# Water Productivity – APSAN Vale Rainfed season 2018/2019

May 2019

**Project:**
APSAN-Vale
*Piloting innovations to increase the Water Productivity and Food security for Climate Resilient smallholder agriculture in the Zambezi valley of Mozambique*

*Projecto Piloto de Inovações para Aumento da Produtividade de Agua e Segurança Alimentar Resilientes às Alterações Climáticas na Agricultura de Pequena Escala no Vale do Zambeze (APSAN – Vale)*

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*(Photo: Image of maize agriculture in Catandica taken with the Flying Sensor)*

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# 1 Introduction

Under work package 2 of the APSAN Vale project, water productivity assessments are performed. The purpose of these assessments is to monitor the effectiveness of technical packages (TP's) introduced in the selected project areas. In addition, the potential for upscaling the technical packages and achieving improvements in water productivity is analyzed. The flying sensor imagery and water productivity data outputs from the water productivity assessment can be used for monitoring, and also has the opportunity to be adopted through practical applications.

This report provides the results for the water productivity assessment of the rainfed crop season from November 2018 to March 2019. The locations of the APSAN Vale project are in Moatize, Barue, and Nhamatanda districts. During this season technical packages were defined and initialized with the purpose for field implementation during the next growing season. For this reason, the water productivity assessment of this report indicates the results of the overall status, whilst future assessments will also add the aspect of improvements that are associated with the technical packages.

Flying sensor imagery are the main basis for the field level water productivity maps, which are achieved by a team of trained drone operators based in Chimoio, who made flights at regular intervals throughout the growing season. The (sub-) basin water productivity analysis was derived using the FAO Water Productivity Database (WaPOR). WaPOR also provided supplemental data for different steps in the analysis. It is thereby integrated in the process of this water productivity assessment.

This report is organized starting with a chapter (2) on methodology, followed by results of different analyses (chapters 3 to 7) and finalized with concluding remarks. The various intermediate results are presented in this report (chapters 3 to 5) to indicate the outputs used for calculating the overall water productivity assessments (chapters 6 and 7). This also gives insight in the process, assumptions made, and potential for making improvements. This report is a deliverable to the Steering Committee of the APSAN-Vale project and can be used within the project team. It is used to further advance the water productivity activities in the project in collaboration with the implementing partners.

# 2 Methodology

## 2.1 Overview

The calculation of water productivity at field level and basin level requires several datasets and processing steps. The schematic overview in figure 1 displays the methodology as adopted in this report, and indicates the connections between the different datasets and processing steps. Each 'box' in figure 1 is described in further detail in the sections below (§2.2 to §2.6).

The main input datasets for spatial analysis are the Flying Sensor imagery, WaPOR database, and supplemental data products. These datasets are derived by remote sensing technology either through Flying Sensors, or satellite platforms. The input data from field observations includes the measurements taken at the TAHMO weather station located at each district office (Moatize, Nhamatanda, Catandica), and field notes taken by project members on crop type, crop conditions, and agricultural management aspects. These field observations are used as input data, calibration data for the crop modelling, and as training data for the crop mapping. Field observations are essential for getting calculated results to represent local conditions optimally. In addition, the canopy cover calculated from Flying Sensor imagery can also be used as additional calibration dataset for the crop modelling.

The calculation of water productivity requires both spatial information on water productivity and the location of the croplands or specific crop types. This is combined at basin level using the WaPOR data and crop mapping at the basin scale, indicating croplands (or agricultural lands). At field level the results of the canopy cover from flying sensor imagery is combined with crop modelling to calculate water productivity for the main crop types in the region. This is then combined with a map indicating the locations of the crop and the field boundaries.

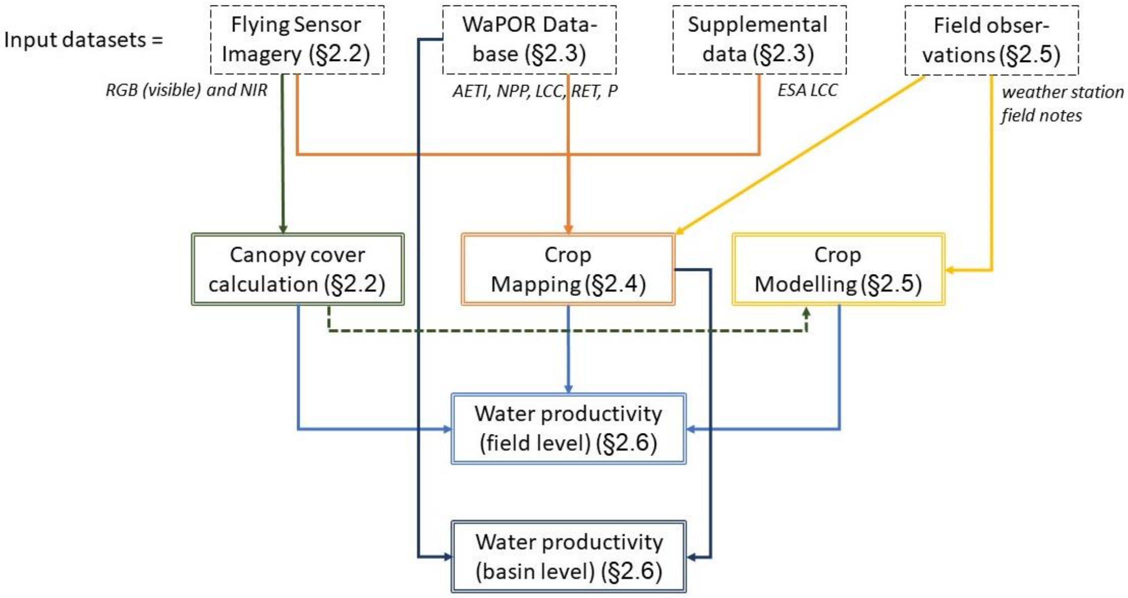


**Figure 1 Schematic overview of methodology including datasets and processing sets**

## 2.2 Flying sensor imagery and processing

*Flying sensor equipment*

The Flying Sensor equipment used in APSAN Vale are a Mavic Pro drone and an additional camera to detect vegetation status. Figure 2 shows a photo of the Flying Sensor used including both cameras. One camera makes RGB (red-green-blue) images, similar to visual images as seen with the human eye. The second camera measures the Near Infrared wavelength, which is not visible to the human eye. The near infrared (NIR) wavelength has a good response to the conditions of the vegetation. Figure 3 gives a illustration of the response to stressed conditions of a leaf. If the leaf is in optimal health the NIR wavelength has a high response. If the leaf is under stressed or sick conditions the NIR wavelength has a lower response. This is already measured by the NIR wavelength before it is visible to the human eye.

**Figure 2 Photo of the Flying Sensor in action**

Another advantage of using the Flying Sensors in this project is the flexibilty for imagery capture and the high-spatial resolution of th acquired imagery. The flying sensors can make flights when required at the desired intervals. For this project the frequency of imagery acquisition was aimed at once every 2-3 weeks, which best captures the crop development stages. This interval was sometimes longer due to weather conditions or logistics. The spatial resolution of the imagery is 4-8 cm, providing sufficient detail to capture the spatial variation of small holder agriculture.

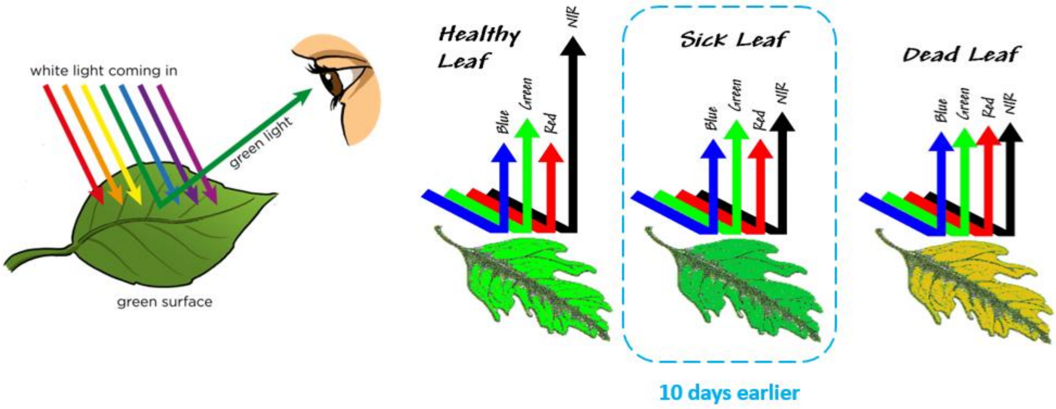


**Figure 3 Illustration explaining the response of near infrared (NIR) wavelength to vegetation status**

*Imagery processing*

The imagery acquired by the Flying Sensors undergoes further processing. Firstly, the single images for each flight are stitched together to form a ortho mosaic. These are then georeferenced so it can be used in further geospatial analysis. These steps are performed using software packages: Agisoft Metashape, ICE (Image Composite Editor), and QGIS (geospatial software). The resulting imagery is then further processed to create a raster image for each flight moment (1 or 2 days of single flights).

The next processing steps are required to achieve a time series of canopy cover maps. Several steps were calculated using Python or R coding to make the processing more efficient. The NIR band of the image is used to determine the vegetation pixels of each image. Pixels above a certain threshold are classified as vegetation pixels, and below they are considered as bare soil (or other surface). This information is then used to calculate the canopy cover, which is an indication of the vegetation cover over a surface in percentage, and is in the same category as other vegetation indices commonly used in remote sensing e.g. Leaf Area Index (LAI) or Normalized Difference Vegetation Index (NDVI). Full vegetation cover will result in a canopy cover of 100%. The calculation of canopy cover is displayed in Figure 4. A grid of 1x1 meter (=1 $m^2$) is overlayed over a crop field, in this example maize crop. The number of vegetation pixels (of 0.08x0.08 meter = 0.016 $m^2$) is counted to determine the percentage of the grid that is covered by vegetation, thus the canopy cover. This information is used in combination with crop modelling to determine the crop yield, and water productivity.

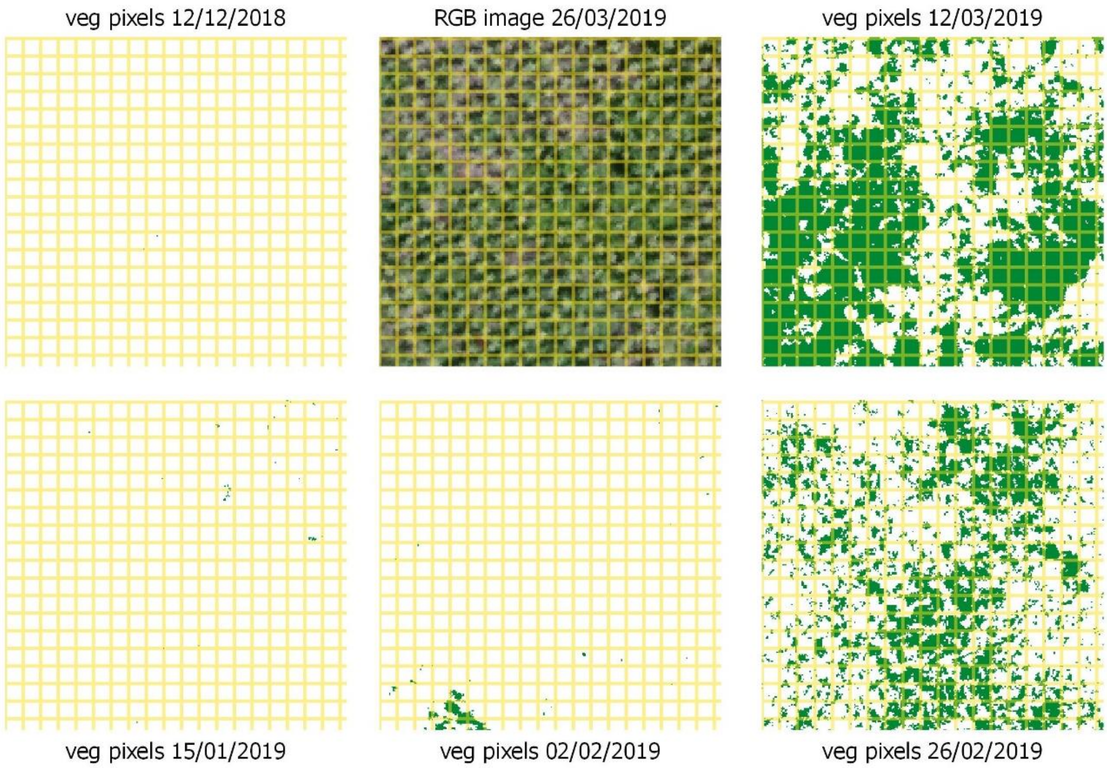


**Figure 4 Detail zoom of 1m. grid over maize field, indicating increase of vegetation pixels**

## 2.3 WaPOR database

The FAO WaPOR database contains several datasets derived with satellite remote sensing and is available through the open access data portal: https://wapor.apps.fao.org. The layers used from WaPOR are: actual and reference evapotranspiration (ET), biomass production, water productivity, precipitation, and land cover. Detailed information on the methodology is found in the reference documents of WaPOR[1]. The data layers were downloaded for Mozambique and aggregated to find seasonal values for the rainfed season: November 2018 to March 2019.

*Actual Evapotranspiration*

The actual evapotranspiration is calculated using a surface energy balance algorithm based on the equations of the ETLook model[2]. It uses a satellite platform with both multi-spectral and thermal imagery acquisition. In additional, meteorological data from remote sensing data products

[1] WaPOR Database Methodology: Level 1 data (September 2018) http://www.fao.org/3/I7315EN/i7315en.pdf
[2] Bastiaanssen et al. (2012)

is used as input. The energy balance components are calculated with the specified algorithm: net radiation, soil heat flux, and sensible heat flux. The latent heat flux is calculated as residual to the energy balance and represents the evapotranspiration (ET) component of the energy balance.
The WaPOR actual ET dataset used in this report is from Level II (100 meter) for each decadal (10 days). A sum for the rainfed season is calculated in QGIS.

*Biomass production*

Biomass production was calculated using the decadal net primary production (NPP) data layer from WaPOR. The NPP data is calculated in WaPOR using a light use efficiency model[1]. This model determines the amount of photosynthetic radiation that arrives at a surface and the amount that is absorbed by vegetation depending on the amount of vegetational cover and (non-)stress conditions. This indicates the result of the photosyntheis process in NPP or dry matter biomass production. The biomass production from WaPOR is summed for the rainfed season. Note that WaPOR calculates biomass production for C3 crops, which are the majority of the crops grown globally. However, determining biomasss production for C4 crops (e.g. maize, sugarcane) requires a multiplication of approximately 1.8 (=4.5/2.5) to correct for the difference in light use efficiency between the two crops. Crop yield can thereafter be calculated using the harvest index, which is specific for each crop type and crop variety (cultivar).

*Supplemental layers*

WaPOR also provides a precipitation data product, namely CHIRPS data. This provides spatial precipitation data at 5 km. resolution at daily time steps. This data is used supplemental to the weather station data to fill in data gaps where the weather station data was not installed.
In addition, reference evapotranspiration (ET) is also provided by the WaPOR data portal at 20 km. resolution and at daily time steps. A time series of this dataset is used as the required weather input data to the crop modelling.

## 2.4 Crop mapping

*Croplands*

Determining the location of croplands is relevant to calculate the water productivity over agricultural lands, thus excluding the water productivity of natural vegetation. At the basin scale cropland maps are available in the public domain.
The land cover map provided on the WaPOR data portal is based on the data provided by the Global Land Service of Copernicus, the Earth Observation programme of the European Commission[2] and has a spatial resolution of 100 m. The most recent land cover dataset is from 2014 and distinguishes (amongst others) croplands under rainfed and irrigated conditions, from natural vegetation.
Alternatively, the CCI Land Cover team from ESA (European Space Agency) provides a land cover dataset for Africa at 20 m spatial resolution for the year 2016[3]. This dataset also distinguishes between cropland from natural vegetation (trees, shrubs, and grasslands).
For the field level maps the flying sensor imagery is used to distinguish in better detail the location of croplands and natural vegetation. The QGIS plugin 'Semi-Automatic Classification'[4] is used for the classification in different land cover classes. A stacked raster is used containing multiple near infrared images from different flight moments. The basis for the classification is that the response of natural vegetation is different than croplands. In figure 5 the difference is illustrated, showing

[1] Hilker et al. (2008) and several other publications
[2] https://wapor.apps.fao.org/catalog/2/L2_LCC_A
[3] http://2016africalandcover20m.esrin.esa.int/
[4] Congedo Luca (2016) http://dx.doi.org/10.13140/RG.2.2.29474.02242/1

that natural vegetation has similar response for all four flights (horizontal line), whilst croplands (or cultivated land) shows a gradual increase for each flight. This follows the crop development with the initial and mid stage of the crop having less vegetation than the peak stage. A third landcover class was also identified, namely the floodplain. This was necessary to prevent the overlap with the other classes, because this class was significantly different. The floodplain is the area that is close to the river so has sufficient water during dry periods. However, at the last flight major flooding caused severe damage in this area, thereby removing most of the vegetation.

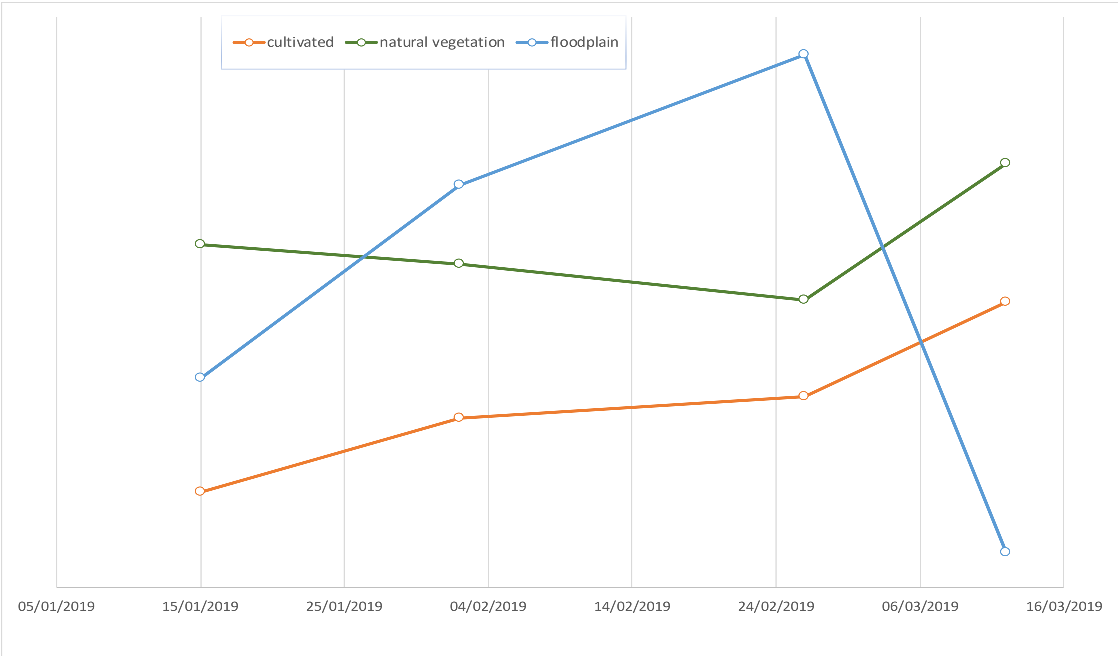


**Figure 5 Near infrared response to different surface: cultivated (cropland), natural vegetation, and flood plain areas**

*Crop classification*

Crop classification identifies the location of the various crop types. This is necessary to create a map of crop specific water productivity. A main crop in the project area grown during the rainfed season is maize. This crop is also easily identifiable with flying sensor imagery, whereas other field crops are more difficult to distinguish and needs supporting ground data.
The fields with maize crops were drawn in QGIS guided with the croplands map, created in the previous step, and RGB (visible) flying sensor imagery. A total of 73 fields were drawn for the project area in Samoa (Moatize district). These fields can contain multiple management regimes, therefore the fields (or also referred to as polygons) should not be considered to be uniform.

## 2.5 Crop modelling

The AquaCrop model was selected for simulating the crop growth and water consumption, which is based on FAO principles as are reported in FAO Irrigation and Drainage Papers #56 and #66. It simulates both crop development and the water balance, resulting in crop water productivity results.

*Input data*

Weather data is required as input for the model, which was derived from different sources. Weather stations (from TAHMO) were installed at each district office to represent the weather conditions in the area. These stations were operational from February / March 2019, which is halfway the rainfed season. Remote sensing data products were used to supplement the weather station data to fill in the gap at the start of the rainfed season. Precipitation and reference ET data were taken from WaPOR. Air temperature data was taken from GLDAS (Global Land Data Assimiliation System)[1], which is a data product provided by NASA.

*Model set-up*

The model was set-up choosing default files guided by field observations of the locations. The selected parameters and data files used for the AquaCrop simulation runs are listed in Table 1. Three parameters were selected as a range in stead of a fixed value, namely: plant density, fertility stress, and weed stress. These parameters are assumed to be different for each field depending on management decisions, and have impact on the canopy cover and ultimately the crop productivity.

**Table 1 Model set-up and selected parameters**

| Model and parameters | Value | Comments |
|---|---|---|
| Planting date | 11 November 2018 | |
| Harvest date | 20 March 2019 | |
| Soil type | Sandy Loam | Default parameters (AquaCrop file) |
| Irrigation | None | Rainfed season |
| Initial soil water conditions | Wilting point | End of dry season will have mostly depleted the soil water storage |
| Groundwater table | None | Assumption that groundwater level is deeper than rootzone |
| Crop type | Maize | Default parameters (AquaCrop file) |
| *Maximum canopy cover* | 0.85 | Fraction to soil cover (under optimal conditions) |
| *Canopy growth coefficient* | 0.12 | Increase in canopy cover |
| *Planting density [plants/ha]* | 8,000 – 40,000 | Range with steps of 2,000 plants/ha |
| Management | | |
| *Fertility stress* | 30 – 50 % | Range with steps of 10 % |
| *Weed stress* | 10 and 20 % | |

*Calibration*

Two parameters were changed to calibrate the model to local conditions, namely maximum canopy cover and canopy growth coefficient. These parameters are assumed to be fixed for the crop type, thus are not influenced by management conditions. However, they are specific for the local maize crop variety selected, and need adjustment to represent the local crop variety. For calibration the canopy cover and yield statistics were used. Additional datasets that can be used are biomass production or evapotranspiration (from remote sensing), and yield reports from the field. Also performing simulation runs over selected crops (e.g. demo plots) for which several field measurementss are made, can be used for calibration in future water productivity assessments.

[1] https://ldas.gsfc.nasa.gov/gldas

*Relationship canopy cover – water productivity*

The maximum canopy cover values for each simulation run (102 runs total) are compared with the water productivity and crop yield for the run. It is assumed that the runs represent the various scenarios possible in farm management and biophysical conditions. A linear relationship is developed to connect maximum canopy cover with crop yield and water productivity. This linear equation is thereafter used with the flying sensor derived maximum canopy cover to achieve maps of water productivity.

## 2.6 Water Productivity mapping

There are two definitions of water productivity made in this project: biomass and crop water productivity. These definitions are in accordance with the WaPOR methodology and are defined as the equations below:

$$Biomass\ water\ productivity\ [kg/m^3]\ =\frac{Biomass\ production\ [kg]}{Evapotranspiration\ [m^3]}$$

$$Crop\ specific\ water\ productivity\ [kg/m^3]\ =\frac{Crop\ harvestable\ yield\ [kg]}{Seasonal\ evapotranspiration\ [m^3]}$$

Note the difference between the two methods are that biomass production is not crop specific. It represents the full plant, whilst crop specific water productivity only considers the part of the plant produced for the market or consumption, thus crop yield.

*Field level maps*

The overview in figure 1 shows that field level water productivity maps are produced by combining the outputs from crop modelling, crop mapping, and canopy cover from the flying sensor imagery. This results in field level results for the location of the fields classifed by crop type. For this season, this consists of the water productivity results for maize crops as identified by the drawing the polygons (field boundaries). The water productivity is calculated for each 1x1m grid and also as average of the polygons.

*(Sub-) Basin level maps*

The (sub-) basin level maps are made by using the administrative boundary of the province (Zobue, Catandica, Nhamatanda). The WaPOR dataset is applicable for this level of analysis to determine spatial variation. The maps present the results from WaPOR and uses crop mapping from ESA and WaPOR land cover products (as listed in section 2.4) to represent only agricultural water productivity.

# 3 Flying Sensor Imagery and Processing

## 3.1 Flying sensor imagery acquisition

Flying Sensor operators made regular flights for the three selected areas (zonas) of the APSAN Vale project. A list of the flights made during the rainfed season is shown in Table 2. The selection of the zona was made end of November, resulting in the first flights to be in December. Each flight day consists of approximately 4-6 flights being made, which are then further processed to give results for the whole area. Results of the imagery for all flights as an ortho-mosaic are shown in Figure 6 for both RGB (red-green-blue, visible) and Near Infrared images.

**Table 2 Flying sensor flights made for APSAN Vale areas during the rainfed season**

| Samoa (Moatize) | Siluvo (Nhamatanda) | Mutangadzi (Barue) |
|---|---|---|
| 12-13 December 2018 | 3-4 December 2018 | *(18-19 December 2018**)* |
| 15-16 January 2019 | 7-8 January 2019 | 10 January 2019 |
| 2-3 February 2019 | *(8-9 February 2019*)* | 24 January 2019 |
| 26-27 February 2019 | 4-5 March 2019 | 12 February 2019 |
| 12-13 March 2019 | | |

* Excluded from analysis due to missing imagery

** Excluded from analysis due to flight over different area (zona)

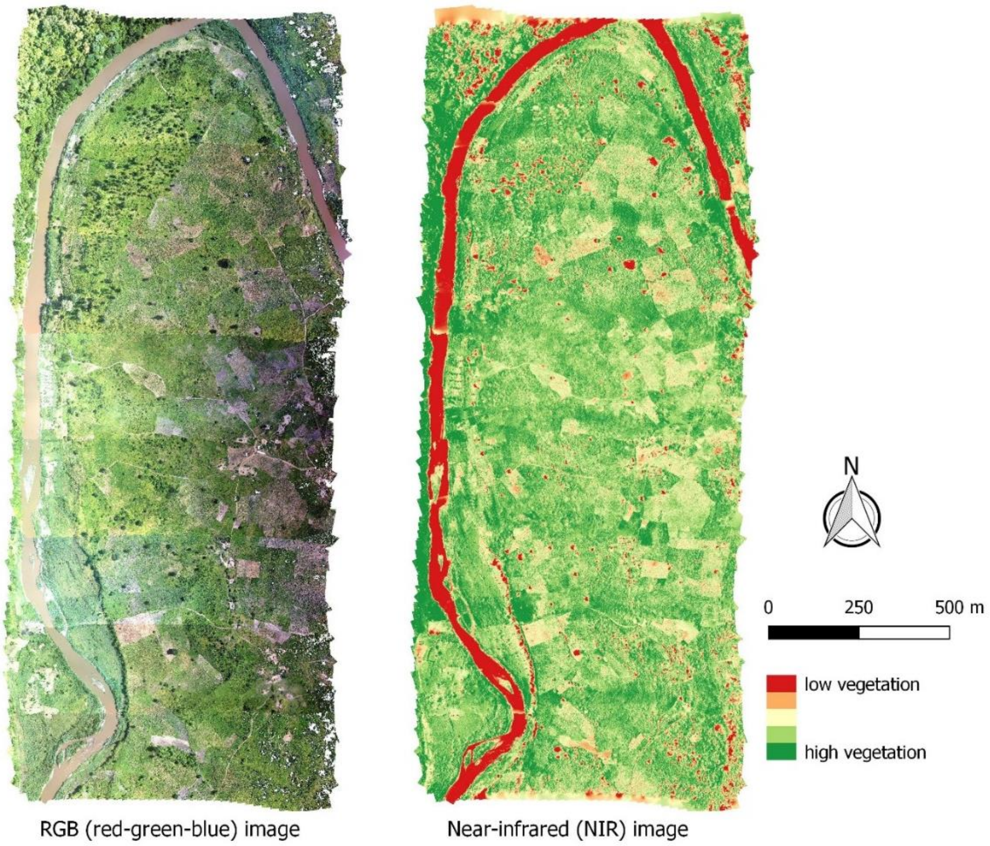


**Figure 6 Flying Sensor imagery of Samoa 26-27th February 2019 (mosaic of 8 flights)**

## 3.2 Temporal change in vegetation pixels

For each flight moment covered by 1-2 days of flights, the Near Infrared imagery was used to classify pixels above a certain threshold to be vegetation. The number of vegetation pixels and total number of pixels for each flying sensor image is displayed in figure 7.
The percentage of vegetation to total pixels is also shown, indicating a gradual increase in vegetation pixels. This pattern follows the expected trend representing the vegetation growth during the season. Note that the vegetation pixels include both croplands and natural vegetation. The stagnancy that occurs in the months of January and February (around 35%) can be associated with a dry period causing limited vegetational growth. Thereafter, the percentage of vegetation increases steeply (up to 45%) when precipitation occurs in early March.
The lack of a decrease in vegetation cover at the end of this period indicates that the dry season has not started yet. Natural vegetation is still in full cover, and possibly the agricultural crops are also at the peak and have not senesced or been harvested yet. If a crop curve should be created from this information, it is recommendable to add another flight moment (perhaps of early April) to create the full crop development including the harvest stage.

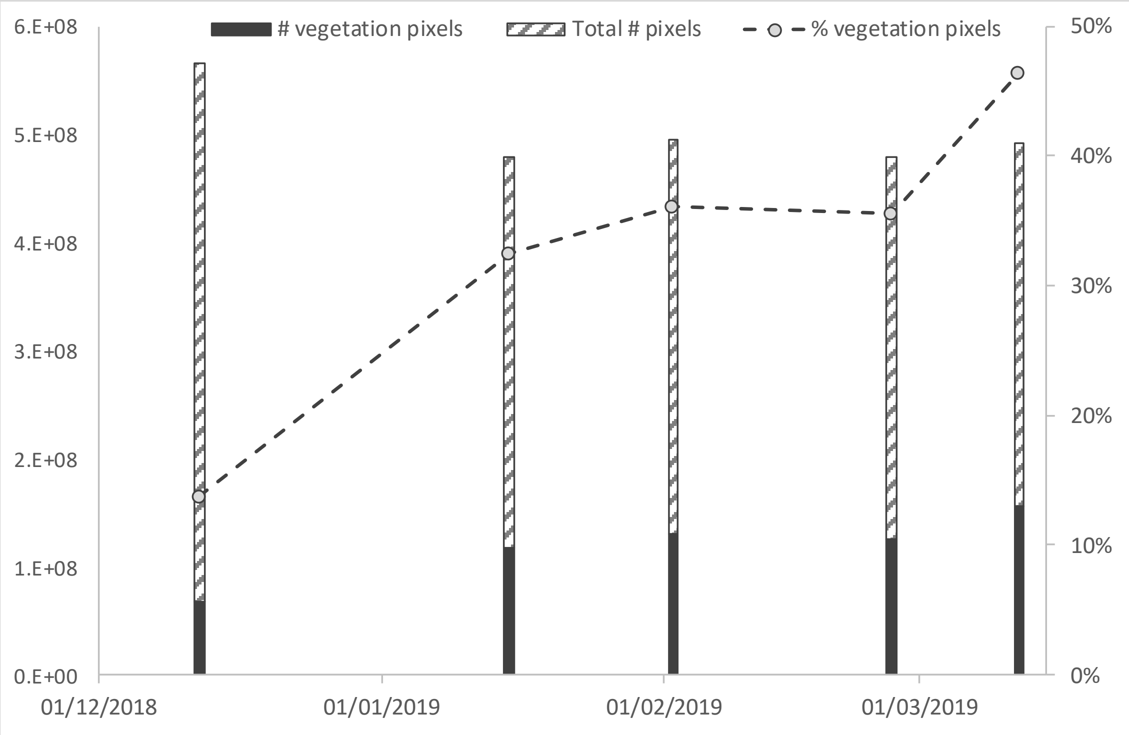


**Figure 7 Number of pixels and % vegetation for each flight in Samoa**

## 3.3 Maximum canopy cover

The canopy cover is derived from using a 1x1 meter grid and the vegetation pixels as were found in the previous section, for each flight moment. In figure 8 the results of maximum canopy cover are shown for one maize field located in Samoa, with an area of 0.35 ha. The layer with the 1x1 meter grid (indicated in yellow lines) is laid over the vegetation pixels. This example displays the imagery and vegetation pixels for the 26th February. Similar process was done for the other 4 flight moments in Samoa, as were listed in Table 2. The result is a calculation of canopy cover (vegetation pixels versus non-vegetation pixels) for each 1x1 meter grid cell. Thereafter, the maximum canopy cover value is selected for each grid cell, which can be taken for different flight dates. Taking the maximum canopy cover for each grid cell individually gives a better representation of the field situation. It was found that within each field there is a variation in crop development due to differences in planting dates and other factors. In figure 8 the maximum canopy cover values are displayed for the maize field. The range is from sparse canopy cover (0-10%) to full cover (90-100%). Within this field boundary the results show that the full range in canopy cover is observed in this field. There are areas that remain mostly bare soil and during this season has hardly any vegetation cover. Whereas there are parts of the field that has full cover, indicating good vegetational status of the maize crop. This large variation within a field indicates that there is potential to improve the management of parts of the field, which currently is underused. This example also shows the necessity for using a 1x1 meter grid to capture the detail of variation within a field and not find an overall average value for each field. By using the flying sensor high-resolution imagery, this is made possible.

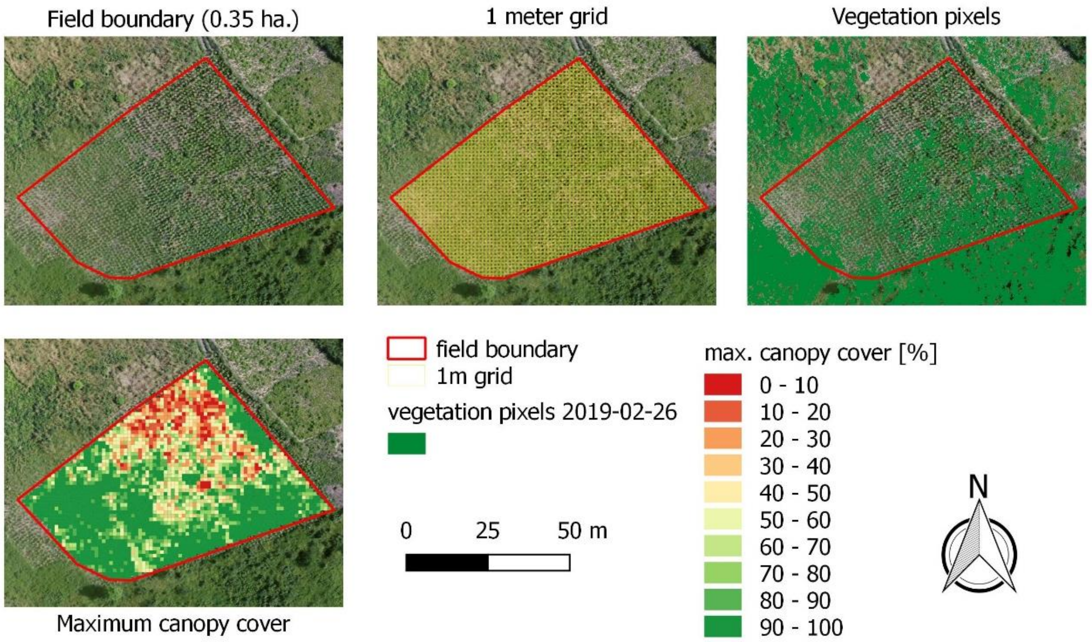


**Figure 8 Steps for estimating the maximum canopy cover of a maize field in Samoa**

# 4 Crop mapping results

## 4.1 Cropland data products

The two data products used for determining the cropland areas at the basin scale are shown in figure 9. These are the cropland product of ESA for 2016 (at 20 meter resolution), and the WaPOR product for 2014 (at 100 meter resolution). These maps show that the ESA map has more variation, which is due to the distinction in different classes and the higher spatial resolution. The map provided by ESA distinguishes between trees, shrubs, and grasslands, whilst in WaPOR these are all considered in the class for natural vegetation. WaPOR is aimed at agricultural production and therefore has more interest in distinguishing the different water management regimes within the croplands (rainfed versus irrigated or under water management). These maps of croplands are used for the calculation of agricultural water productivity at basin level, discussed in chapter 7 of this report.

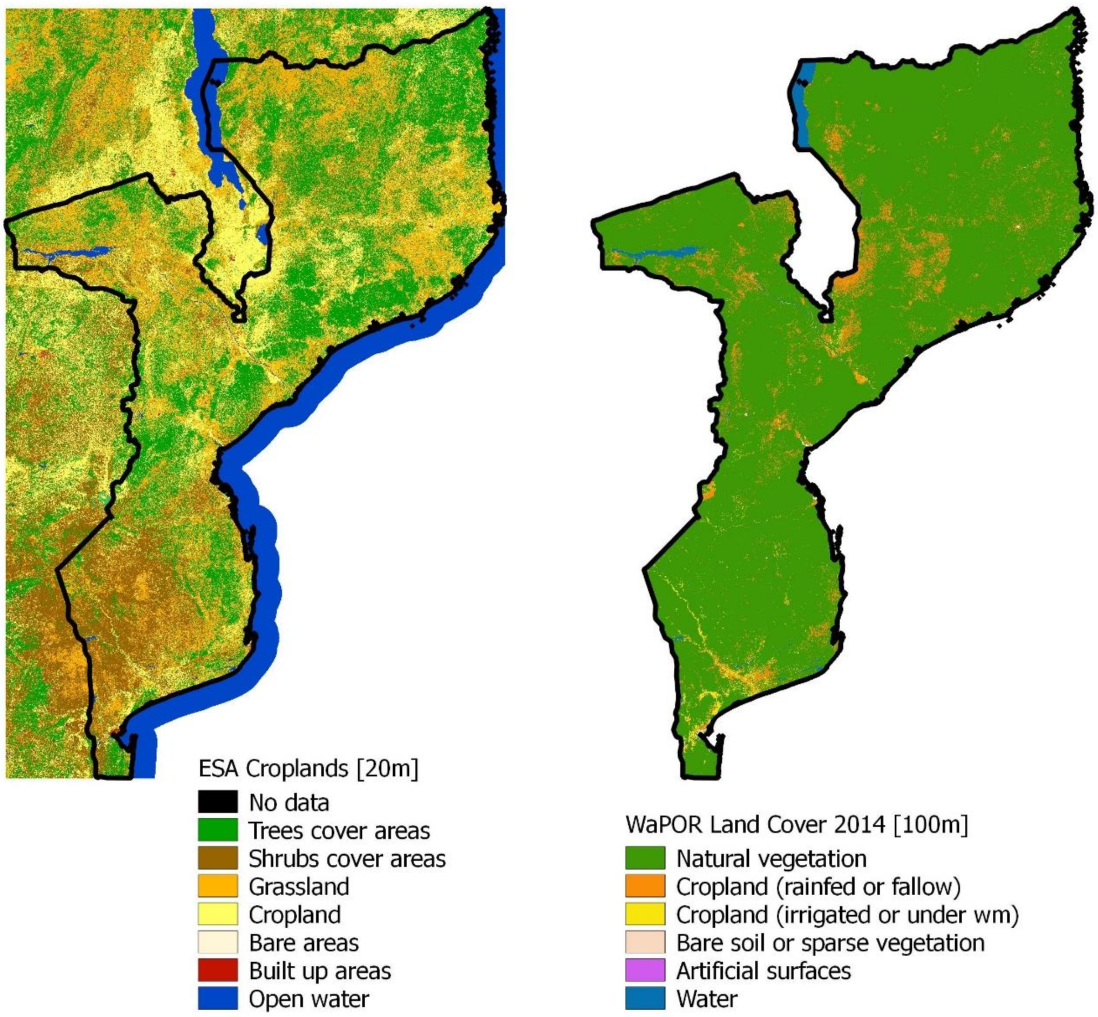


**Figure 9 Cropland data products available by ESA (left) and WaPOR (right)**

## 4.2 Cropland classification

For field level analysis of water productivity, it is necessary to gain more insight in the cropland area. Figure 10 shows on the right the ESA and WaPOR cropland products zoomed in for the area in Samoa. Due to the coarse resolution these products are not able to distinguish the variation in natural vegetation and crop fields at this spatial level. The overall ratio between natural vegetation and croplands seems reasonable but it is necessary to create a map of croplands to pinpoint the location of cultivated fields during this season.

Figure 10 shows the RGB image and stacked NIR image from the Flying Sensors that is used for classification. The stacked NIR image indicates the areas under cultivation (croplands) as darker blue hues due to the higher vegetation cover at the end of the crop season, whilst the natural vegetation is white in color due to the constant level of vegetation during the season (as was explained in figure 5).

The middle image shows the result from the semi-automatic classification performed with the QGIS plugin, distinguishing between croplands, natural vegetation, and flood plains. The red polygons drawn indicate the location of maize fields. These are not necessarily under uniform farm management, but are homogenous fields with crops, thus excluding e.g. roads, paths, or residences. The result of the classification in area for each class is shown in table 3. A total of 73 polygons were drawn indicating the location of maize fields, with an average area per polygon of 0.36 hectares.

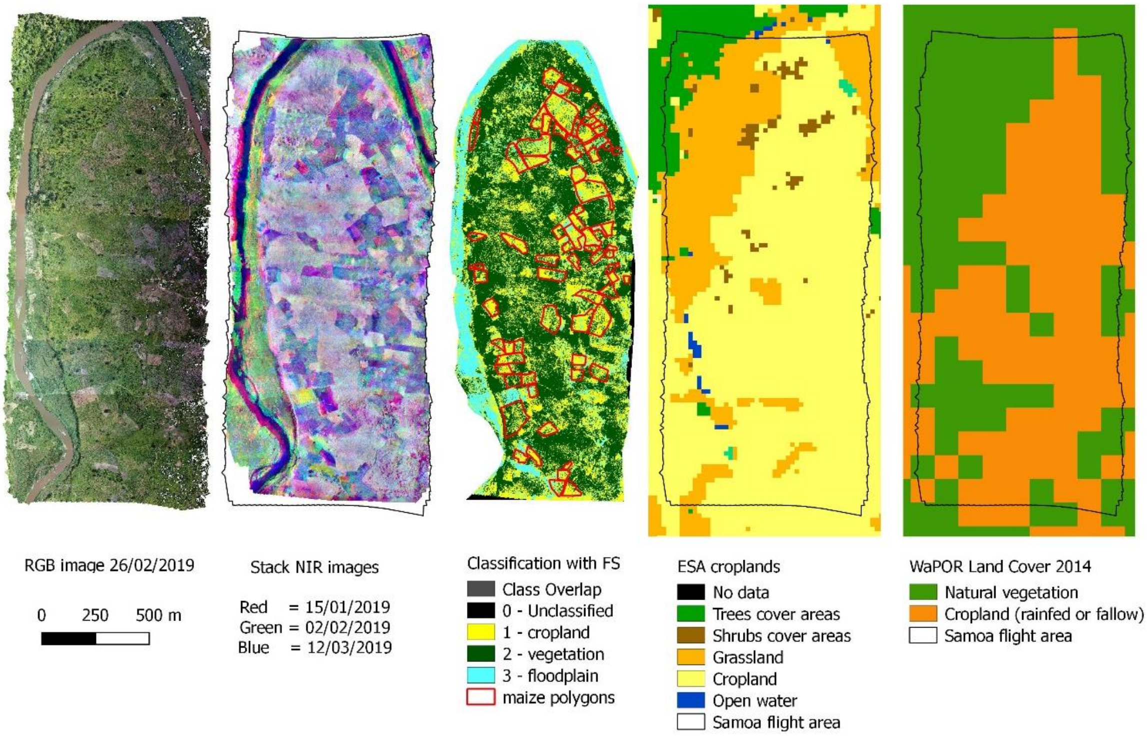


**Figure 10 Cropland mapping for Samoa using Flying Sensor imagery (left) and cropland data products of ESA and WaPOR (right)**

**Table 3 Total area of croplands in Samoa using Flying Sensor imagery**

| | # pixels / *polygons* | Area [ha] | Average area per polygon [ha] |
|---|---|---|---|
| Vegetation | 7.9E+07 | 127 | |
| Cropland | 1.2E+08 | 195 | |
| *Maize* | *73* | *26* | *0.36* |
| Floodplain | 3.6E+07 | 58 | |
| Unclassified | | 4 | |
| Total | 2.4E+08 | 384 | |

# 5 Crop modelling

## 5.1 Weather data

Weather data is an important input to the crop model AquaCrop. The data used to represent the meteorological conditions during the simulation period are displayed in Figures 11, 12, and 13 for precipitation, air temperature, and reference evapotranspiration (ET) respectively.

For precipitation and air temperature the weather station data is displayed showing the measurements since the installation of the station from end of February onwards. Public domain data products are used to fill in the data gap for the start of the rainfed season. For precipitation the CHIRPS data (downloaded from the WaPOR database) was used. However, some inaccuracies are expected because it is a global dataset and can perform differently for the local setting. It was found that the CHIRPS total precipitation of 913 mm overestimates the actual conditions. Field observations in Samoa indicated that in January there were 4 weeks without precipitation, whilst CHIRPS indicates regular precipitation events in this period. For this reason, the CHIRPS data was adjusted to have a better representation of the conditions expected in the field. In future analyses it is recommended to continue using the TAHMO weather station, which gives local measurements of precipitation. This will improve results for the rainfed season, which is mainly driven by the availability of water through precipitation events.

The weather data for air temperature and reference ET followed trends expected for this region. However, both are measured at the weather station and can be used in the analysis for future crop seasons in this project.

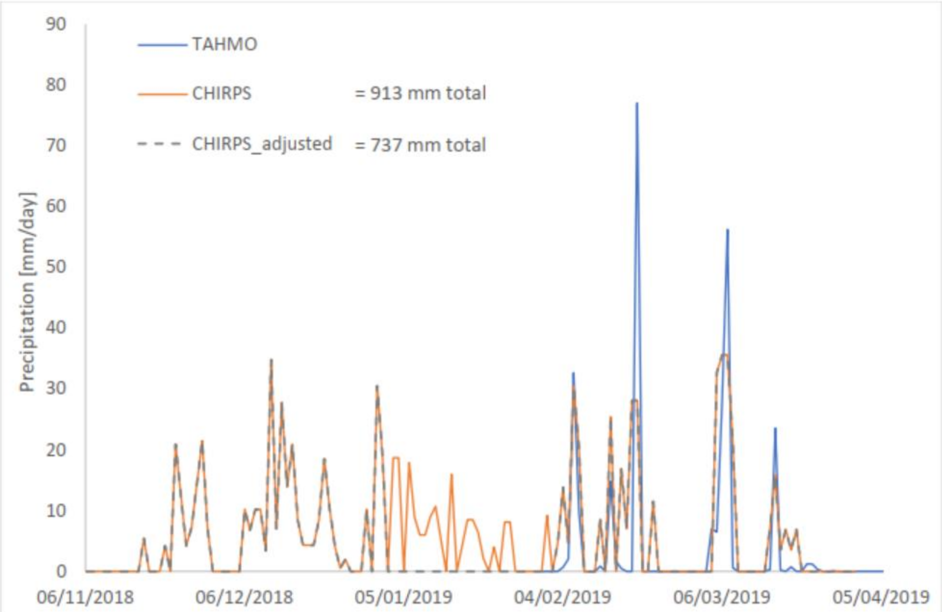


**Figure 11 Time series of daily precipitation in Samoa measured at the TAHMO weather station (in Moatize) and reported by WaPOR using CHIRPS data product**

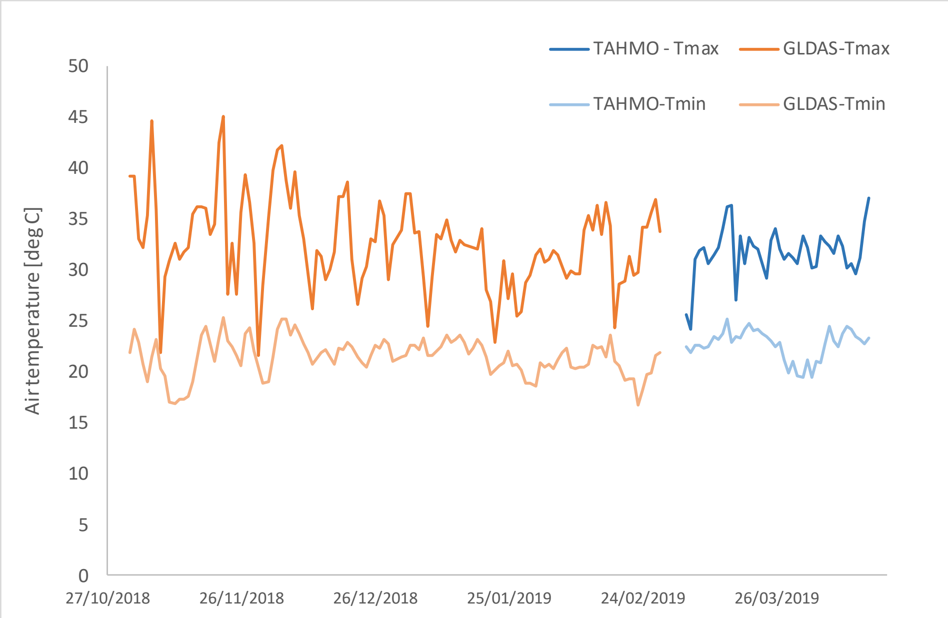


**Figure 12 Time series of daily minimum/maximum air temperature in Samoa measured at the TAHMO weather station (in Moatize) and reported by GLDAS data product**

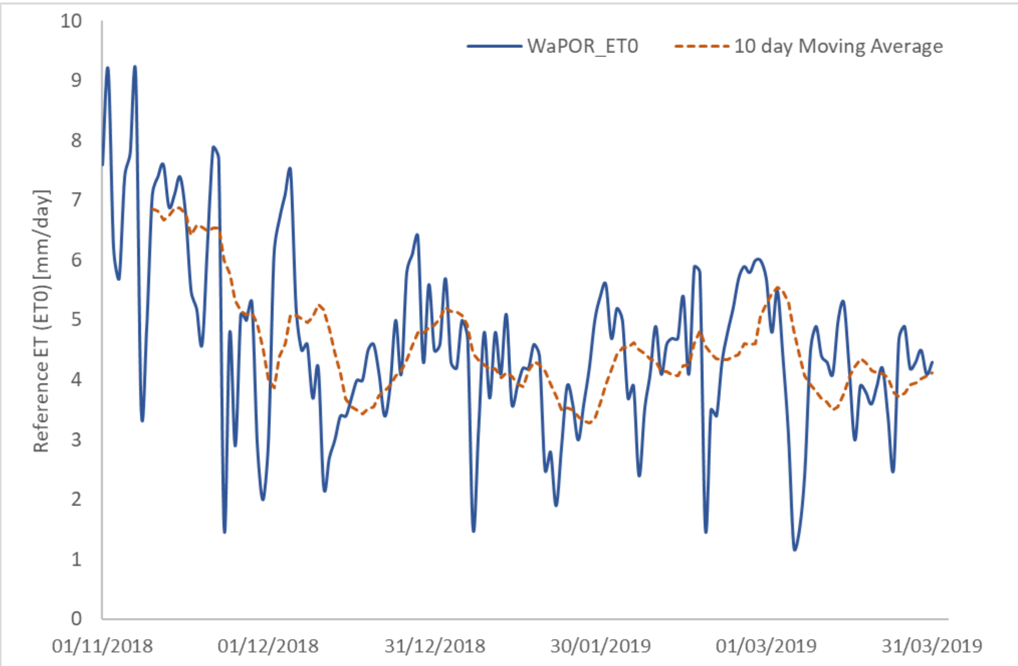


**Figure 13 Time series of daily reference evapotranspiration in Samoa as reported by WaPOR, including the 10-day moving average**

## 5.2 AquaCrop results

AquaCrop simulates both the water balance and crop production. Results for the water balance from all the AquaCrop simulation runs are shown in Figure 14. The precipitation is the same for each run and is taken from the input data for weather during the growing period. The variation (error bar) for runoff is narrow, indicating that it is hardly impacted by the variation in plant density, fertility stress, or weed stress. Both plant density and weed cover are expected to impact the runoff component, so the limited impact is likely due to the runoff component being a small part in this overall water balance (45 mm over the 735 mm of the precipitation = 6%). The soil evaporation component displays more variation between different runs. Soil evaporation is likely to be higher with lower vegetation cover associated with scenarios of low plant density. Whereas transpiration will be higher for scenarios of high plant density. The soil water storage is the component calculated from the volume of infiltration minus the volume used by soil evaporation or transpiration. Throughout the rainfed season the soil storage is expected to have a positive change, indicating that water is being stored in the root zone.

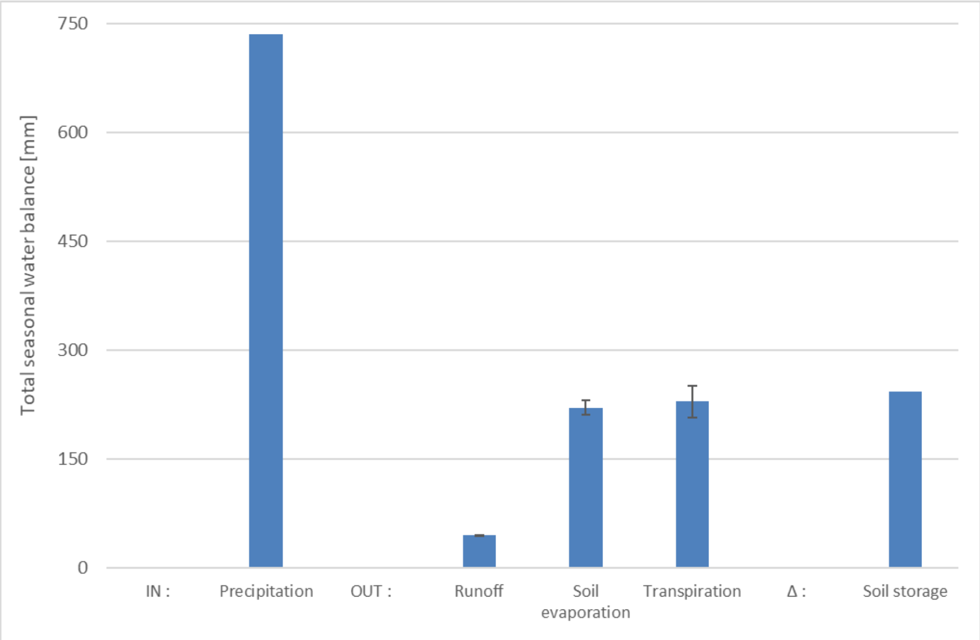


**Figure 14 Results of AquaCrop for water balance components indicating the average and the variation for all AquaCrop runs representing maize production in Samoa**

Figure 15 shows the results for crop productivity indicating the average values found for the several AquaCrop runs, and the minimum and maximum values. The variable factors selected (plant density, fertility, and weed stress) have significant impact on the results for productivity. Both biomass and crop yield are variable with the maximum value of crop yield being 1.5 times higher than the minimum value. The variation in crop water productivity is smaller than for biomass production and crop yield. A reason for this is the limited variation in evapotranspiration (ET) as shown in figure 14. The crop water productivity is calculated as combination of both soil evaporation and transpiration.

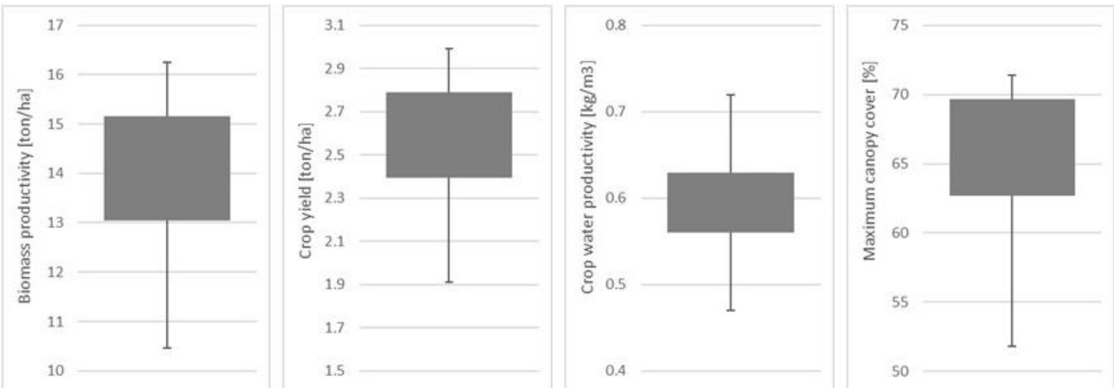


**Figure 15 Boxplots displaying the results for productivity, yield, and maximum canopy cover, from all AquaCrop runs representing maize production in Samoa**

## 5.3 Canopy cover vs Land / Water productivity

Figure 15 showed that the range of canopy cover is from 52% to 71%, which does not include the full range as observed in the flying sensor canopy cover (in figure 8). However, the number of runs is sufficient to be able to develop a linear relationship between canopy cover and crop yield (land productivity) or water productivity. Results for the linear relationship is shown in figures 16 and 17 for crop yield and water productivity respectively. The equation displayed in the figures are used to calculate the crop yield and water productivity with the results for canopy cover from the flying sensor imagery.

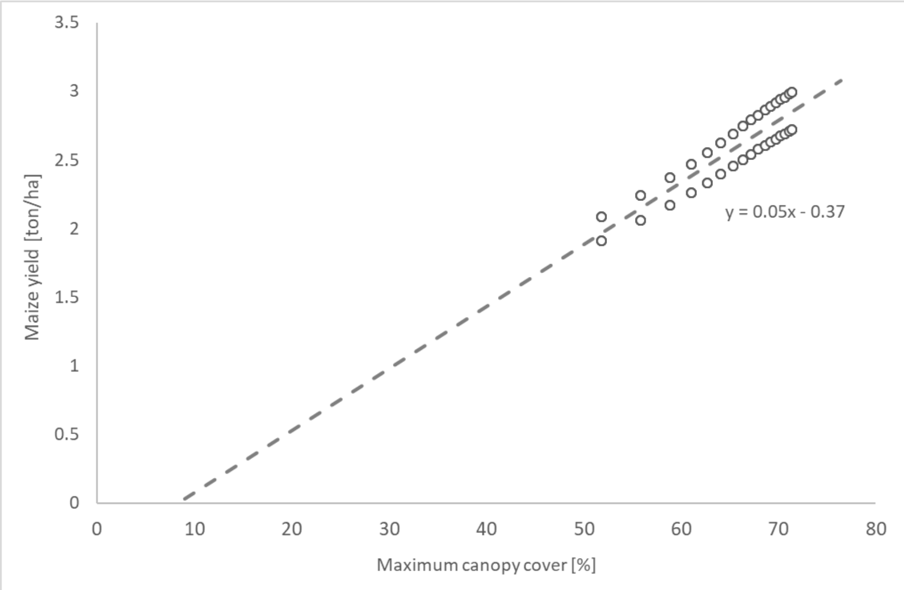


**Figure 16 Plot of relationship between maximum canopy cover and maize yield according to results of all AquaCrop runs for maize production in Samoa**

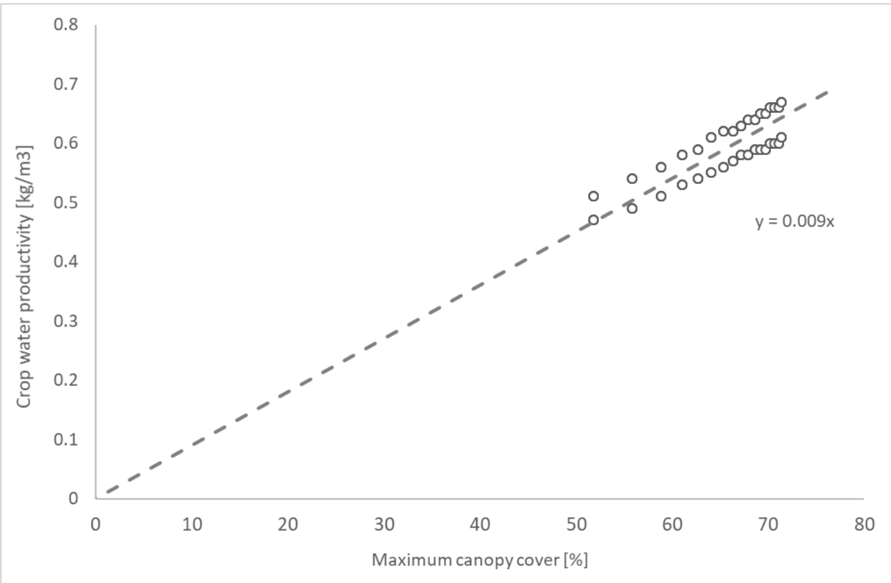


**Figure 17 Plot of relationship between maximum canopy cover and maize water productivity according to results of all AquaCrop runs for maize production in Samoa**

# 6 Field level water productivity

## 6.1 Water productivity maps

The results for crop modelling, crop mapping for maize fields, and the flying sensor derived canopy cover, are brought together to calculate field level maize water productivity. The water productivity maps are displayed in figure 18. The left image shows the result as represented by each 1x1 meter grid cell. Due to the linear relationship between water productivity and canopy cover, the spatial patterns are similar to the canopy cover results. It indicates low water productivity for areas with mostly bare soil (low canopy cover) and high values for fully vegetated areas indicating low stress conditions. A review article[1] indicates a range of water productivity for irrigated maize of 1.1 to 2.7 kg/m$^3$. Rainfed conditions are expected to have a different water productivity value than irrigated, but this does indicate the potential for increase in water productivity compared to the maximum values for water productivity currently calculated of 0.7-0.8 kg/m$^3$. Figure 18 also indicates the average per polygon and the standard deviation (indicating the variation) within each polygon. It shows that most polygons with lower water productivity values are also association with the polygons with high variation in water productivity. This can be due to the delineation of the field boundaries (including different management regimes) and also the variation in plant density with areas having sparse vegetation during the crop season.

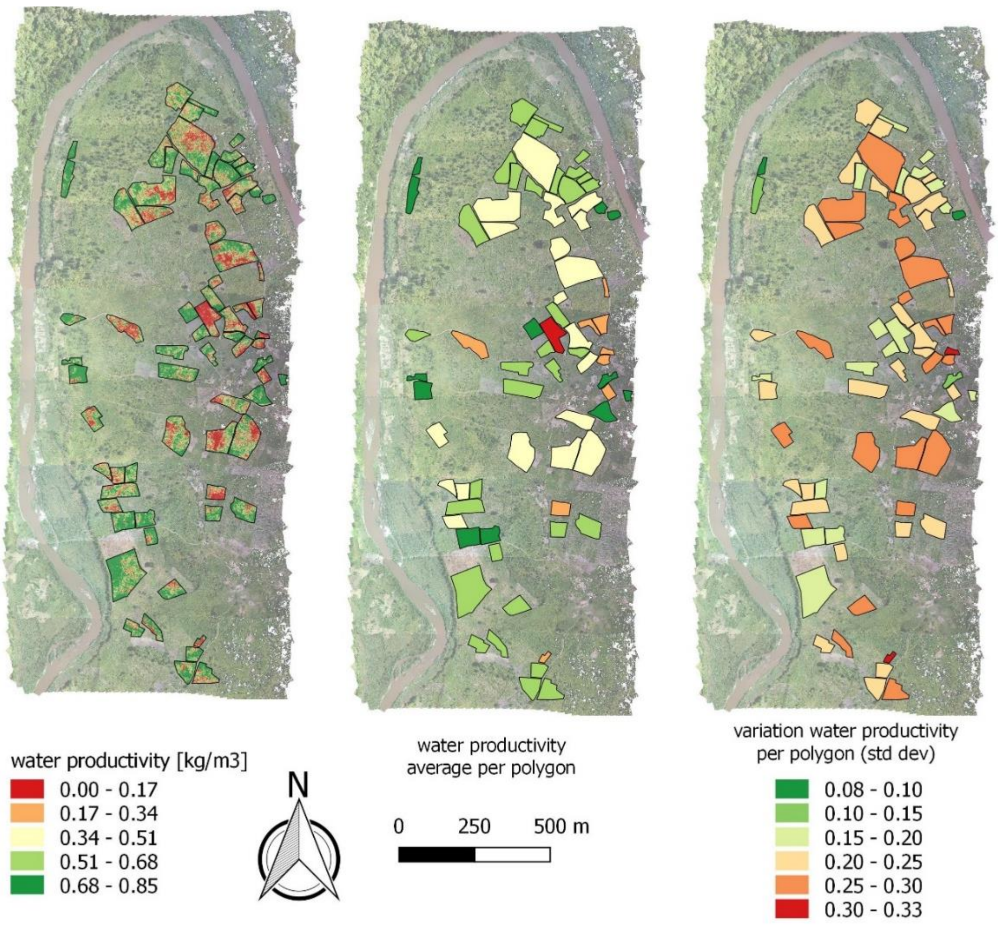


**Figure 18 Map of water productivity of maize fields in Samoa, displaying the variation within each polygon and average per polygon**

[1] Zwart and Bastiaanssen (2004) doi:10.1016/j.agwat.2004.04.007

The histogram in figure 19 displays the statistical output for water productivity indicating the frequency that a certain water productivity value occurs. Despite the large range in values, the positive outcome is that the curve appears to be skewed towards higher water productivity values.

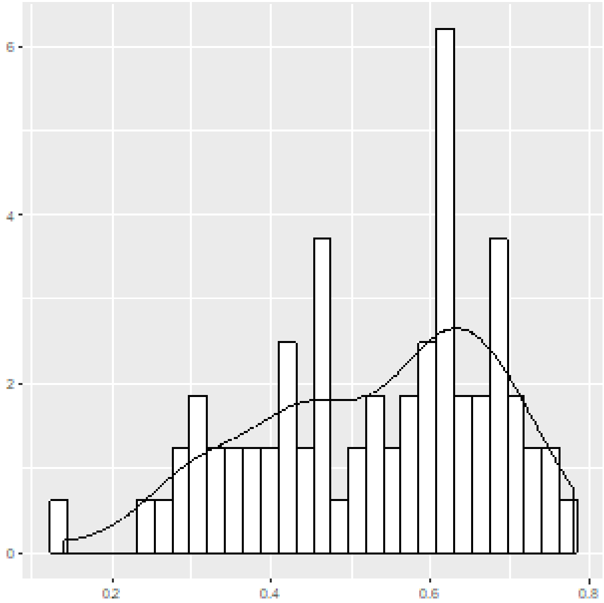


**Figure 19 Histogram indicating the frequency distribution of water productivity using the average per polygon values**

## 6.2 Case study A

The result for water productivity are connected with field examples by presenting two case studies. This first case study (A) is based on observations made in a maize field in Samoa. Results are shown in figure 20. The visual image (left) shows that the field is mostly green on the top end and at the bottom end shows sparse vegetation. Field notes taken on 26th February 2019 including the photo (right) indicates that the top end has several weeds growing in between the maize crops. From the flying sensor images the calculated canopy cover has higher values due to the vegetation cover contributed by weed growth. The resulting water productivity is high for the field. This example shows that it is necessary to make further calibrations for weed growth using field observations. The water productivity results indicate correctly that the area with sparse vegetation, also has lower water productivity values.

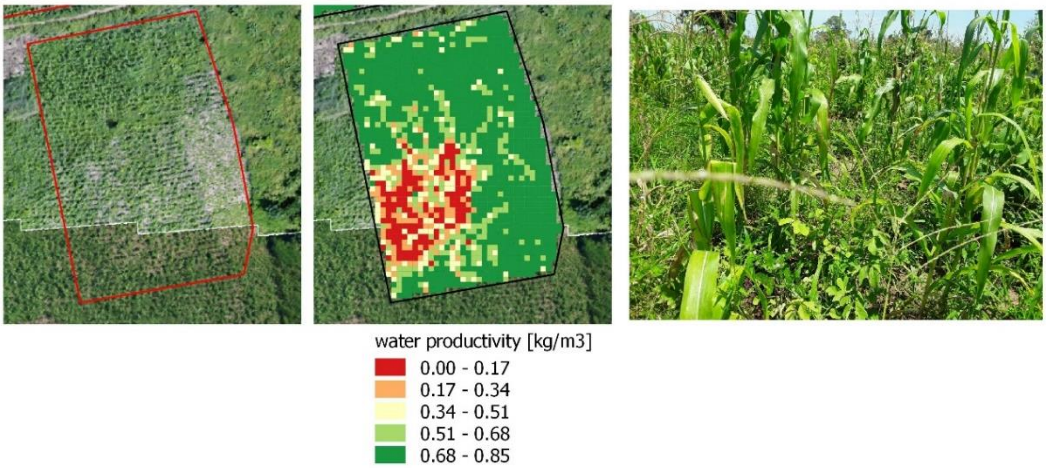


**Figure 20 Case Study A - Detail zoom of maize field with RGB image (left), water productivity (middle) and field photo (right)**

## 6.3 Case study B

The second case study (B) is an example from a different maize field in Samoa, with results shown in figure 21. Field observations on 26th February 2019 indicated that the maize crop was small and stressed with dry conditions. This is also clear from the photo taken at the field observation. The water productivity map indicates larger areas with low water productivity that is associated with the sparse vegetation. The point where the observations were taken (top left corner) displays a variation of water productivity with some higher values were maize was growing and lower values for the bare soil in between the crops.

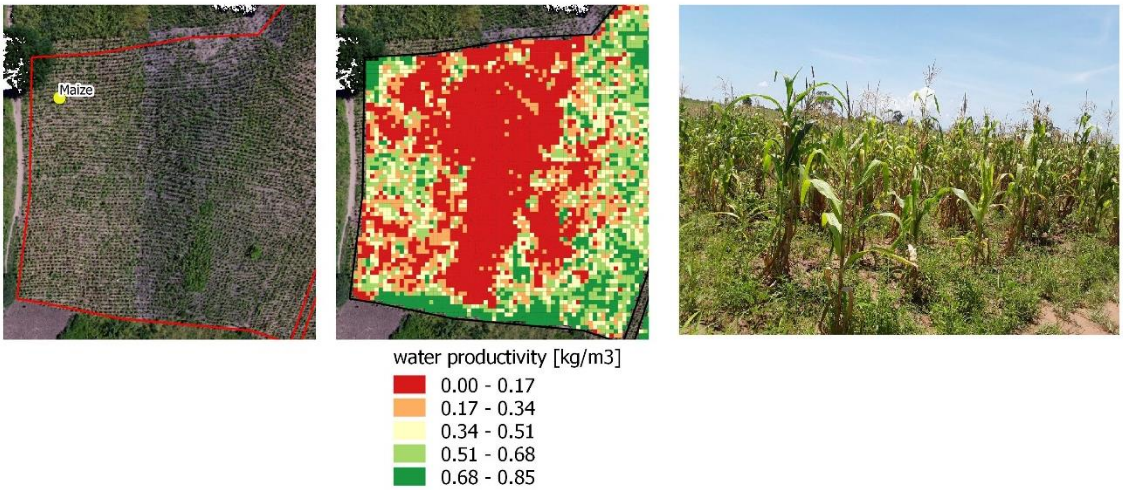


**Figure 21 Case Study B - Detail zoom of maize field with RGB image (left), water productivity (middle) and field photo (right)**

# 7 (Sub) Basin level water productivity

## 7.1 Water productivity maps

WaPOR data is used to display water productivity maps for the basin scale. In this report the administrative boundaries are taken for the provinces in the three districts selected by the project. Future analyses can cover the sub-basin and basin level after verified catchment delineation. The result for biomass water productivity is shown in figure 22. Note that these are biomass water productivity and not connected by crop type nor represents the crop yield. In addition, the biomass production in WaPOR is calculated as a C3 crop, thus values differ from the field level analysis performed for maize fields, which is a C4 crop.

Figure 22 indicates that both the Zobue (includes Samoa area) and Catandica provinces have higher water productivity values. These are associated with the natural vegetation in the mountainous areas that receive more rainfall. The province of Nhamatanda shows lower water productivity values according to figure 22. The detailed maps for the selected areas of the project shows the pixels representing only the areas classified as croplands according to the cropland maps from WaPOR and ESA. The average water productivity is highest for Mutangadzi (in Catandica), followed by Samoa (in Zobue), and lastly Siluvo (in Nhamatanda).

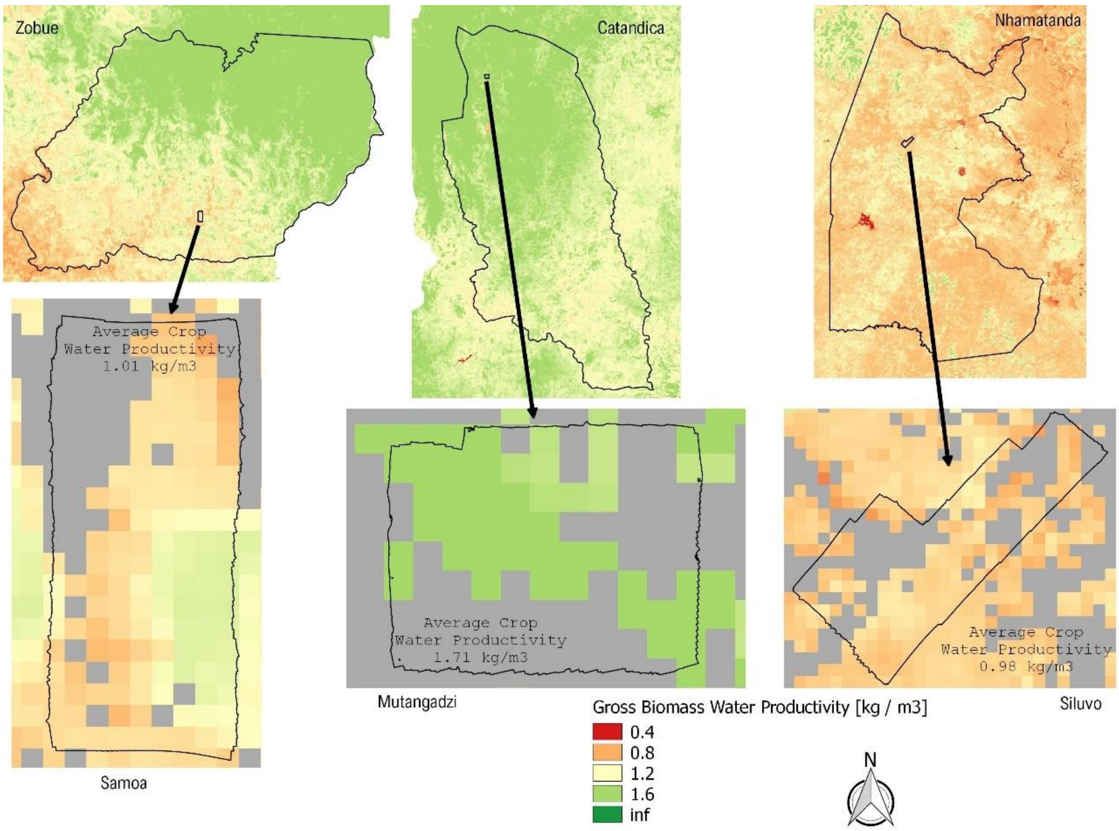


**Figure 22 Gross biomass water productivity (C3 crops) from WaPOR for each administrative province boundary and detail zoom of the three APSAN Vale areas filtering only the cropland pixels using ESA croplands data product**

## 7.2 Comparison with field level results

The results from WaPOR are compared with the field level results achieved for the Samoa area and displayed in figure 23. The resolution of WaPOR is more coarse with 100 meter pixels. The pattern for water productivity appears to be largely associated with the spatial variation in actual ET (right image) rather than biomass production. The range of values between water productivity from the flying sensor imagery combined with crop modelling, is not comparable with biomass water productivity because it does not represent the crop yield.

The calculation to convert biomass production from WaPOR data to crop yield is shown in table 4. An average biomass production of 12 ton/ha was found for the cropland pixels in WaPOR in the area of Samoa. The harvest index for maize crop found from AquaCrop results was 0.18, and the correction factor from C3 to C4 crops is 1.8 (=4.5/2.5). In table 4 the results shows that the calculated crop yield for WaPOR of 2.18 ton/ha is similar to that found from AquaCrop runs (2.58 ton/ha) and the average found for the Samoa maize polygons (2.48 ton/ha). The country statistical reports (published on FAOSTAT) indicates an average in Mozambique of 0.98 ton/ha for maize yield. According to the FAO Irrigation and Drainage Paper No, 66, crop yields are reported to be in the range of 1-2 ton/ha for less industrialized areas and 3-4 in industrious countries. The values found in this report for field level and (sub-) basin level water productivity falls within the expected range, being slightly higher than the low range of maize yields.

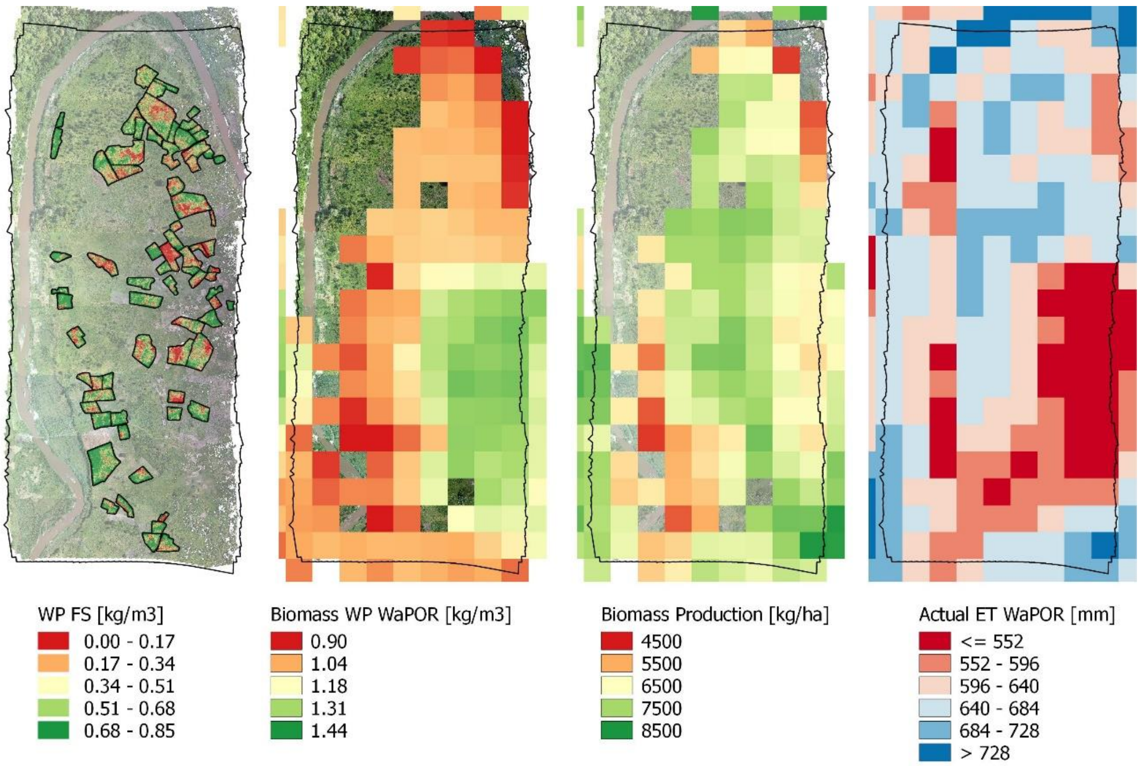


**Figure 23 WaPOR results for water productivity (C3 crops), biomass production (C3 crops), and Actual Evapotranspiration, in comparison with water productivity from Flying Sensor imagery (left)**

**Table 4 Comparison of dry maize yield and evapotranspiration from AquaCrop runs, combined Flying Sensor and AquaCrop results, WaPOR database, and FAOSTAT**

| | | AquaCrop | AquaCrop Ccmax | WaPOR | FAOSTAT (2011-2017) |
|---|---|---|---|---|---|
| biomass | ton/ha | | | 12 | |
| harvest index | [-] | | | 0.18 | |
| dry yield | ton/ha | 2.58 | 2.48 | 2.18 | 0.98 |
| Evapotranspiration | mm | 449 | | 616 | |

# 8 Concluding remarks

This report displays a description of the approach and methods used for calculating water productivity at field level and at (sub-)basin level. It is a basis that will be used throughout the APSAN-Vale project to calculate water productivity for each crop growing season and each district.

Further steps are expected to improve the methodology and results. In following seasons, it is expected to receive more observations and measurements from the field. This field data is valuable for further calibration of the AquaCrop model and achieving better estimates of water productivity. In addition, field observations for crop type will assist with the identification of other crop types and give a broader analysis of water productivity.

Water productivity in the APSAN Vale project is mainly calculated for the purpose of monitoring and evaluation. However, the high-resolution data from the flying sensor imagery gives the opportunity to use this information in the field for practical purposes and possibly increase water productivity. Practical applications are defined in collaboration with the implementing partners following the findings from this first season of water productivity analysis. The main stakeholders defined in the project are small commercial farmers (SCF's), smallholder farmers, and the surrounding communities. Groups that can have a role in bringing the information to the field are field extensionists and owners of demo-plots.