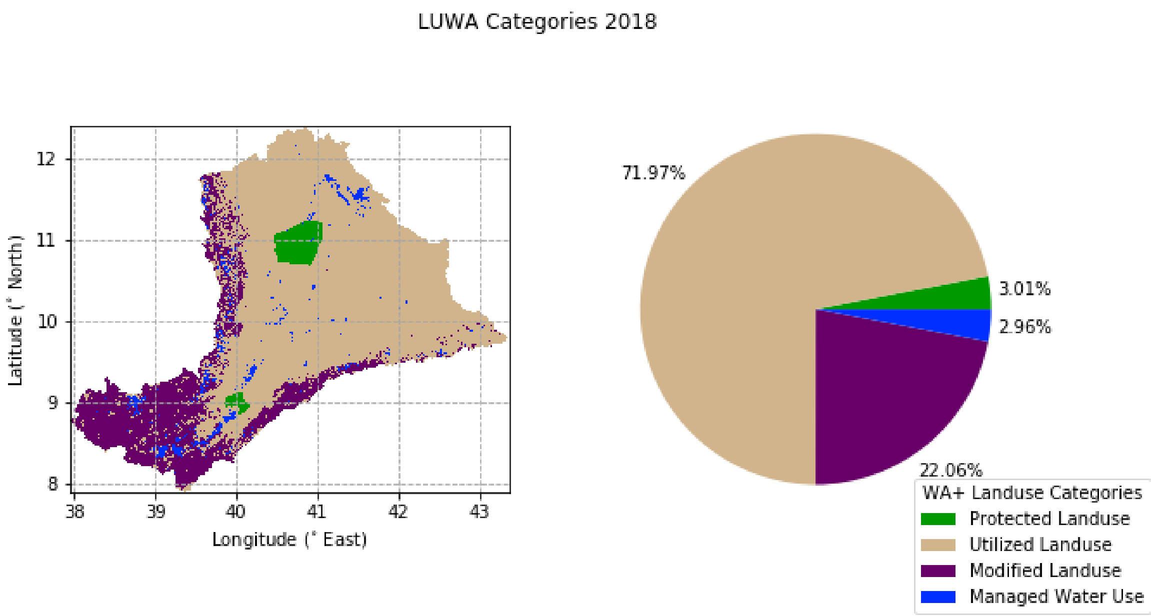



Figure 12. Area percentage of WA+ Land Use categories in Awash River basin

## 2.3. WA+ methodology

The longer term planning process of water and environmental resources in river basins requires a measurement – reporting – monitoring system in place. The Water Accounting Plus (WA+) framework is based on the early WA work of Molden (1997) focusing on agriculture and irrigation systems. WA+ was further developed by Karimi and Bastiaanssen (2015) and Karimi et al. (2015) for river basin analyses and incorporating of all water use sectors. Further developments include more hydrological and water management processes and focus on specific land uses.

A key element of WA is that it separates ET into rainfall ($ET_{rain}$) and incremental ET ($ET_{inc}$), thereby clearly identifying managed water flows. WA+ includes thus the hydrology of natural watersheds that provide the main source of water in streams and aquifers, as well as quantifying water consumption. The current study utilises the WaPOR v2.0 Level 2 data (100 m resolution) for the analyses. It presents a rapid WaPOR-based water accounting framework.

The output of WA+ is in a number of sheets and supporting spatial maps. Remote sensing, GIS and spatial models form the core methodology, so all data has a spatial context. The accounts are reported on an annual basis, as WA+ is meant for longer term planning. Software tools have been developed that automatically collect and download data from WaPOR database as well as for the calculations. The models and scripts for the creation of the water accounts and the elaboration of the reports are available on GitHub under the Water Accounting account[1]. The WA+ framework is public and open for all users.

Figure 13 shows the flow chart of the rapid WA+ process and the data used. The rapid WA+ mainly uses WaPOR data such as the level 1 monthly precipitation and level 2 annual time series of land cover classification, interception and actual evapotranspiration and interception. External data sources used include GRACE satellite data for estimating the change in storage in the basin, Global Reservoir and Dam Database (GRanD) to identify dam locations and extents, the World Database on Protected Areas to identify the protected land uses, and the map of top soil saturated water content (de Boer, 2016).

[1] https://github.com/wateraccounting

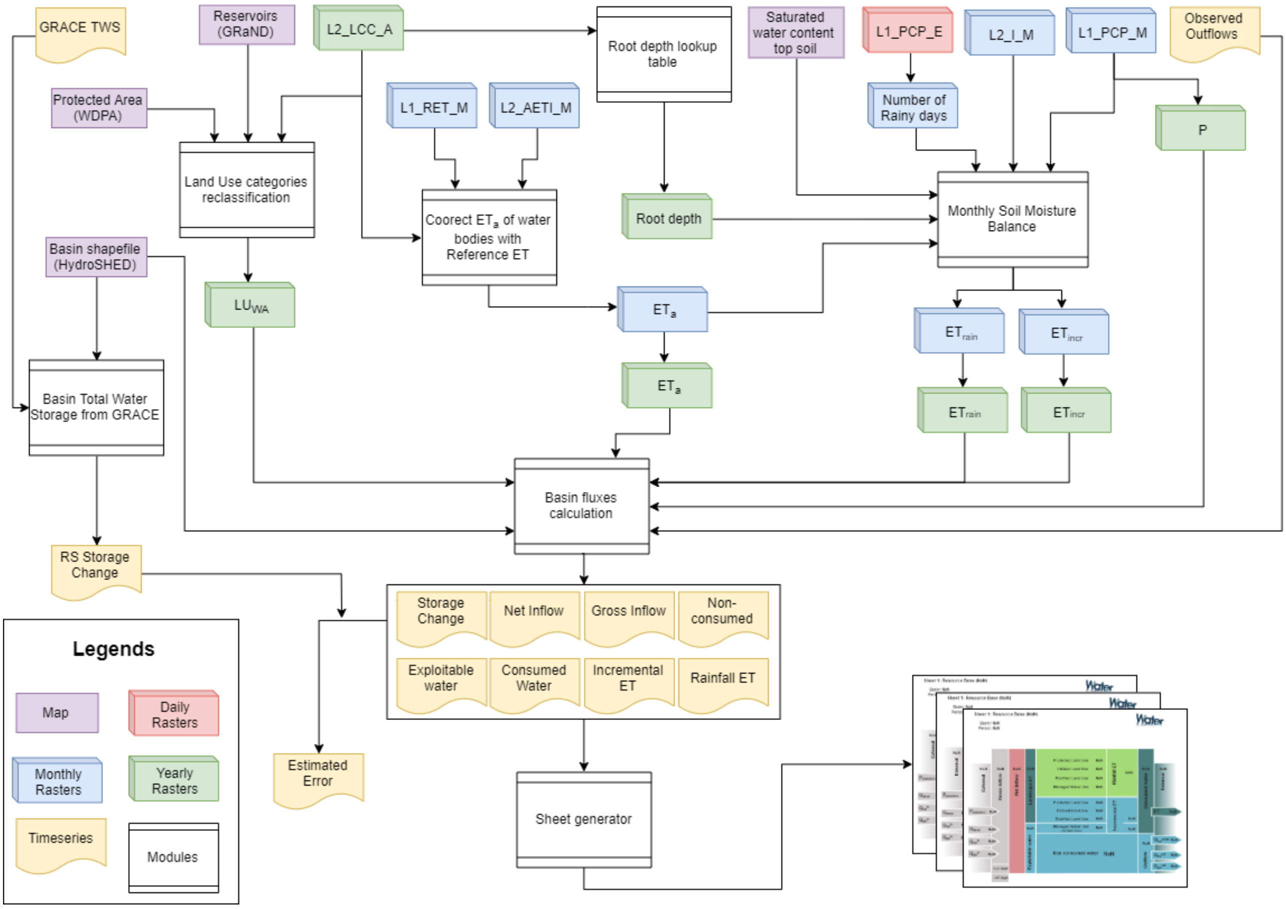



Figure 13. Water accounting flow chart using WaPOR data

## 2.3.1. Pixel scale analysis

The water accounting framework distinguishes between a vertical and horizontal water balance. A vertical water balance is made for the unsaturated root zone of every pixel and describes the exchanges between land and atmosphere (i.e. rainfall and evapotranspiration) as well as the partitioning into infiltration and surface runoff. Percolation and water supply are also computed for every pixel, to facilitate attributing water supply and consumption to each land use class.

The WaterPix model calculates for each pixel the vertical soil water balance (See Figure 14 and described below). $ET_{rain}$ and $ET_{incr}$ are separated by keeping track of the soil moisture balance and determining if $ET_a$ is satisfied only from rainfall or stored in the soil moisture or additional source (supply) is required. The main inputs into WaterPix are provided in Table 4 and the outputs are provided in Table 5. Each parameter is calculated at the model resolution of 100m and available for monthly and annual time steps.

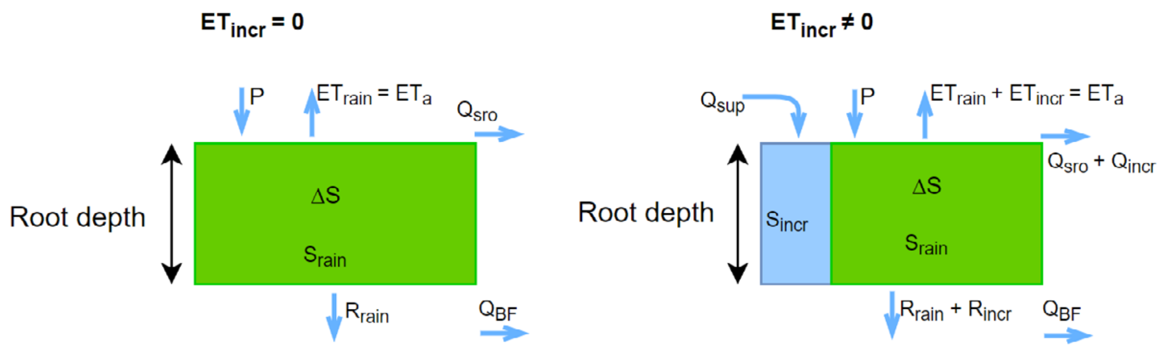



Figure 14. Main schematization of the flows and fluxes in the WaterPix model

Table 4. Inputs of WaterPix

| Variable | Parameter | Source | Spatial Resolution | Temporal resolution |
|---|---|---|---|---|
| Precipitation | P | WaPOR | 5,000 m | Daily |
| Actual Evapotranspiration | $ET_a$ | WaPOR | 100 m | Monthly |
| Interception | I | WaPOR | 100m | Monthly |
| Land use land cover | LULC | WaPOR | 100 m | Yearly |
| Saturated Water Content | | HiHydroSoil | 0.008333 degree (about 900m at the equator) | Static |

Table 5. Outputs of the water balance model at pixel level

| Variable | Calculation step | Definition |
|---|---|---|
| S | 1 | Soil Moisture |
| $Q_{sro}$ | 1,4 | Surface Runoff |
| R | 1,4 | Recharge |
| $ET_{rain}$ | 2 | Rainfall ET |
| $ET_{incr}$ | 2 | Incremental ET |
| $Q_{sup}$ | 3 | Supply |

*Step 1. Compute soil moisture*

The soil moisture ($S_{rain,t}$) is computed as the soil moisture storage at the end of the previous timestep ($S_{rain,t-1}$) plus the effective rainfall (P-I) minus recharge ($R_{rain}$) and surface runoff ($Q_s$):

$$\mathbf{S_{rain,t} = S_{rain,t-1} + P - I - R_{rain} - Q_{sro,rain}}$$

Where the surface runoff ($Q_{sro,rain}$) is calculated using an adjusted version of the Soil Conservation Service runoff method. The adjusted version replaces the classical Curve Numbers by a dynamic soil moisture deficit term that better reflects the dry and wet season infiltration versus runoff behaviour (see Schaake et al., 1996; Choudhury & DiGirolamo, 1998). As the Curve Number method is developed for event based runoff, we calculated $Q_{sro,rain}$ on daily basis, dividing the effective rainfall by the number of rainy days (n) and a calibration parameter to account for the soil moisture variation due to drying up and filling with in a month. The total surface runoff for a month is then multiplied by n:

$$Q_{sro,rain} = \begin{cases} 0 \; if \; P = 0 \\ \dfrac{\left(\frac{P-I}{n}\right)^2}{\frac{P-I}{n} + f\left(S_{sat} - S_{rain,t-1}\right)} * n \; if \; P \neq 0 \end{cases}$$

Where the saturated soil moisture ($S_{sat}$) is calculated by multiplying the Saturated Water Content ($\theta_{SAT}$) by the effective root depth (RD) for each land cover class estimated based on the effective root depth by Yang et al. (2016) (Table 6).

Table 6. Root depth look-up table. The values of root depth for each land cover class is based on study by Yang et al. (2016)

| WaPOR Land cover class | Root depth (mm) |
|---|---|
| Shrubland | 370 |
| Grassland | 510 |
| Cropland, rainfed | 550 |
| Cropland, irrigated or under water management | 550 |
| Fallow cropland | 550 |
| Built-up | 370 |
| Bare/sparse vegetation | 370 |
| Permanent snow/ice | 0 |
| Water bodies | 0 |
| Temporary water bodies | 0 |
| Shrub or herbaceous cover, flooded | 0 |
| Tree cover: closed, evergreen needle-leaved | 1,800 |
| Tree cover: closed, evergreen broad-leaved | 3,140 |
| Tree cover: closed, deciduous broad-leaved | 1,070 |
| Tree cover: closed, mixed type | 2,000 |
| Tree cover: closed, unknown type | 2,000 |
| Tree cover: open, evergreen needle-leaved | 1,800 |
| Tree cover: open, evergreen broad-leaved | 3,140 |
| Tree cover: open, deciduous needle-leaved | 1,070 |
| Tree cover: open, deciduous broad-leaved | 1,070 |
| Tree cover: open, mixed type | 2,000 |
| Tree cover: open, unknown type | 2,000 |
| Seawater | 0 |

*Step 2. Separate $ET_a$ into $ET_{rain}$ and $ET_{incr}$ and update S*

To compute the rainfall and incremental component of $ET_a$, $ET_a$ is subtracted from $S_{rain,t}$. When $S_{rain,t}$ is insufficient for $ET_a$, the difference will be supplied by surface or groundwater uptake. $ET_{rain}$ becomes the amount which can be supplied by the soil moisture, whereas the difference will become $ET_{incr}$:

$$ET_{rain} = \text{if } (S_{rain,t} > ET_a,\ ET_a, S_{rain,t})$$

$$ET_{incr} = ET_a - ET_{rain}$$

The new soil moisture storage then becomes:

$$S_{rain,t} = S_{rain,av} - ET_{rain}$$

*Step 3. Estimation of Water Supply*

The amount of water supplied to each pixel is a function of $ET_{incr}$ and the so called consumed fraction ($f_c$).

$$Q_{sup} = f(ET_{incr}, LU) = \frac{ET_{incr}}{f_c}$$

$f_c$ is dependent on the land use class and was suggested to replace the classical irrigation efficiencies (Molden, 1997; Simons et al., 2016). The consumed fractions applied in this study are specified in Table 6.

Table 7: Consumed fraction per land use class

| Land use class | Consumed fraction ($f_c$) |
|---|---|
| Natural land use classes | 1.00 |
| Rainfed crops | 1.00 |
| Irrigated crops | 0.80 |

*Step 4. Estimating incremental soil moisture*

A separate soil moisture storage (blue area in Figure 14 is added to store $Q_{sup}$ and calculate incremental recharge and runoff as follows:

$$S_{incr,\,t} = S_{incr,\,t\text{-}1} + Q_{supply} - ET_{incr} - R_{incr} - Q_{sro,\,incr}$$

And total soil moisture storage ($S_t$) becomes:

$$S_t = S_{rain,\,t} + S_{incr,\,t}$$

Then total recharge ($R_t$) is calculated as exponential function of the soil moisture. If the soil moisture is above a certain percentage (calibration parameter) of the saturated content, the percolation will be computed using the following simple exponential function:

$$R_t = S_t * \exp\left(-\frac{1}{S_t}\right)$$

And the incremental recharge ($R_{incr}$) and the recharge from rainfall ($R_{rain}$) are computed as proportions of the incremental and rain soil moisture values.

The surface runoff is updated to account the increase due to incremental surface runoff from the supply

$$Q_{sro\ tot} = \begin{cases} 0\ if\ P = 0 \\ \dfrac{\left(\frac{P+Q_{sup}-I}{n}\right)^2}{\frac{P+Q_{sup}-I}{n} + f\left(S_{sat} - \left(S_{rain,t} + S_{incr}\right)\right)} * n\ if\ P \neq 0\ or\ Q_{sup} \neq 0 \end{cases}$$

The incremental surface runoff ($Q_{sro,incr}$)is then computed as:

$$Q_{sro,\,incr} = Q_{sro,\,tot} - Q_{sro,\,rain}$$

The results of the calculation for $ET_{rain}$ and $ET_{incr}$ for the different land cover classes are shown in Figure 15. It shows that trees, irrigated crop land, flooded shrubs and water bodies have high incremental ET. For trees the method estimates about 38% to 56% of $ET_a$ is from $ET_{incr}$. Although for the tree land covers $ET_a$ is higher than the precipitation (103% to 153% of the precipitation), the estimated $ET_{incr}$ is higher than expected.

Similarly, the $ET_{rain}$ for irrigated croplands and flooded shrubs is 83% and 66% of the rainfall and $ET_{incr}$ is 104% and 159% respectively. The land cover classes with higher amount of incremental ET cover a small proportion of the basin. Irrigated croplands, with 3% of the area of the basin, have significant $ET_{incr,}$ only 45% of the ET is from rainfall whereas the remaining 55% is from blue water. Open tree covers also consume a significant amount of blue water. The source of the $ET_{incr}$ from open trees could be from overflows of Awash River in the middle of the basin which inundate the open tree cover lands. Most of the runoff in the basin is generated from rainfed croplands, grasslands and bare land or spares vegetation cover types.

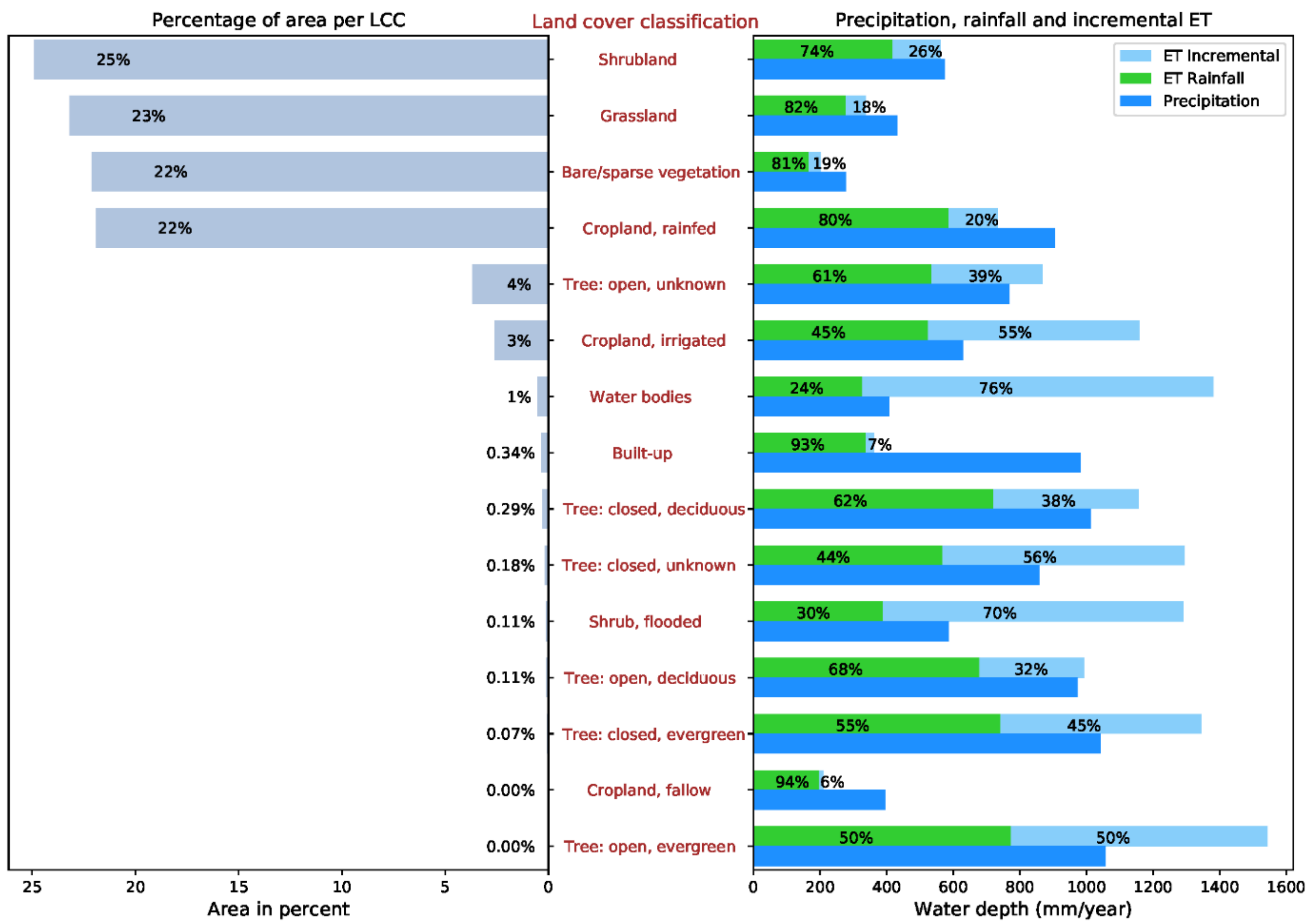



Figure 15. Precipitation, $ET_{rain}$ and $ET_{incr}$ per land cover of Awash River Basin for the period 2009 to 2018 - the percentages indicate the proportion of $ET_{rain}$ and $ET_{incr}$ to the precipitation.

## 2.3.2. WaPOR based Water Accounting Plus sheet 1

The water accounts sheet 1 provide an overview of the water resources and its current utilisation per different land use categories. The rapid WaPOR-based Water Accounting Plus looks at the gross inflow, rainfall and incremental evapotranspiration for each of the WA+ land use categories. It assesses the current utilisation rate of a river basin.

A further analysis was done, using a set of key indicators for water accounting developed by Dost et al (2013) in consultation with the Land and Water Division of FAO:

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

1. ET Fraction = $\frac{ET_{tot}}{P + Q_{in}}$ (%)

   - ET fraction indicates which portion of the total inflow of water is consumed and which part is converted into renewable resources. A value higher than 100% indicates over- exploitation or a dependency on external resources.

2. Stationarity Index = $\frac{\Delta \text{ Storage}}{ET_{tot}}$ (%)

   - Stationarity Index is an indication of the depletion of water resources. Positive values indicate that water is added to the groundwater and/or surface water storage. Negative values indicate a depletion of the storage.

3. Basin Closure = $\frac{1 - \text{Outflow}}{P + Q_{in}}$ (%)

   - Basin Closure defines the percentage of total available water resources (Precipitation + basin inflow) that is consumed and/or stored within the basin. A value of 100% indicates that all available water is consumed and/or stored in the basin.

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

4. **Available Water** (AW) = **Gross inflow – Landscape Evapotranspiration - Reserved Flow** (**km$^3$/year**), where landscape evapotranspiration is all water lost to evapotranspiration minus the evapotranspiration from managed land uses
   - Total amount of water that is available to be managed.

5. **Managed Water** (MW) = **Incremental ET of Managed Water Use** (**km$^3$/year**)

6. **Managed Fraction** = **Managed Water / Available Water** (%)
   - Percentage of water that is actually managed from the total amount of water that is available.

# 3. Water Accounting Plus

## 3.1. The resource base

### 3.1.1. Overview: Average over the entire period

The 10 year average exploitable water resources in the Awash River Basin is 8.7 $km^3$/year (5.9 $km^3$/year exploitable water and 2.8 $km^3$/year increase in storage) (Figure 16). The increase in storage, as observed by GRACE could be in the reservoirs, lakes and in the groundwater. The stored amount is equivalent to about 57mm/year. The water balance shows an outflow to the groundwater of 3.8 $km^3$/year. This is similar to the values estimated by Karimi et al. (2015), who considered a regional groundwater out flow of 3.8 $km^3$/year likely, which is equivalent to 31 mm/year recharge.

The population in the basin is estimated to be 18.6 million people in 2017. Based on the available water resources, the per capita water availability in the basin would be about a mere 263 $m^3$/year which is well below the 500m /cap/year threshold below which severe water stress is indicated (Falkenmark, 1986). It is therefore essential that the available water resources are used and managed sustainably.

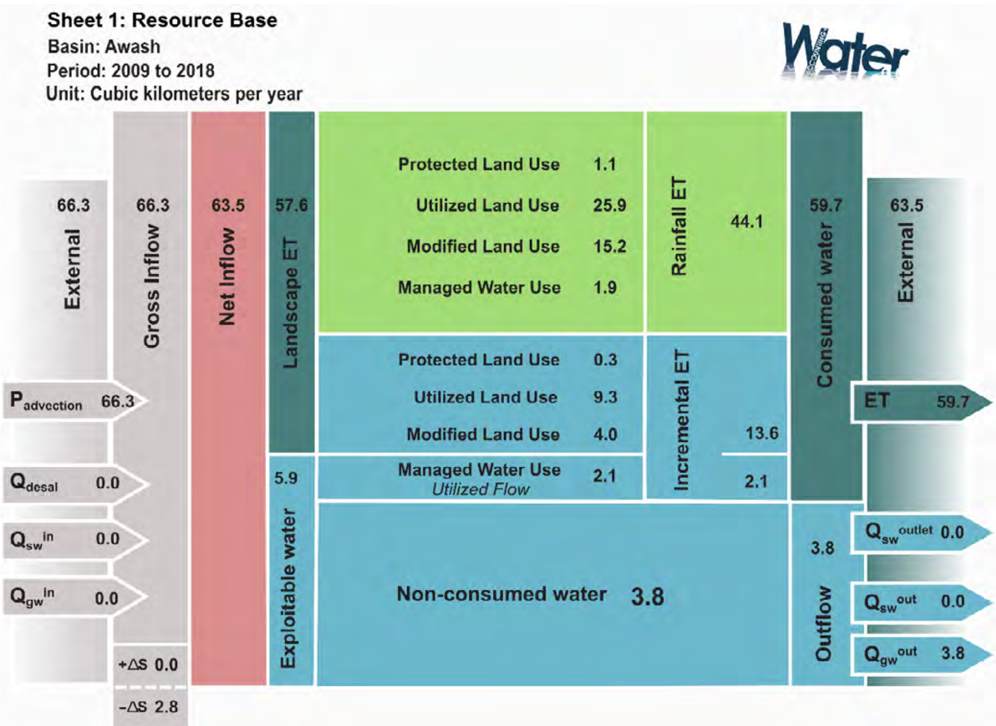



Figure 16. WA+ sheet 1 for the Awash River Basin containing average flow values for the period 2009 – 2018. Yearly Resource Base Sheets are included in Annex 5

The majority of $ET_{incr}$ (total volume 15.7 $km^3$/year) originates from natural withdrawals (13.6 $km^3$/year). The anthropic withdrawals (2.1 $km^3$/year) is only about 13% of $ET_{incr}$. The majority of the available water resources goes to Utilized Land Use (ULU) with 9.3 $km^3$/year and Modified Land Use (MLU) with 4.0 $km^3$/year. Protected Land Use (PLU) uses only 0.3 $km^3$/year. Rarely this usage of blue water appears in water allocation plans, because this consumption occurs naturally and is out of sight from water managers. The fact that natural land use classes utilize blue water can be explained by capillary rise and Awash River overflows and inundating these natural land

use classes for long period during wet season period in low plains. Groundwater dependent ecosystems such as bushland and forests would tap into shallow aquifers and intercept drainage flows.

The outflow from the basin is in the form of groundwater outflow as there is no observed surface water outflow. While detailed groundwater studies were not available, Karimi et al. (2015) considered a regional groundwater outflow of 3.8 $km^3$/year likely, which is equivalent to 31 mm/year recharge. For this water accounting, the same amount was also used to represent the yearly groundwater outflow.

The total consumed water (the sum of rainfall and incremental ET) is 59.7 $km^3$/year which is about 90% of the total precipitation. $ET_{incr}$ accounts 26.3% of the consumption.

Irrigated cropland cover covers 3,126.8 $km^2$ which is about 3% of the Awash River Basin area and the average $ET_{incr}$ used by this land cover is 635.4 mm/year (see Figure 15) which implies about 1.99 $km^3$/year of the exploitable water or 37% is used for irrigation. Of the managed water use the irrigated croplands consume about 95%.

The water resources situation described above shows the average condition over the decade from 2009 to 2018, however the situation varies greatly from year to year depending on the amount of rainfall the basin receives, as described in the following section.

### 3.1.2. Variability of the annual Water Accounts

Figure 17 shows the yearly changes in precipitation, $ET_a$ and rainfall and incremental ET per water accounting land use categories. It shows that both $ET_{rain}$ and $ET_{incr}$ seem directly proportional to the precipitation. This implies that the $ET_{incr}$ maybe from surface runoff

The year 2010 was the wettest year from the period analysed receiving 82.6 $km^3$/year of rainfall (Figure 18). The exploitable water resources is 5.6 $km^3$/year which is not very different from that of the average situation. The main difference is in the amount of water stored in the basin which now increases to 13.5 $km^3$/year and in the $ET_{rain}$. The exploitable water resources in the basin for this year (considering the same population as 2017) was 1,059 $m^3$/year which is more than tripled the average situation.

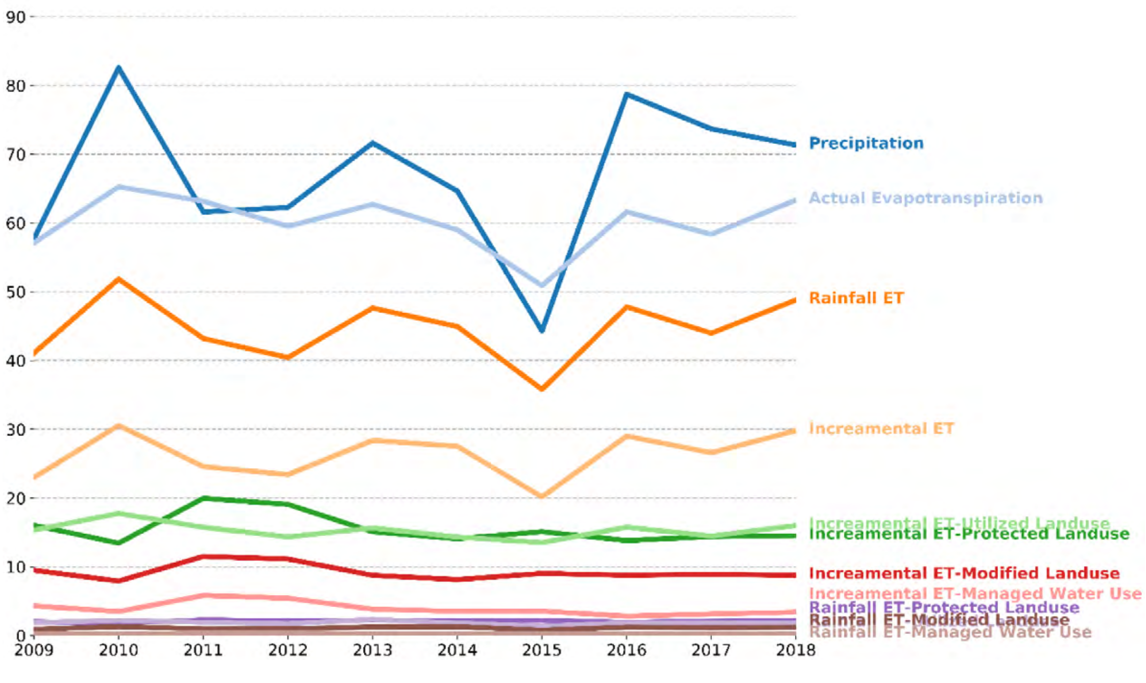



Figure 17. Awash River Basin water fluxes by year in $km^3$/year from 2009 to 2018

$ET_{incr}$ (the blue component of ET) shows a reduction (13.4 km³/year) as part of it was satisfied by rainfall. The total consumption is 65.3 km³/year which accounts 79% of the precipitation the basin received. $ET_{incr}$ is only 20% of the total consumption.

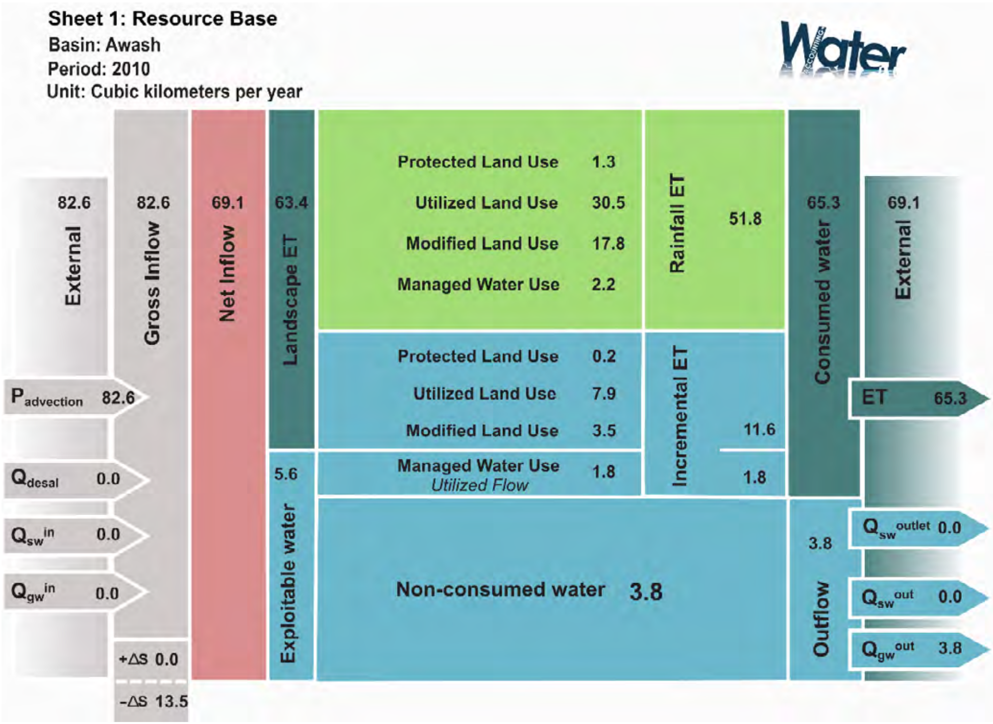



Figure 18. WA+ sheet 1 for the Awash River Basin for the wettest year (2010)

On the other hand, 2015 was the driest year receiving just 44.3 km³/year which is less than the consumed water (50.9 km³/year), the difference supplied from depleting the storage in the basin. $ET_{incr}$ (15.1 km³/year) is now 30% of the total consumed water (Figure 19).

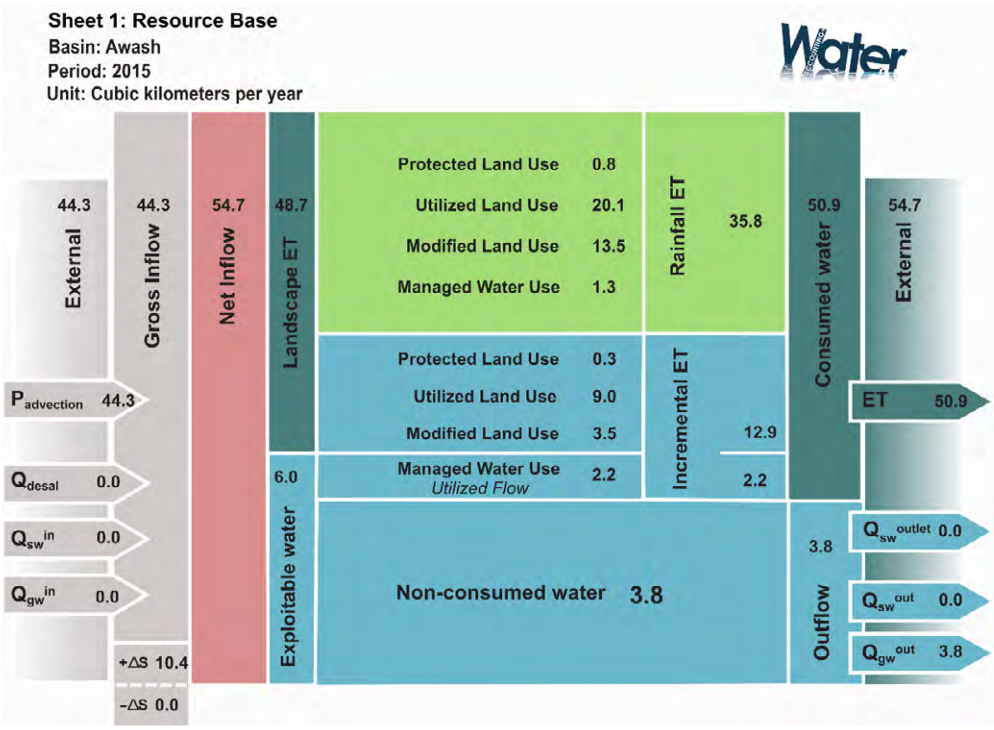



Figure 19. WA+ sheet 1 for the Awash River Basin for the driest year (2015)

## 3.2. Key Indicators

The key performance indicators are presented in Table 8. Since there were discrepancies between the storage change computed from WaPOR data, GRACE gravity measurements, and change in storage computed from yearly water balance (Table 3), we used the later for computation of the key indicators as shown in Table 8. The same indicators computed using the change in storage from GRACE gravity measurements is presented in Annex 7, and show similar results. We therefore conclude that the results can be used for decision making purposes.

Table 8. WA+ Sheet 1 key indicators of Awash River Basin from 2010 to 2018 based on water balance derived from WaPOR datasets

| Year | ET fraction (%) | Stationarity index (%) | Basin Closure (%) | Available water ($km^3$/year) | Managed water ($km^3$/year) | Managed fraction (%) |
|---|---|---|---|---|---|---|
| 2009 | 98.9 | - 5.5 | 93.4 | 2.6 | 2.0 | 75.8 |
| 2010 | 79.0 | 20.7 | 95.4 | 19.1 | 1.8 | 9.5 |
| 2011 | 102.5 | - 8.5 | 93.8 | 0.7 | 2.3 | 316.7 |
| 2012 | 95.6 | - 1.7 | 93.9 | 4.9 | 2.1 | 43.6 |
| 2013 | 87.6 | 8.2 | 94.7 | 11.1 | 2.2 | 20.0 |
| 2014 | 91.3 | 3.1 | 94.1 | 7.8 | 2.2 | 27.8 |
| 2015 | 114.9 | - 20.4 | 91.4 | - 4.4 | 2.2 | - 50.8 |
| 2016 | 78.3 | 21.6 | 95.2 | 19.0 | 1.9 | 10.1 |
| 2017 | 79.2 | 19.7 | 94.8 | 17.4 | 2.1 | 12.1 |
| 2018 | 88.8 | 6.6 | 94.7 | 10.2 | 2.2 | 21.3 |
| Numerical average | 95.7 | - 0.6 | 93.8 | 6.0 | 2.1 | 63.2 |

### 3.2.1. ET fraction, Stationarity index and Basin Closure

The key performance parameters presented in Table 8 describes the river basin system by a few indicators. The ET fraction is highest in 2015 with about 115% indicating more than the precipitation amount consumed in that year. The additional amount consumed (15%) comes from storages in the basin. The ET fraction is lowest for the year 2016 with 78% indicating that not all rainfall is consumed so that surplus of rainfall is used to increase storage and/or generate non-utilized outflow from the basin. The representative value for ET fraction across the decade (2009 to 2010) is 92%. The wet years when the basin receives higher amount of precipitation increase the intra annual storage in the basin.

The Stationarity Index indicator describes what percentage of the consumption is originating from storage changes. An average positive indicator of 3.9% means that groundwater is not over-exploited however, its recharge is not that significant. In wet years such as years 2010, 2013, 2014 and 2016 -2018, the groundwater is recharging indicated by the positive stationarity index while in dry years abstraction of the groundwater occurs.

The average basin closure index is 94.1%, which shows that almost all water resources is consumed and/or stored in the basin; only 5.9% is flowing out of the basin.

### 3.2.2. Available water, managed water and managed fraction

The second set of indicators in Table 4 focuses on the actual amount of water that is currently managed, or is available to be managed. The total amount of Available Water is 8.6 $km^3$/year. From this, a total amount of 2.1 $km^3$/year is managed which is about 24% of the available amount. The available water as calculated here includes the outflow water from the basin in the form of groundwater outflow. To calculate the safe cap of water withdrawals, it is essential to evaluate where the outflow ends up. If it is used for some purpose outside of the basin, then the outflow can be considered as reserved flow and the available water will reduce by the same amount.

In wet years the available water increases and the managed fraction becomes less while in dry years the available water decreases and the managed fraction increase. A negative managed fraction indicates that the managed water provided by depleting storage in the basin such as in years 2015 where the managed fractions are -50.8%. These are the periods where the storage is being depleted.

A part of the available water amount can be contaminated by anthropogenic pollution loads to the extent that exceeds the basin's assimilation capacity. The water pollution level of the Awash River Basin related to anthropogenic Nitrogen and Phosphorus loads from diffuse and point sources from 2002 to 2010 was estimated to be less than 0.6 (Mekonnen and Hoekstra, 2015) and between 5 and 10 (Mekonnen and Hoekstra, 2018) respectively. In these studies, the water pollution levels were calculated as the ratio of Grey Water Footprint over the annual actual runoff of the basin. These values indicate that it would take more than 5 to 10 times of actual runoff of the basin to dilute the pollution related to anthropogenic Nitrogen and Phosphorus loads. As a result, the estimated available water might not be suitable for some uses (irrigation, drinking water, etc.). It should be, however, noted that the uncertainty range of the global GWF is of -33% to +60% (Mekonnen and Hoekstra, 2015).

# 4. Conclusions

The Awash River Basin is the most utilized river basin in Ethiopia hosting most of the industrial activities, small to large scale irrigation schemes and more than 18.6 million people. The basin faces high water stress during the peak irrigation time and frequent flooding in rainy seasons. The average yearly precipitation as quantified in the decade from 2009 to 2018 is 560 mm/year and the average yearly evapotranspiration is calculated as 503 mm/year indicating about 90% of the precipitation is consumed through evapotranspiration. The remaining 10% contributes to outflow from the basin in the form of groundwater outflow and change in storage within the basin. Based on the estimated water availability, the inhabitants are facing severe water shortage (<500 $m^3$/cap/year).

The availability of water in the basin shows annual variability depending on the amount of precipitation the basin receives. In wet years, the basin generates surplus of water in excess of managed water and in dry years, the storage is depleted to satisfy managed water requirement. The overall managed water fraction is almost half (50%) of the available water. 37% the exploitable water is used for irrigation, this amounts to 95% of the managed water use. To satisfy the growing demand of water in the basin, strategies focusing on increasing water use efficiency and storage capacity need to be implemented to reduce the inter-annual variability. A safe cap on the exploitable water could not be determined without knowing where the outflow ends up.

The use of WaPOR data for water accounting analysis is showcased in this study. One of the reasons for slow uptake of water accounting, lack of data, has been overcome by relying heavily on remotely sensed data. Remote sensing technique have been developed over the last years and nowadays there are several remotely sensed products. However, their quality varies greatly from one product to another and they are found from a number of providers. WaPOR database makes access to most of the remotely sensed products for water accounting relatively easy. This study has shown that the quality of the data provided through WaPOR 2.0 Level 2 provides reasonable estimates of P, $ET_a$ at basin scale, general spatial distribution and analyses for different land use classes were also consistent. However, in the highlands there are a few patches where $ET_a$ exceeds P (identified as irrigated areas) where there is no known irrigation taking place. Similarly in the Afar depression, P generally exceeds $ET_a$ indicating net generation of water, which is not consistent with observations. These discrepancies require further investigation.

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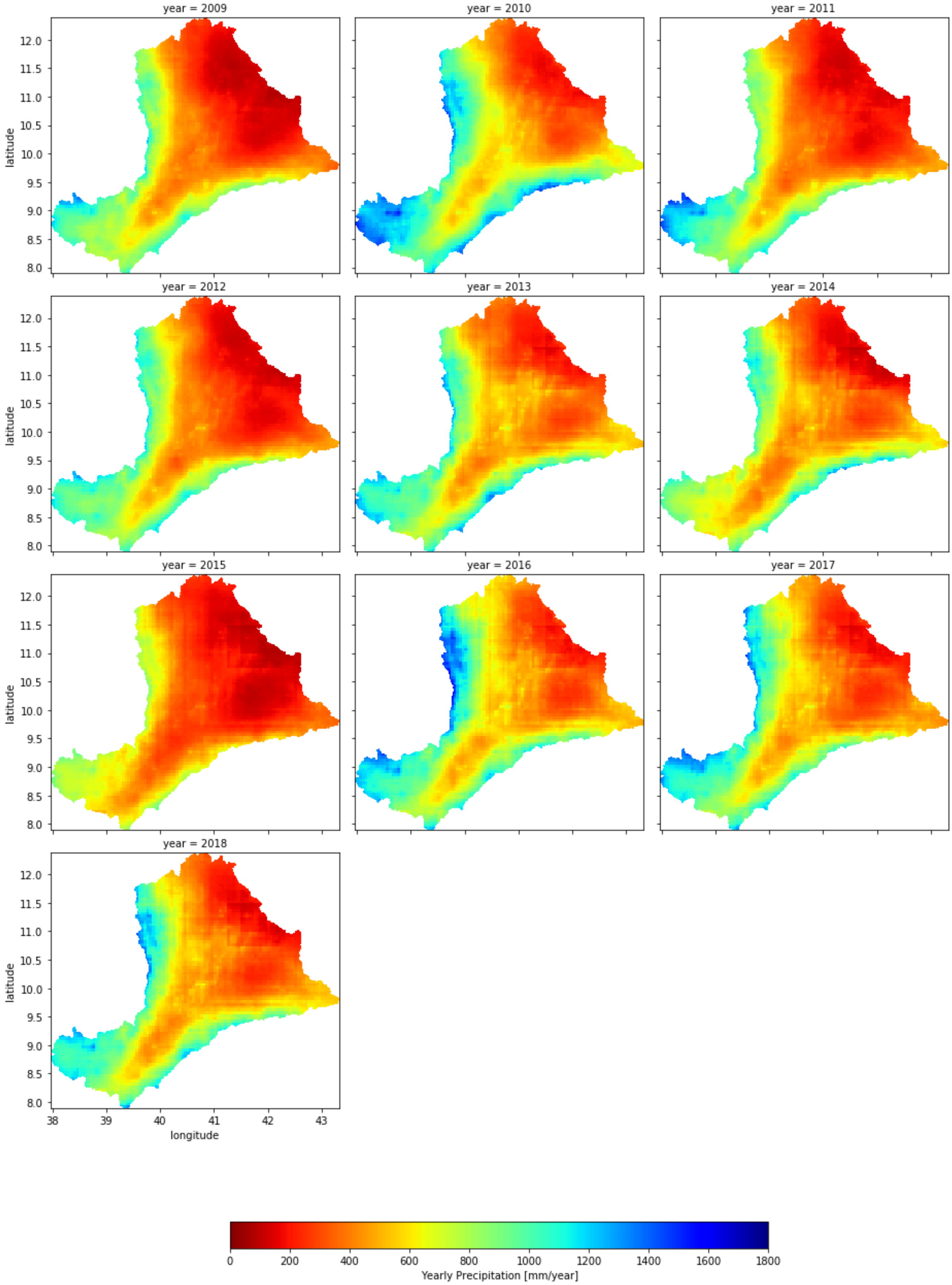
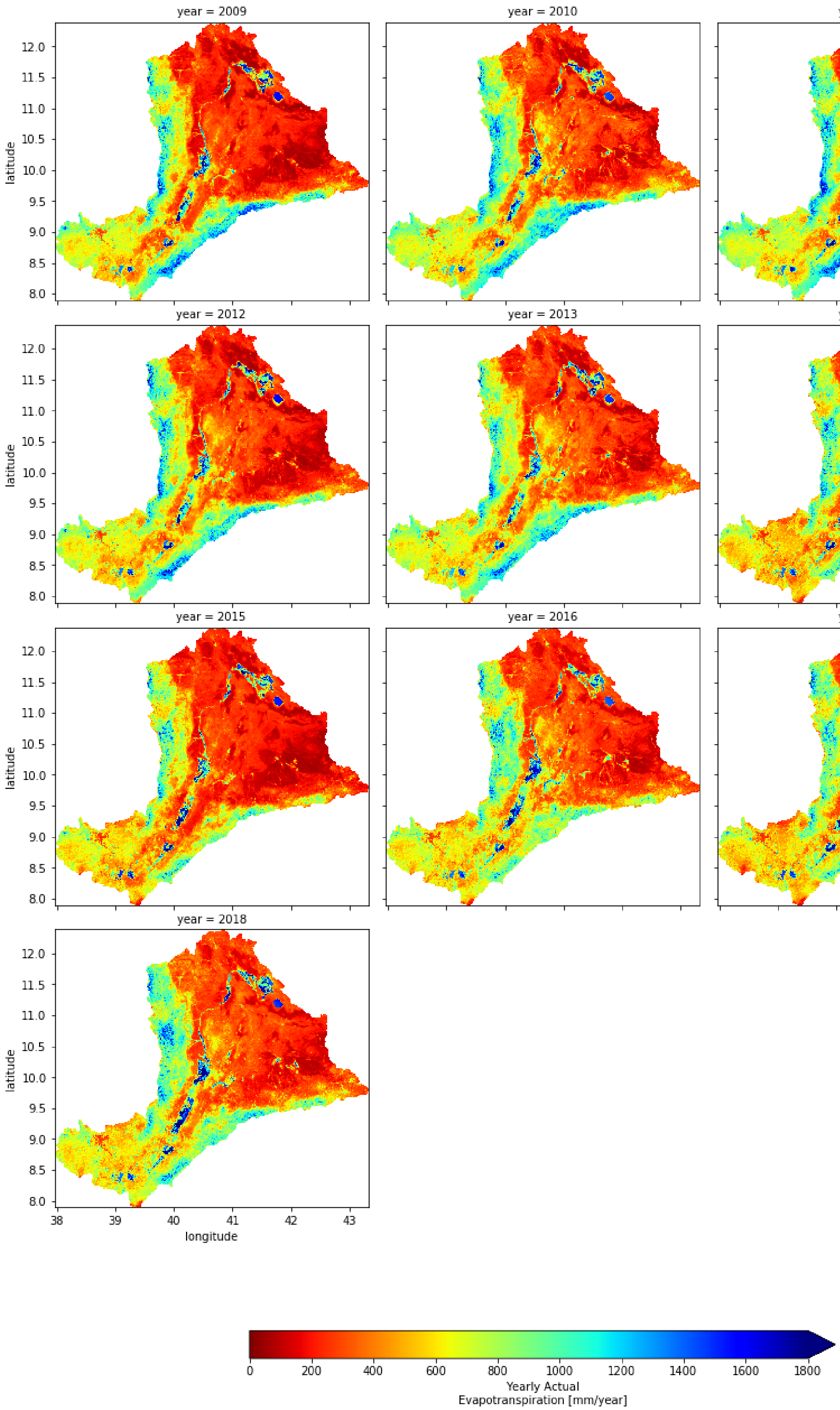
# Appendixes

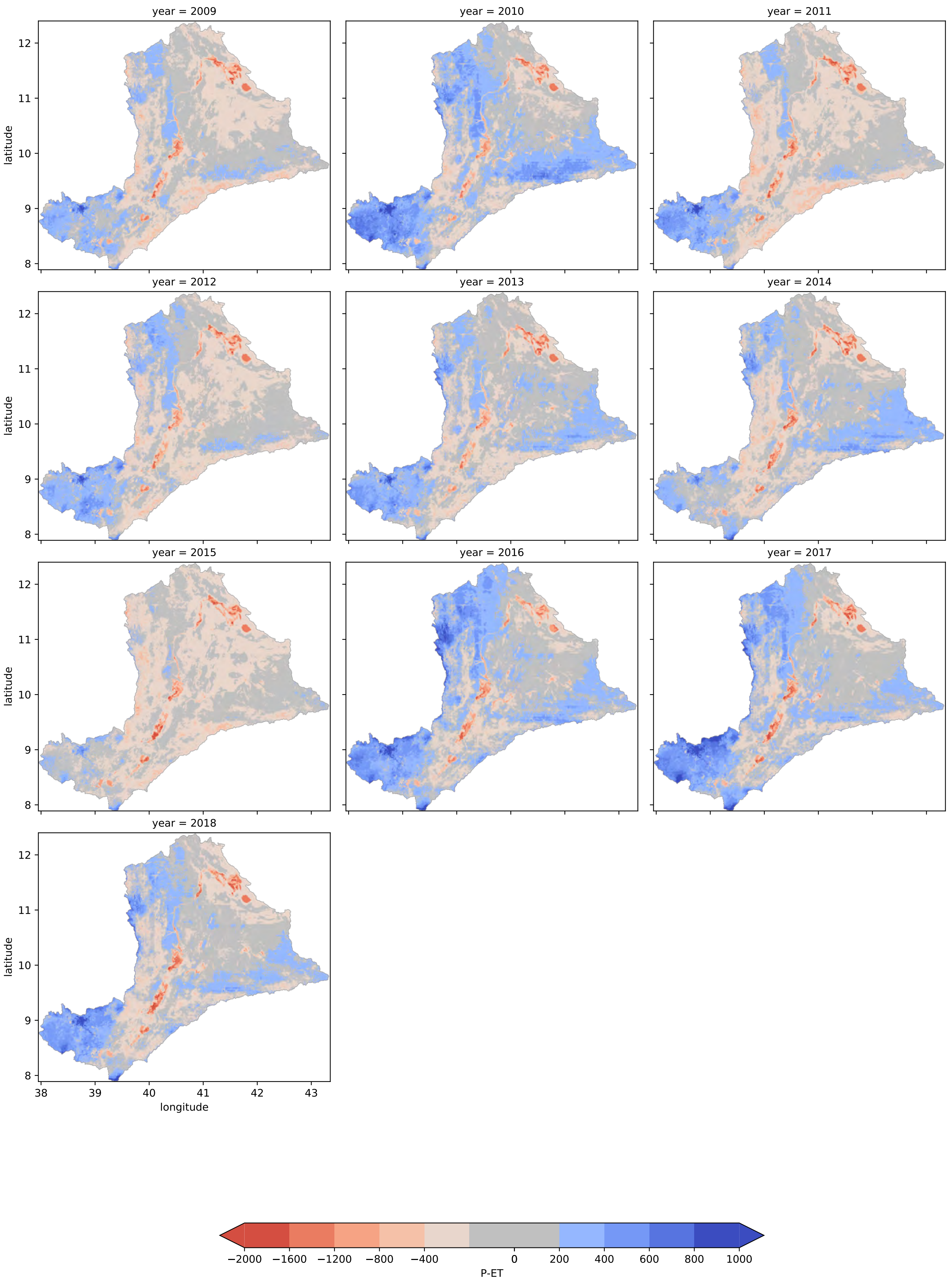
Annex 1. Plots of Annual Precipitation of Awash River Basin in mm/year



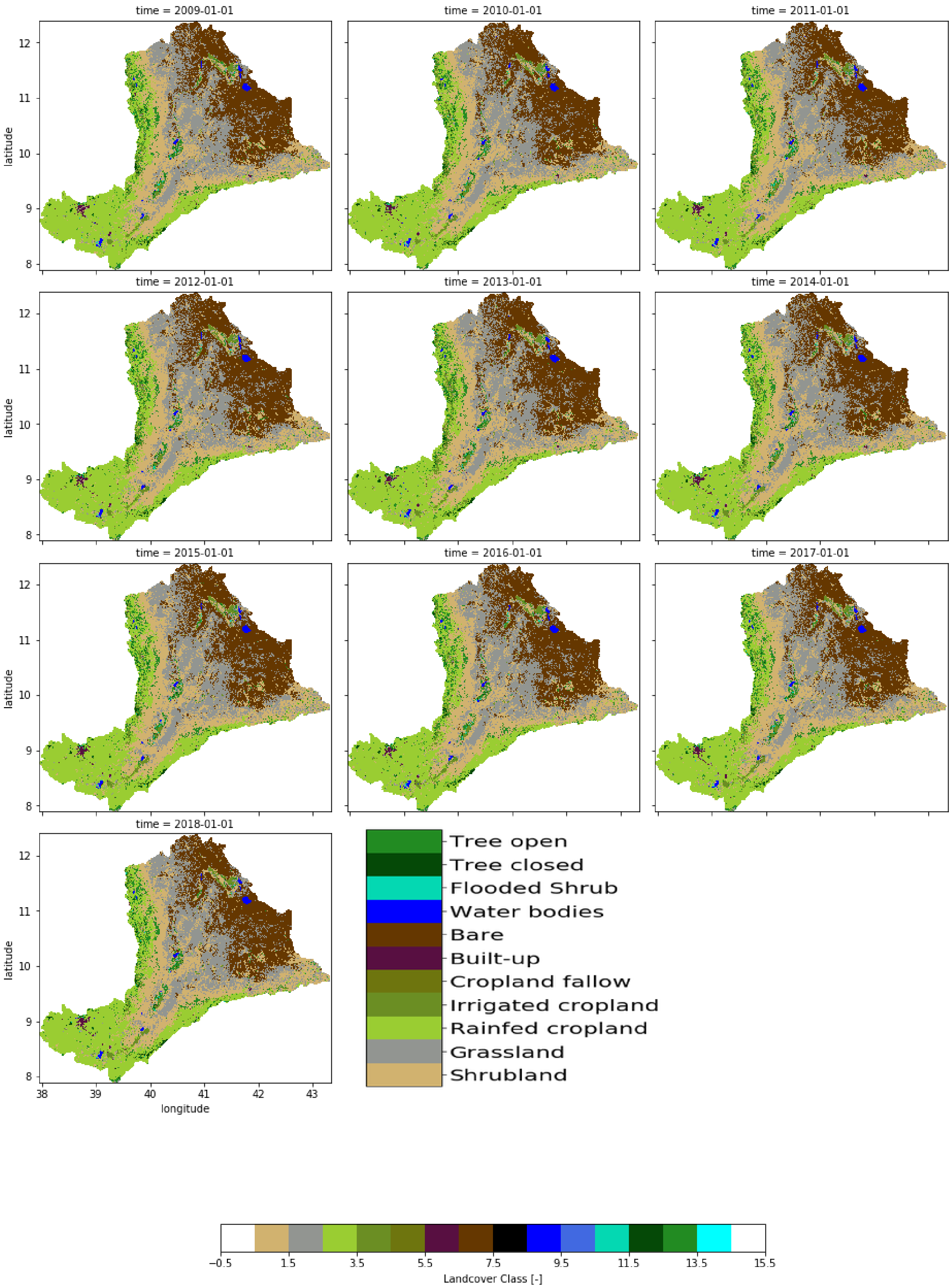
**Annex 2.** Plots of Annual Actual Evapotranspiration of Awash River Basin in mm/year



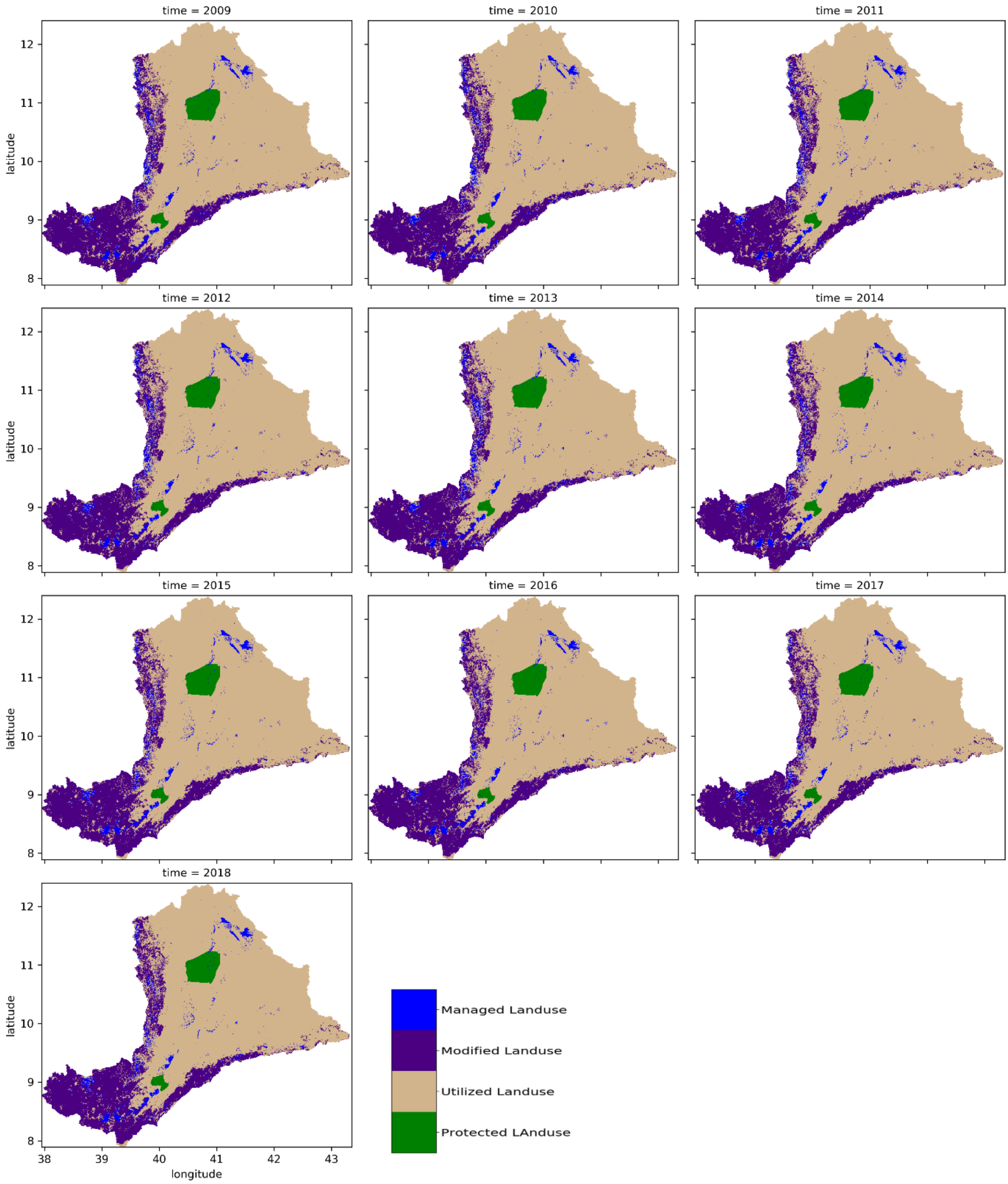
## Annex 3. Plots of Annual P-$ET_a$ of Awash in mm/year

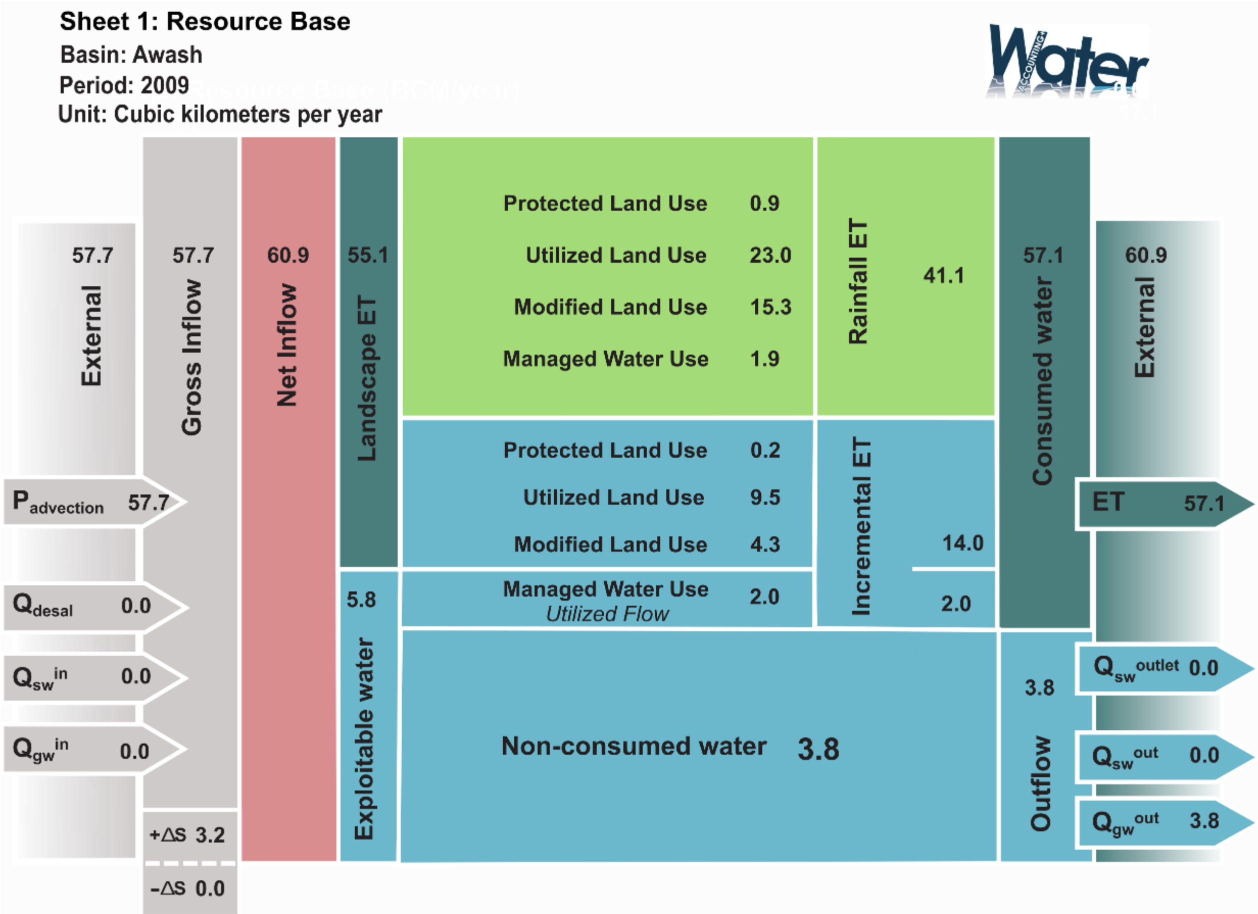


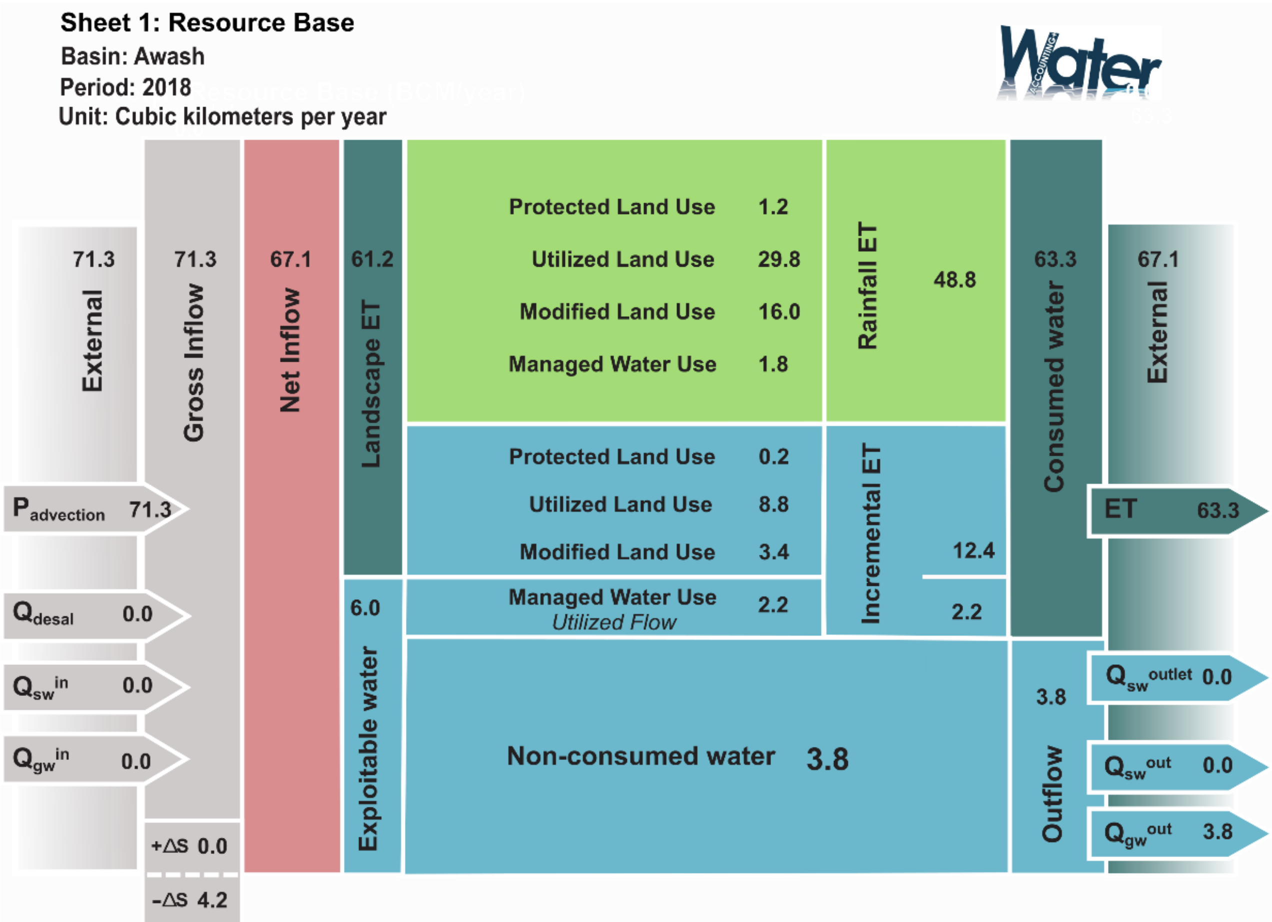
## Annex 4. Plots of Annual Land cover classification maps



## Annex 5. Plots of Annual Land Use maps based on WA+ Categories




Sheet 1: Resource Base
Basin: Awash
Period: 2009
Unit: Cubic kilometers per year
External 57.7
Gross Inflow 57.7
Net Inflow 60.9
Landscape ET 55.1
Protected Land Use 0.9
Utilized Land Use 23.0
Modified Land Use 15.3
Managed Water Use 1.9
Rainfall ET 41.1
Consumed water 57.1
External 60.9
P advection 57.7
Protected Land Use 0.2
Utilized Land Use 9.5
Modified Land Use 4.3
Incremental ET 14.0
ET 57.1
Q desal 0.0
5.8
Managed Water Use 2.0
Utilized Flow
2.0
Q sw in 0.0
Q gw in 0.0
Exploitable water
Non-consumed water 3.8
Outflow 3.8
Q sw outlet 0.0
Q sw out 0.0
Q gw out 3.8
+ΔS 3.2
-ΔS 0.0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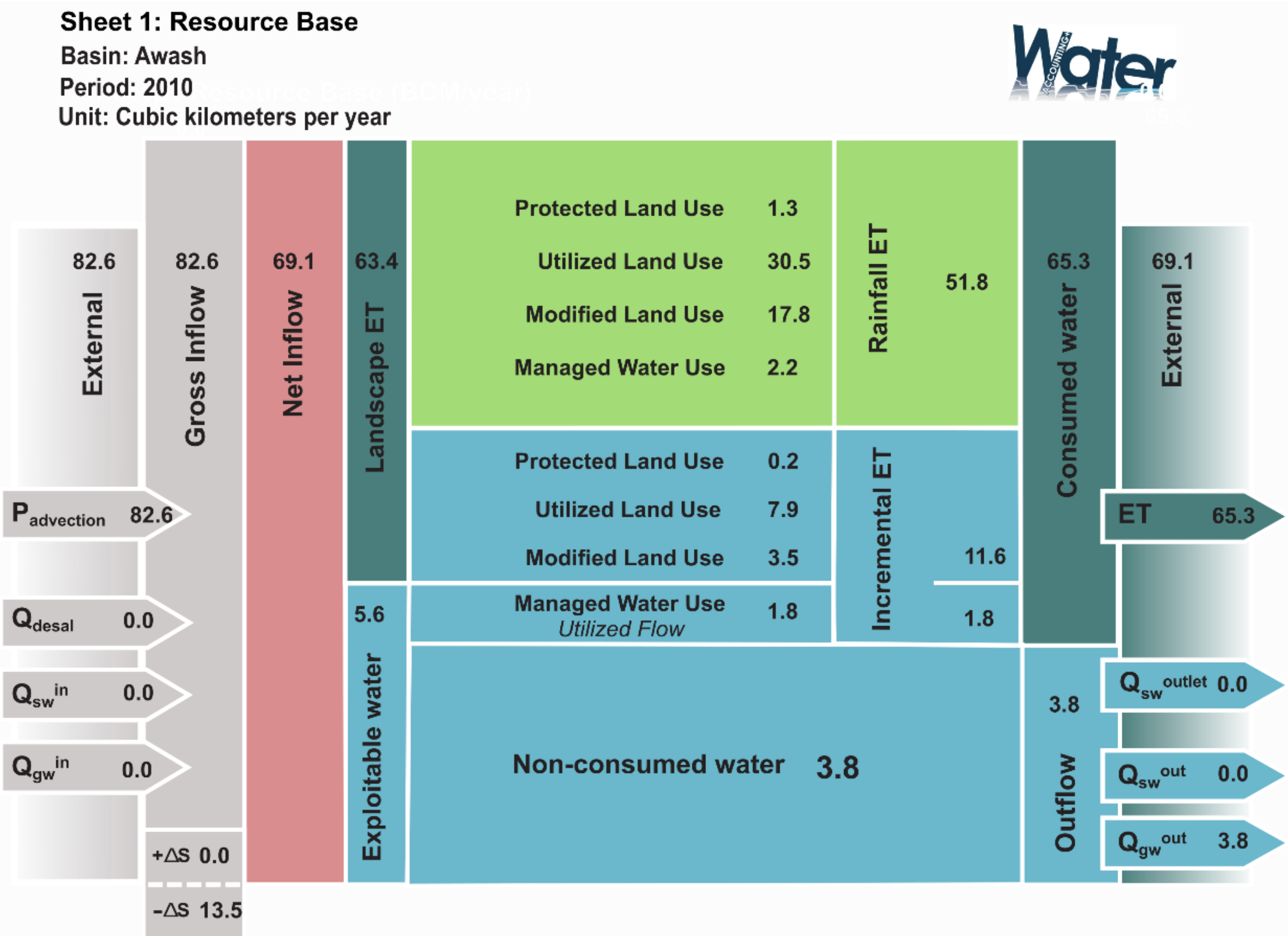
Basin: Awash
Period: 2018
Unit: Cubic kilometers per year
External 71.3
Gross Inflow 71.3
Net Inflow 67.1
Landscape ET 61.2
Protected Land Use 1.2
Utilized Land Use 29.8
Modified Land Use 16.0
Managed Water Use 1.8
Rainfall ET 48.8
Consumed water 63.3
External 67.1
P advection 71.3
Protected Land Use 0.2
Utilized Land Use 8.8
Modified Land Use 3.4
Incremental ET 12.4
ET 63.3
Q desal 0.0
6.0
Managed Water Use 2.2
Utilized Flow
2.2
Q sw in 0.0
Q gw in 0.0
Exploitable water
Non-consumed water 3.8
Outflow 3.8
Q sw outlet 0.0
Q sw out 0.0
Q gw out 3.8
+ΔS 0.0
-ΔS 4.2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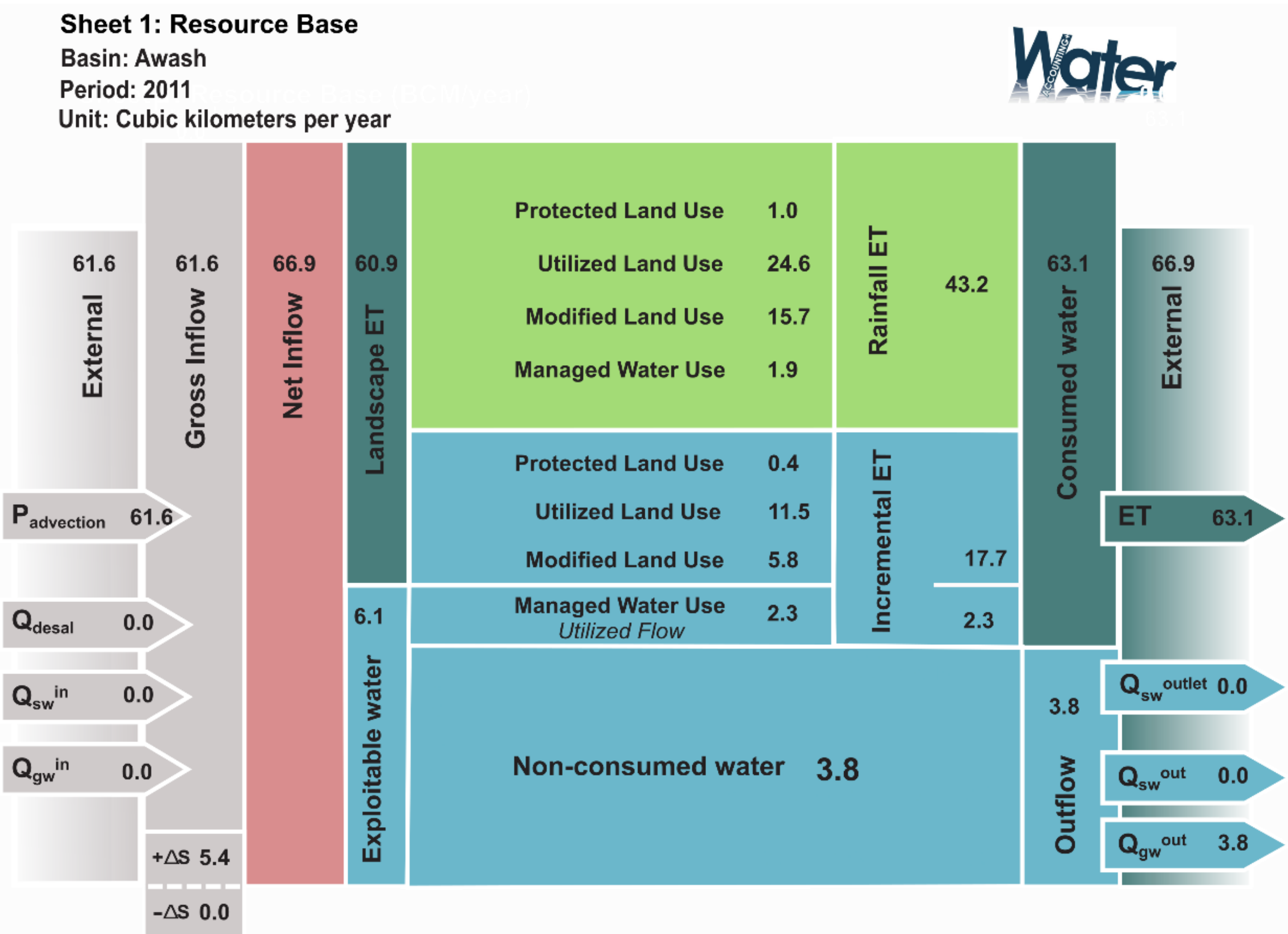
Basin: Awash
Period: 2010
Unit: Cubic kilometers per year
Water Accounting+
External 82.6
Gross Inflow 82.6
Net Inflow 69.1
Landscape ET 63.4
Protected Land Use 1.3
Utilized Land Use 30.5
Modified Land Use 17.8
Managed Water Use 2.2
Rainfall ET 51.8
Consumed water 65.3
External 69.1
$P_{advection}$ 82.6
Protected Land Use 0.2
Utilized Land Use 7.9
Modified Land Use 3.5
Incremental ET 11.6
ET 65.3
$Q_{desal}$ 0.0
5.6
Managed Water Use 1.8
Utilized Flow
1.8
$Q_{sw}^{in}$ 0.0
Exploitable water
Non-consumed water 3.8
3.8
Outflow
$Q_{sw}^{outlet}$ 0.0
$Q_{gw}^{in}$ 0.0
$Q_{sw}^{out}$ 0.0
$Q_{gw}^{out}$ 3.8
+ΔS 0.0
-ΔS 13.5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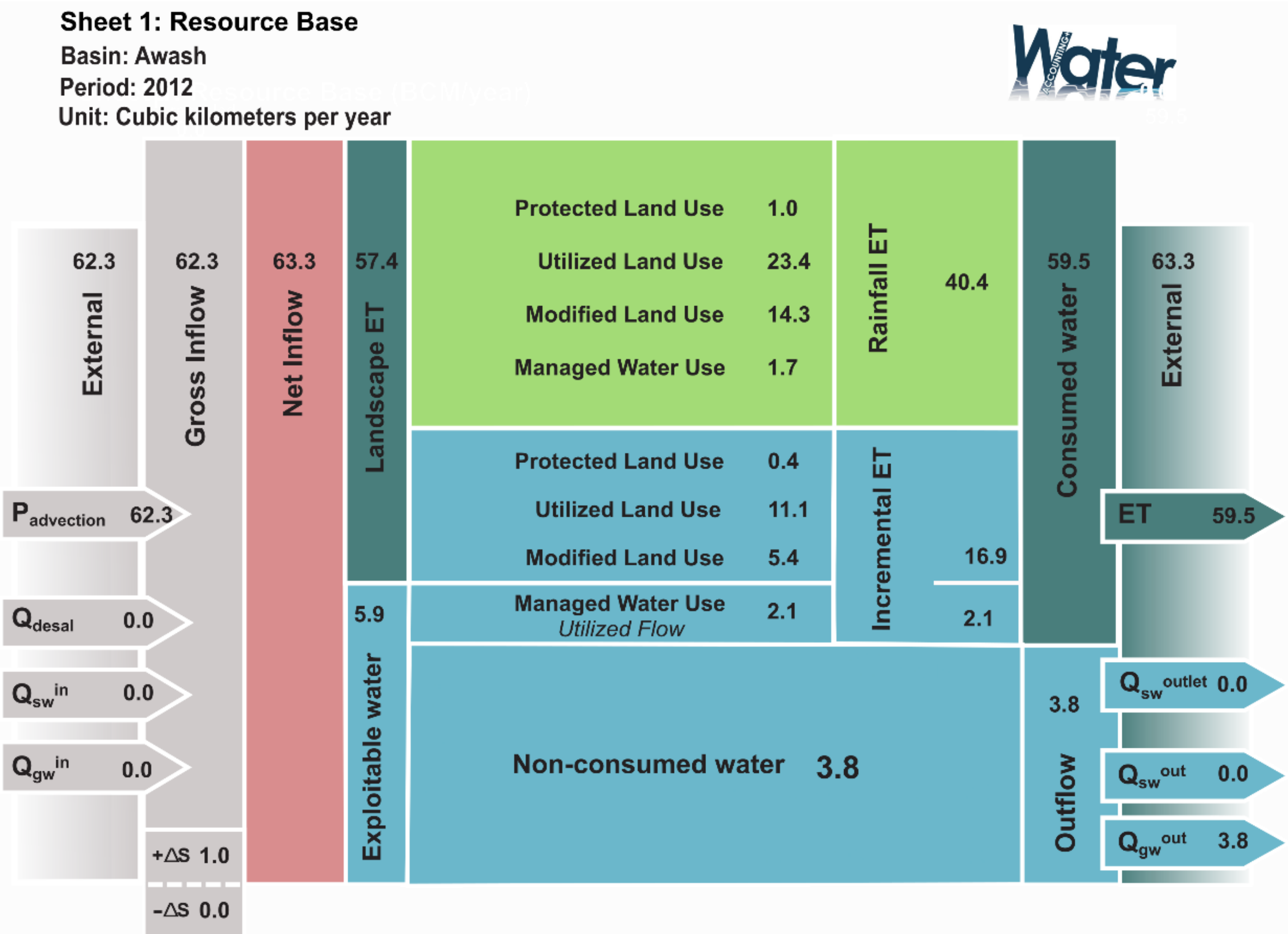
Basin: Awash
Period: 2011
Unit: Cubic kilometers per year
Water Accounting+
External 61.6
Gross Inflow 61.6
Net Inflow 66.9
Landscape ET 60.9
Protected Land Use 1.0
Utilized Land Use 24.6
Modified Land Use 15.7
Managed Water Use 1.9
Rainfall ET 43.2
Consumed water 63.1
External 66.9
$P_{advection}$ 61.6
Protected Land Use 0.4
Utilized Land Use 11.5
Modified Land Use 5.8
Incremental ET 17.7
ET 63.1
$Q_{desal}$ 0.0
6.1
Managed Water Use 2.3
Utilized Flow
2.3
$Q_{sw}^{in}$ 0.0
Exploitable water
Non-consumed water 3.8
3.8
Outflow
$Q_{sw}^{outlet}$ 0.0
$Q_{gw}^{in}$ 0.0
$Q_{sw}^{out}$ 0.0
$Q_{gw}^{out}$ 3.8
+ΔS 5.4
-ΔS 0.0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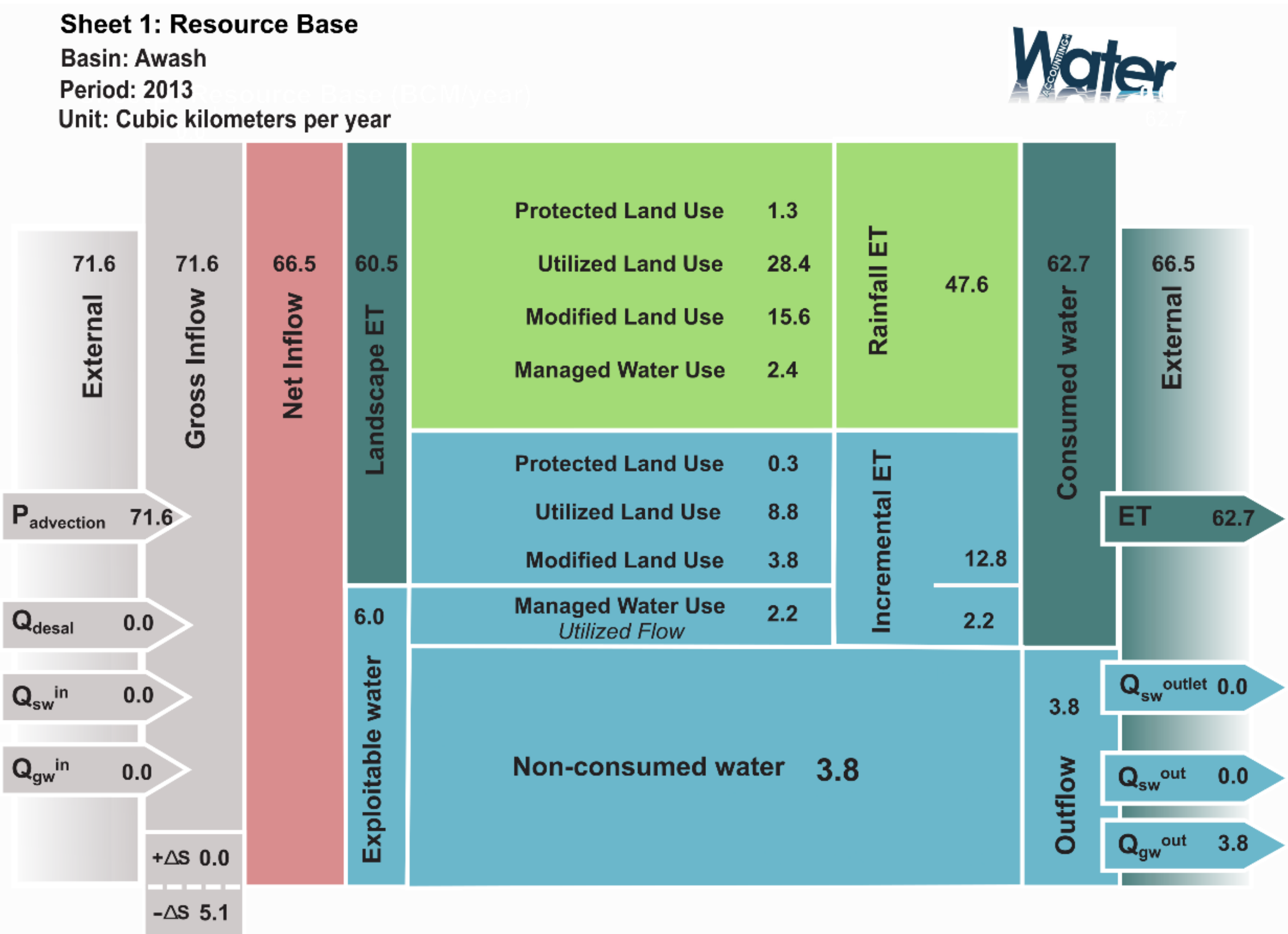
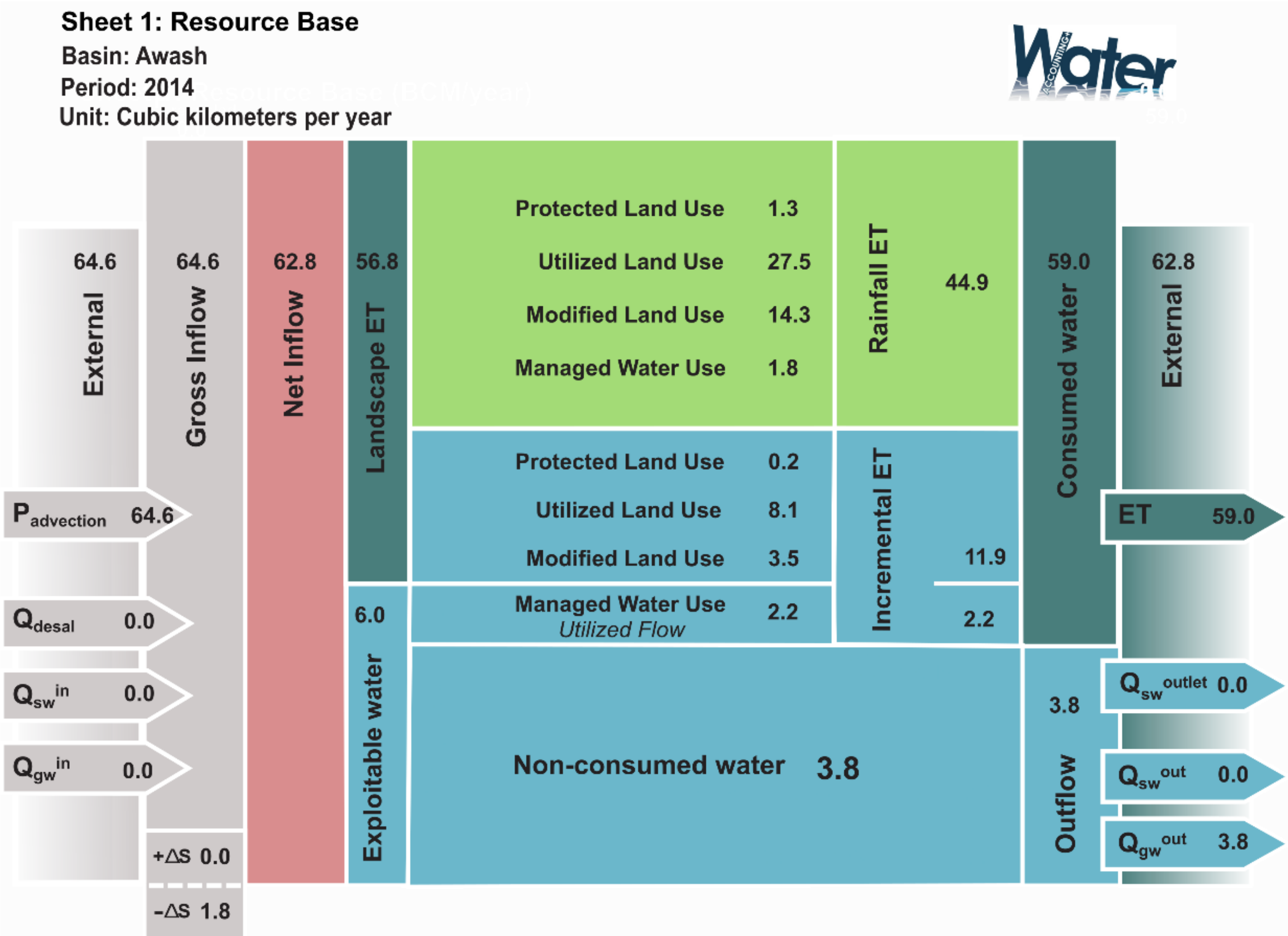
Basin: Awash
Period: 2012
Unit: Cubic kilometers per year
Water Accounting+
External 62.3
Gross Inflow 62.3
Net Inflow 63.3
Landscape ET 57.4
Protected Land Use 1.0
Utilized Land Use 23.4
Modified Land Use 14.3
Managed Water Use 1.7
Rainfall ET 40.4
Protected Land Use 0.4
Utilized Land Use 11.1
Modified Land Use 5.4
Incremental ET 16.9
Managed Water Use 2.1
Utilized Flow
2.1
Consumed water 59.5
External 63.3
ET 59.5
P advection 62.3
Q desal 0.0
Q sw in 0.0
Q gw in 0.0
+ΔS 1.0
-ΔS 0.0
Exploitable water 5.9
Non-consumed water 3.8
Outflow 3.8
Q sw outlet 0.0
Q sw out 0.0
Q gw out 3.8


Sheet 1: Resource Base
Basin: Awash
Period: 2013
Unit: Cubic kilometers per year
Water Accounting+
External 71.6
Gross Inflow 71.6
Net Inflow 66.5
Landscape ET 60.5
Protected Land Use 1.3
Utilized Land Use 28.4
Modified Land Use 15.6
Managed Water Use 2.4
Rainfall ET 47.6
Protected Land Use 0.3
Utilized Land Use 8.8
Modified Land Use 3.8
Incremental ET 12.8
Managed Water Use 2.2
Utilized Flow
2.2
Consumed water 62.7
External 66.5
ET 62.7
P advection 71.6
Q desal 0.0
Q sw in 0.0
Q gw in 0.0
+ΔS 0.0
-ΔS 5.1
Exploitable water 6.0
Non-consumed water 3.8
Outflow 3.8
Q sw outlet 0.0
Q sw out 0.0
Q gw out 3.8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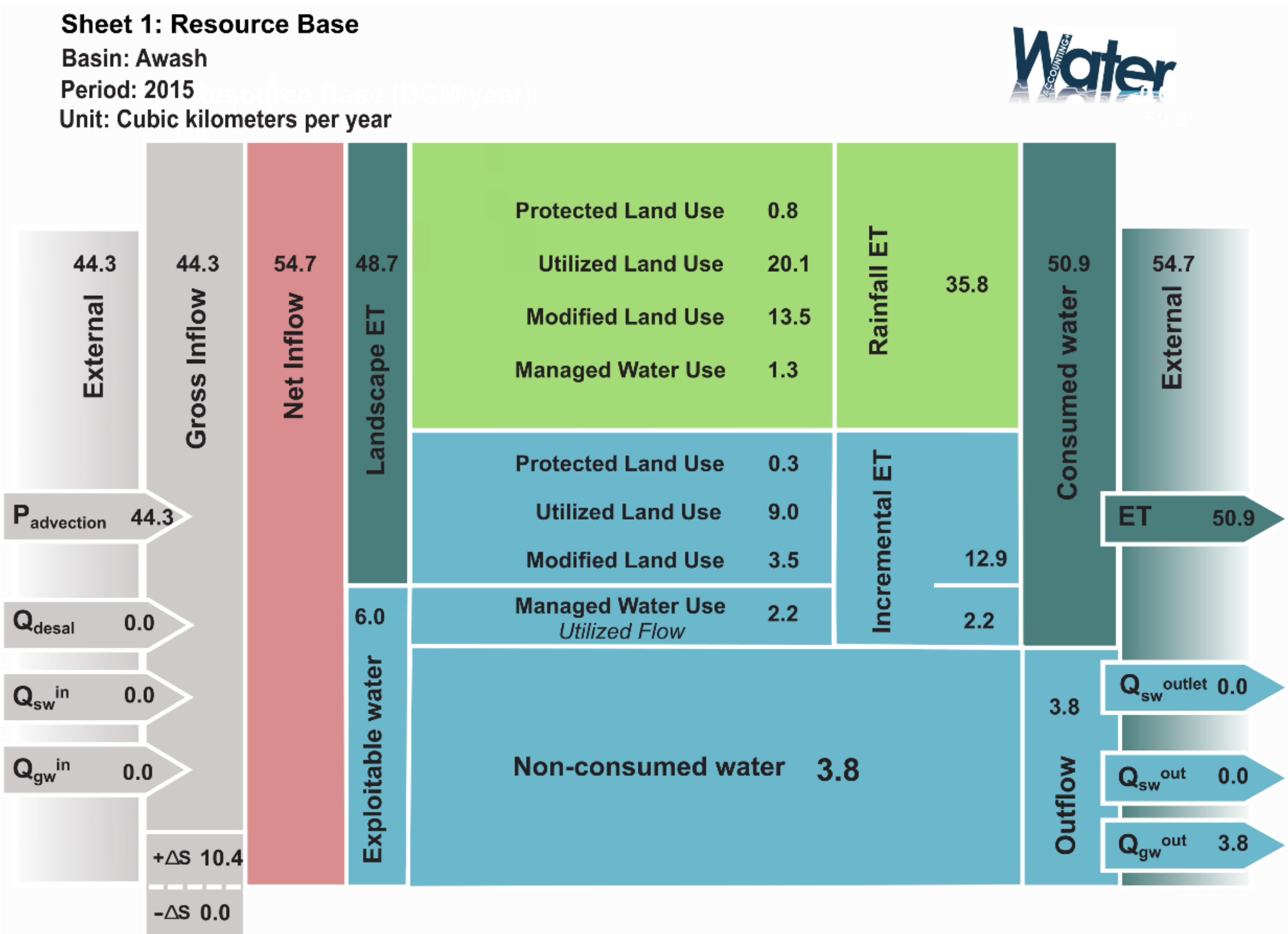
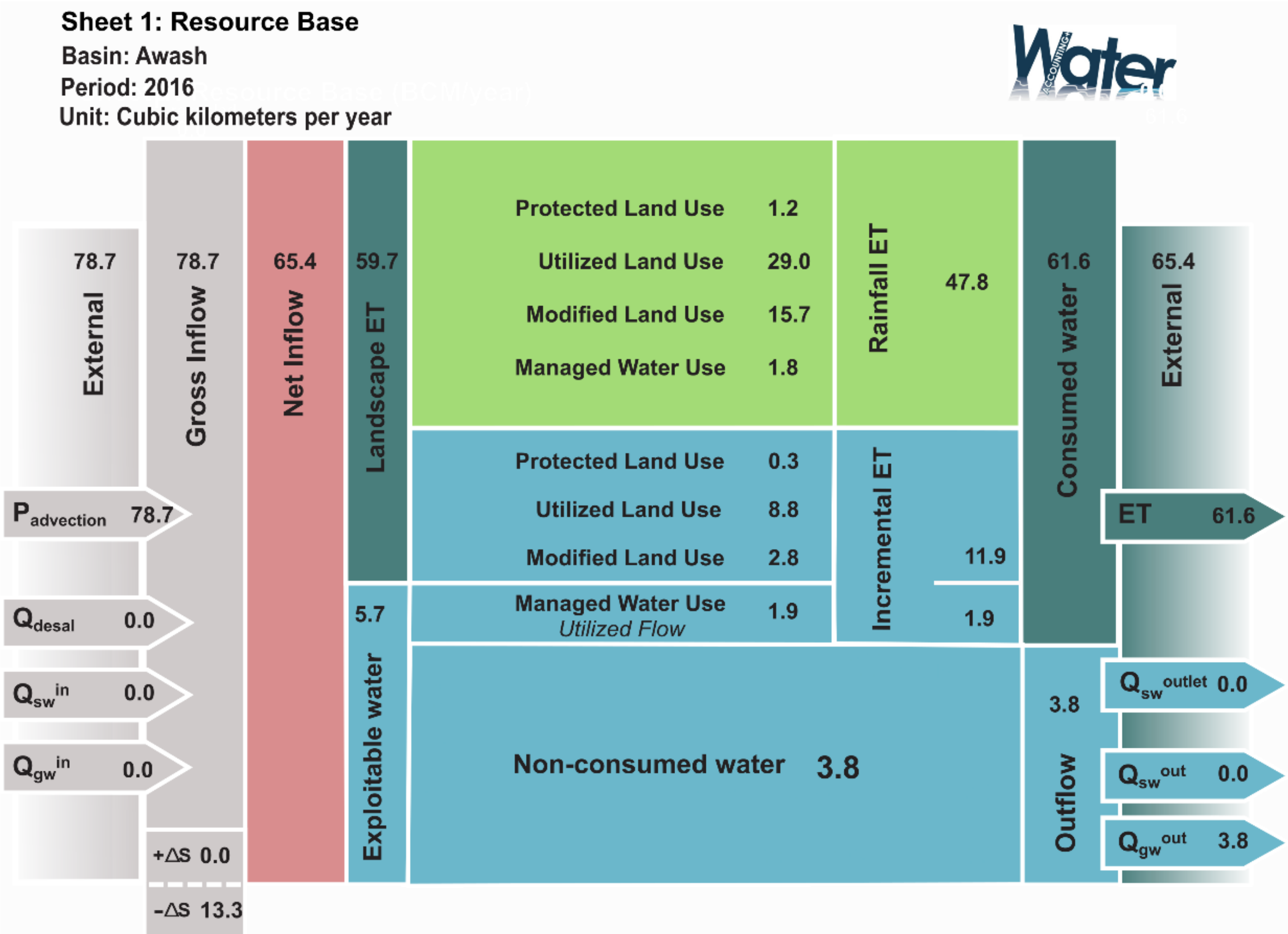
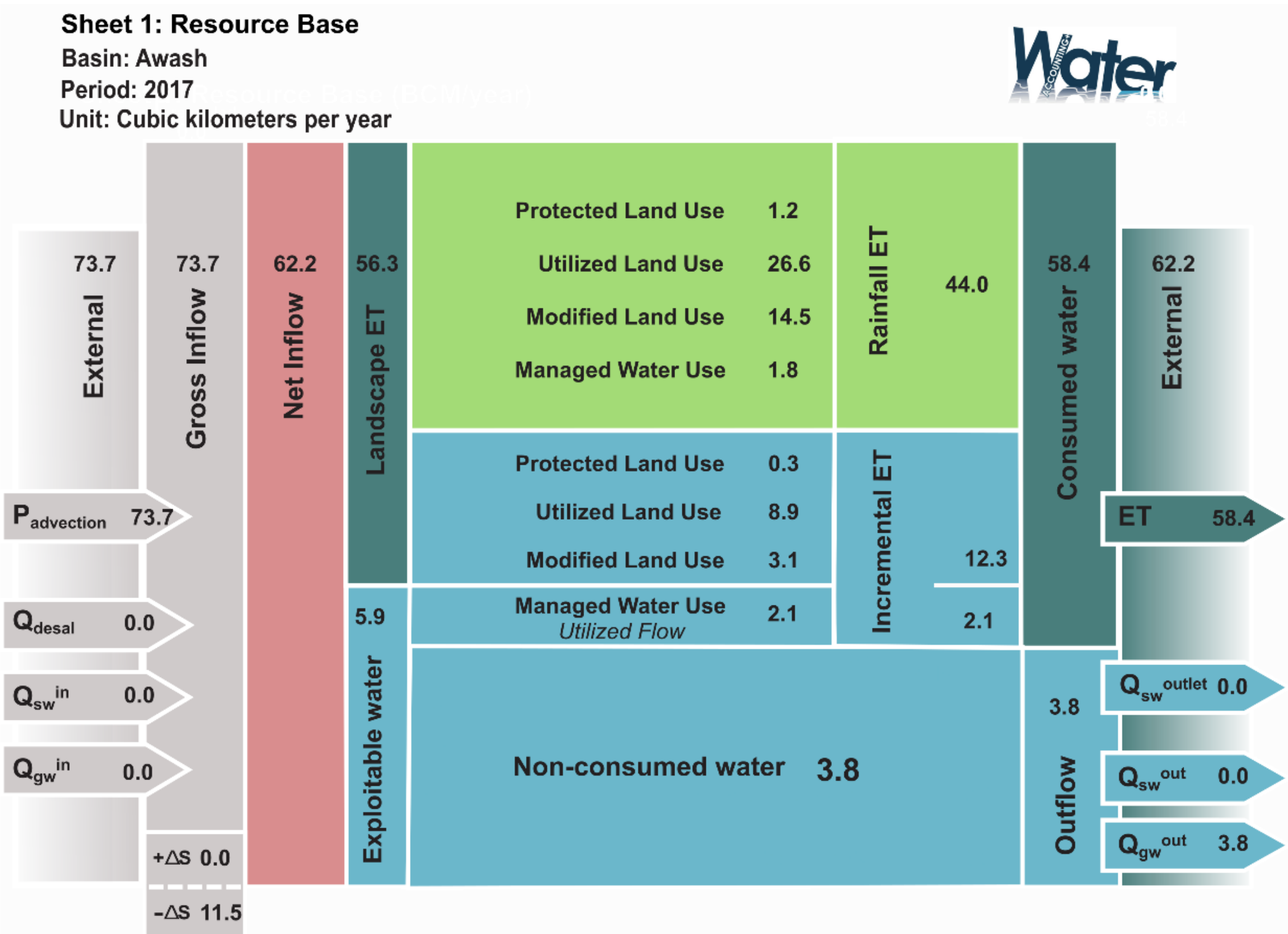
Basin: Awash
Period: 2014
Unit: Cubic kilometers per year
Water Accounting+
External 64.6
Gross Inflow 64.6
Net Inflow 62.8
Landscape ET 56.8
Protected Land Use 1.3
Utilized Land Use 27.5
Modified Land Use 14.3
Managed Water Use 1.8
Rainfall ET 44.9
Consumed water 59.0
External 62.8
P advection 64.6
Protected Land Use 0.2
Utilized Land Use 8.1
Modified Land Use 3.5
Incremental ET 11.9
ET 59.0
Q desal 0.0
6.0
Managed Water Use 2.2
Utilized Flow
2.2
Q sw in 0.0
Q sw outlet 0.0
3.8
Q gw in 0.0
Non-consumed water 3.8
Exploitable water
Q sw out 0.0
Outflow
Q gw out 3.8
+ΔS 0.0
-ΔS 1.8


Sheet 1: Resource Base
Basin: Awash
Period: 2015
Unit: Cubic kilometers per year
Water Accounting+
External 44.3
Gross Inflow 44.3
Net Inflow 54.7
Landscape ET 48.7
Protected Land Use 0.8
Utilized Land Use 20.1
Modified Land Use 13.5
Managed Water Use 1.3
Rainfall ET 35.8
Consumed water 50.9
External 54.7
P advection 44.3
Protected Land Use 0.3
Utilized Land Use 9.0
Modified Land Use 3.5
Incremental ET 12.9
ET 50.9
Q desal 0.0
6.0
Managed Water Use 2.2
Utilized Flow
2.2
Q sw in 0.0
Q sw outlet 0.0
3.8
Q gw in 0.0
Non-consumed water 3.8
Exploitable water
Q sw out 0.0
Outflow
Q gw out 3.8
+ΔS 10.4
-ΔS 0.0


Sheet 1: Resource Base
Basin: Awash
Period: 2016
Unit: Cubic kilometers per year
External 78.7
Gross Inflow 78.7
Net Inflow 65.4
Landscape ET 59.7
Protected Land Use 1.2
Utilized Land Use 29.0
Modified Land Use 15.7
Managed Water Use 1.8
Rainfall ET 47.8
Protected Land Use 0.3
Utilized Land Use 8.8
Modified Land Use 2.8
Managed Water Use 1.9
Utilized Flow
Incremental ET 11.9
1.9
Consumed water 61.6
External 65.4
ET 61.6
P advection 78.7
Q desal 0.0
Q sw in 0.0
Q gw in 0.0
+ΔS 0.0
-ΔS 13.3
Exploitable water 5.7
Non-consumed water 3.8
Outflow 3.8
Q sw outlet 0.0
Q sw out 0.0
Q gw out 3.8


Sheet 1: Resource Base
Basin: Awash
Period: 2017
Unit: Cubic kilometers per year
External 73.7
Gross Inflow 73.7
Net Inflow 62.2
Landscape ET 56.3
Protected Land Use 1.2
Utilized Land Use 26.6
Modified Land Use 14.5
Managed Water Use 1.8
Rainfall ET 44.0
Protected Land Use 0.3
Utilized Land Use 8.9
Modified Land Use 3.1
Managed Water Use 2.1
Utilized Flow
Incremental ET 12.3
2.1
Consumed water 58.4
External 62.2
ET 58.4
P advection 73.7
Q desal 0.0
Q sw in 0.0
Q gw in 0.0
+ΔS 0.0
-ΔS 11.5
Exploitable water 5.9
Non-consumed water 3.8
Outflow 3.8
Q sw outlet 0.0
Q sw out 0.0
Q gw out 3.8

## Annex 7 . WA+ Sheet1 Key indicators using change in storage from GRACE gravity measurements

Table 9. WA+ Sheet 1 key indicators of Awash River Basin from 2010 to 2018 based on water balance derived WaPOR dataset and from GRACE gravity measurements

| Year | ET fraction (%) | Stationarity index (%) | Basin Closure (%) | Available water ($km^3$/year) | Managed water ($km^3$/year) | Managed fraction (%) |
|---|---|---|---|---|---|---|
| 2009 | 98.9 | 4.6 | 93.4 | 2.6 | 2.0 | 75.8 |
| 2010 | 79.0 | 7.3 | 95.4 | 19.1 | 1.8 | 9.5 |
| 2011 | 102.5 | -3.3 | 93.8 | 0.7 | 2.3 | 316.7 |
| 2012 | 95.6 | -1.3 | 93.9 | 4.9 | 2.1 | 43.6 |
| 2013 | 87.6 | 5.4 | 94.7 | 11.1 | 2.2 | 20.0 |
| 2014 | 91.3 | 5.1 | 94.1 | 7.8 | 2.2 | 27.8 |
| 2015 | 114.9 | -10.3 | 91.4 | -4.4 | 2.2 | -50.8 |
| 2016 | 78.3 | | 95.2 | 19.0 | 1.9 | 10.1 |
| 2017 | 79.2 | | 94.8 | 17.4 | 2.1 | 12.1 |
| 2018 | 88.8 | | 94.7 | 10.2 | 2.2 | 21.3 |
| **Numerical average** | 95.7 | -0.2 | 93.8 | 6.0 | 2.1 | 63.2 |
| **Integrated average** | 92.0 | -0.2 | 94.1 | 8.6 | 2.1 | 49.9 |

# Water accounting in the Awash River Basin

This report provides the water accounting study for Awash River basin in Ethiopia carried out by IHE-Delft using the Water Productivity (WaPOR) data portal of the Food and Agricultural Organization (FAO).
The Awash River Basin is the most utilized river basin in Ethiopia hosting most of the industrial activities in the country, a number of small to large scale irrigation schemes and the main population centres of the country with more than 18.6 million people (2017 estimate). The basin faces high water stress during the peak of the irrigation season and frequent flooding in rainy seasons.

The Water Accounting Plus (WA+) system designed by IHE Delft with its partners FAO and IWMI has been applied to gain full insights into the state of the water resources in the basin for the period 2009 to 2018. The WA+ framework is a reporting mechanism for water flows, fluxes and stocks that are summarized by means of WA+ sheets. The role of land use and land cover on producing and consuming water is described explicitly.

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