A First-Order Water Productivity Assessment for the APROVALE Project, Mozambique

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Authors
Gijs Simons
Nadja den Besten
Peter Droogers

Client
HUB Lda, Maputo, Mozambique

FutureWater Report 170

FutureWater
Costerweg 1V
6702 AA Wageningen
The Netherlands

+31 (0)317 460050

info@futurewater.nl

www.futurewater.nl

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1 Introduction

1.1 Background

Global water resources are under increasing pressure due to climate change, population growth and changing diets. In the context of the Sustainable Development Goal 6 (“ensure availability and sustainable management of water and sanitation for all”) the Government of the Netherlands has adopted the monitoring of target 6.4 (“change in water use efficiency over time”). Water-related projects financed by the Ministry of Foreign Affairs are therefore requested to report against a target of 25% water productivity improvement in agriculture.

FutureWater was asked by HUB Lda. to provide support to the development of a methodology for quantifying the water productivity indicator in the APROVALE project. This report presents a first-order assessment of water productivity of selected fields in the first phase of APROVALE and provides recommendations for enhanced monitoring of water productivity in the second project phase.

1.2 Project APROVALE

The Zambezi Valley is Mozambique’s most productive and suitable site for agriculture; rich in natural resources. The agricultural output increased significantly over the last few decades. However, despite the abundant resources, the agricultural productivity per acreage did not increase in the last decades, the increase in output was primarily due to an increase in area. With a rising population and increased variability in rainfall, the natural resources in Zambezia are increasingly under pressure. The need for an increase in agricultural productivity, but primarily water productivity is needed to combat these accelerating changes.

The Agency for Development in Zambezia (ADVZ) is a public institution that is initiating public and/or private initiatives that ensure economic development in the Zambezi Valley. Project APROVALE – “Productive Water in the Zambezi Valley” - is a 12-month pilot project led by ADVZ that aims to strengthen the agricultural practices of local small commercial producers in the Zambezi Valley, in order to combat climate change and ensure food security. The project wants to increase on-land productivity by implementing good practices (“boas practicas”) in different areas and link the products to the market. The so-called best practices will be monitored and evaluated by taking water productivity as an important indicator.

Many of the existing producers lack market access. Therefore, project APROVALE aims to implement a structure that links farmers to existing markets and at the same time tries to facilitate extension services (see Figure 1). The core feature of this structure are the CAVAs, which are companies that collect harvest for certain regions and link them to markets. These CAVAs work together with extension officers (ADA) that assist farmers in improving their practices. The structure aims to spread knowledge about farming and share best practices amongst the farm holders and technicians involved, to accelerate productivity. A lot of the techniques and knowledge distributed concern water, such as the installation of sprinklers, drilling of boreholes (Foros), and many others.

HUB Lda is co-financer and executor of Project APROVALE. The project is granted by IGG-Water, a department of The Dutch Ministry of Foreign Affairs, and requires an extensive documentation of its results and impact. HUB Lda is very knowledgeable on all aspects of the Mozambican agricultural market and seed practices, but hydrological knowledge is not their expertise. Therefore, HUB Lda has requested assistance of FutureWater to support the APROVALE project in their water productivity assessment.

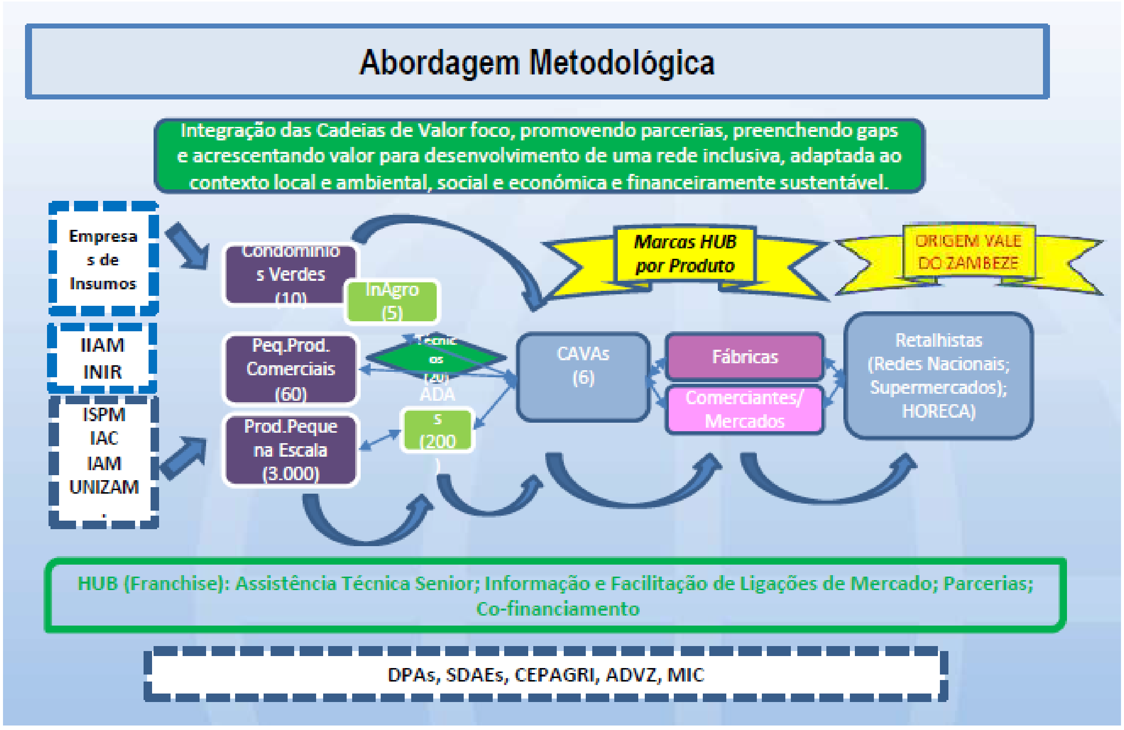

Figure 1. Organizational chart of the APROVALE project.

2 Methodology for quantifying water productivity

2.1 Introduction to water productivity

Water productivity is generally defined as the quantity of output per quantity of water consumed. This can relate to any production process that uses water (e.g. cars, trees, nature). More specifically in agriculture, water productivity is defined as the output of crop per unit of water consumed and is calculated by:

$$WP = \frac{Y}{ET_{act}}$$

where WP = water productivity (kg/m^3), Y = crop yield (kg/ha) and ET_{act} = actual evapotranspiration (m^3/ha)

As can be seen from the equation above, water consumption in agriculture is commonly regarded as equal to the actual evapotranspiration (ET_{act}) that occurs during the growth process of the crop. ETact is defined as the sum of plant transpiration through the stomata in the leaves, and evaporation that occurs from the soil surface and intercepted water by the leaves.

Higher water productivity can be obtained in two ways: maintaining the same production while consuming less water resources, or achieving a higher production while consuming an equal amount of water. A standardized methodology to monitor water productivity has yet to be developed and should be based on the two components: yield and water consumption. The new FAO-WAPOR[1] data portal offers a promising monitoring methodology for large spatial scales and annual time steps. However, since APROVALE takes place at small scales and shorter time intervals, other monitoring methods are needed.

2.2 Monitoring water productivity on different spatial scales

As shown above, ET_{act} and crop yield are the necessary variables for quantifying water productivity. Reliable data on these two parameters are unfortunately often difficult to obtain. Field measurement of ET_{act} is challenging and associated with large uncertainties, and collection of crop yield information requires elaborate farmer surveys. To cope with these challenges, it is common practice to make use of remote sensing techniques, both from satellite platforms and, more recently, Unmanned Aerial Vehicles (UAV's). This paragraph illustrates the potential of remote sensing technology for monitoring water productivity on different spatial scales, with an example from the Xai-Xai area, Mozambique.

Remote sensing technologies have the big advantage that they provide spatially discrete data that enable comparisons between fields, and even within fields. Satellites and UAV's can be used to monitor crop growth, for example by quantifying vegetation indices at different times during the growing season. An example of such a vegetation index is the Normalized Difference Vegetation Index (NDVI), which uses the reflection of red and near-infrared light from the crop leaves to assess vegetation health. NDVI values are closely linked to biomass production (kg) and thus, at

[1] http://www.fao.org/in-action/remote-sensing-for-water-productivity/wapor/en/#/home

the final stages of the season, to crop yield. For quantifying ET_{act}, data on vegetation cover together with auxiliary information can be used as input to agro-hydrological models that simulate the soil water balance and water consumption. An alternative approach for quantifying ET_{act} makes use of measurements from thermal sensors, but this approach is difficult at high spatial resolutions and highly sensitive to cloud cover.

Which approach to choose depends heavily on the availability of information. Another important factor is the size of the fields that need to be monitored. Figures 2 to 4 show water productivity maps of maize fields in the Xai-Xai region, Mozambique, which are part of the ThirdEye project[1]. Each of the maps is based on a different type of remotely sensed data. The WAPOR database of FAO[2] provides a huge resource on water productivity data in Africa, but with its 250 x 250 m pixel size it is insufficient for monitoring at the level of the individual fields (Figure 2). Landsat satellite data (30x30 m) provide much more spatial detail (Figure 3), while UAV data allow for detailed assessment of within-field variability (Figure 4). It is an important conclusion that the selected approach should always be consistent with the spatial scale of the analysis.

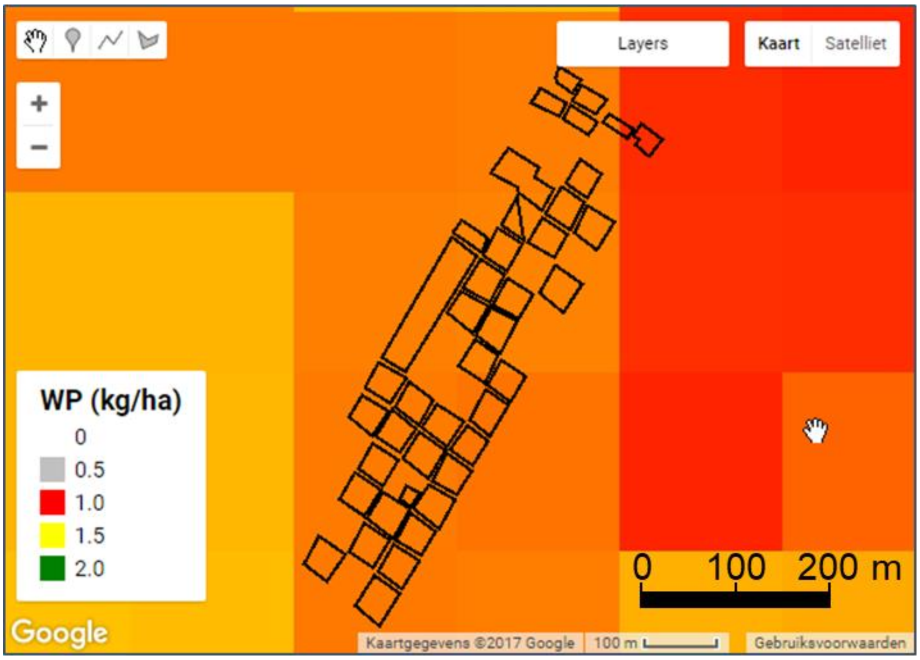

Figure 2. Annual water productivity (kg/m³) for the year 2016 based on the FAO-WAPOR database for demonstration fields in Xai-Xai area Mozambique (source: FutureWater, 2017).

[1] See www.thirdeyewater.com
[2] http://www.fao.org/in-action/remote-sensing-for-water-productivity/wapor/en/#/home

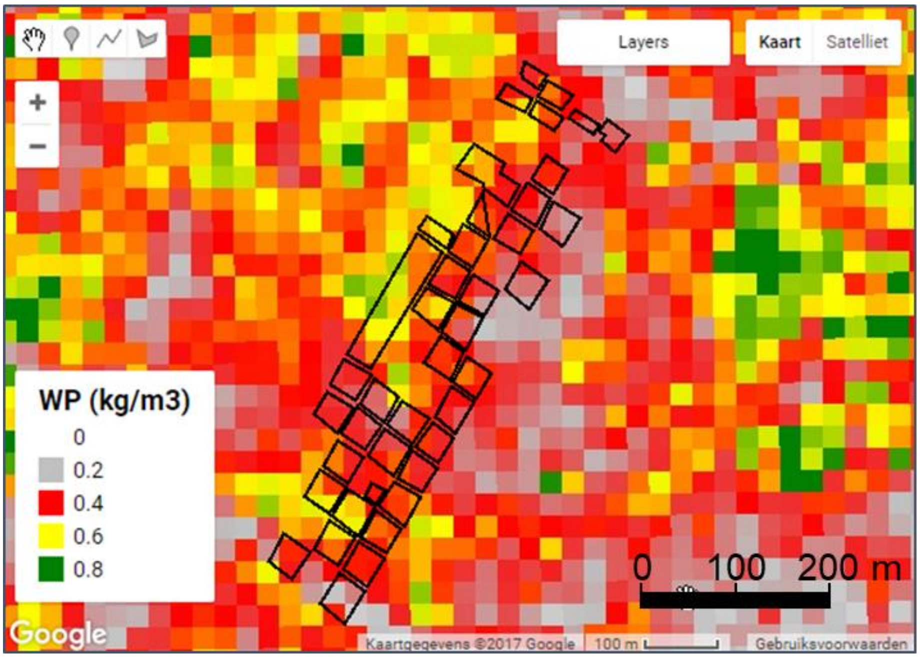

Figure 3. Growing season Water Productivity (kg/m^3) for the year 2016 based on the LANDSAT satellite for maize fields in the Xai-Xai area in Mozambique (source: FutureWater, 2017)

Figure 4. Growing season Water Productivity (kg/m^3) for the year 2017 based on Flying Sensor (UAV's) information for maize fields in the Xai-Xai area. White fields are bare (source: FutureWater, 2017)

2.3 APROVALE approach

As crop yields are being registered through surveys as part of the APROVALE project, it is not necessary to apply a method based on remote sensing or crop models to quantify crop production.

ET_{act} is however unknown, and is generally regarded as a very difficult parameter to measure in the field. For this reason, the Spatial Processes in HYdrology (SPHY) model was used to simulate daily soil water conditions and ET_{act} during the growing season.

The SPHY model was developed by FutureWater using state-of-the-art components of existing and well-tested simulation models, and was developed with the objective to simulate terrestrial hydrology at flexible scales under various land use and climate conditions (Terink et al., 2015). SPHY is a spatially distributed leaky bucket type of model and is applied on a cell-by-cell basis. The model is written in the Python programming language using the PCRaster dynamic modelling framework. Compared to other hydrological models, that typically focus on the simulation of streamflow only, the SPHY model has several advantages: it (i) integrates most relevant hydrological processes, (ii) has a modular setup, (iii) is easy adjustable and applicable at different spatial scales, (iii) can easily be linked to remote sensing data, and (iv) can be applied for operational as well as strategic decision support

SPHY simulates the impact of a dynamic vegetation cover on soil water conditions, based on NDVI time series. Landsat 7 and Landsat 8 satellite imagery[1] was used to calculate NDVI values for the selected APROVALE locations. These dynamic vegetation data, together with weather information, terrain data and soil properties, are used in SPHY to calculate ET_{act} and the full soil water balance for every day of the growing season. Irrigation amounts are added to the rainfall data to account for the full supply of water to the crop. Model concepts and hydrological flows are depicted in Figure 5. The main sources of model input data for the APROVALE application are listed in Table 1.

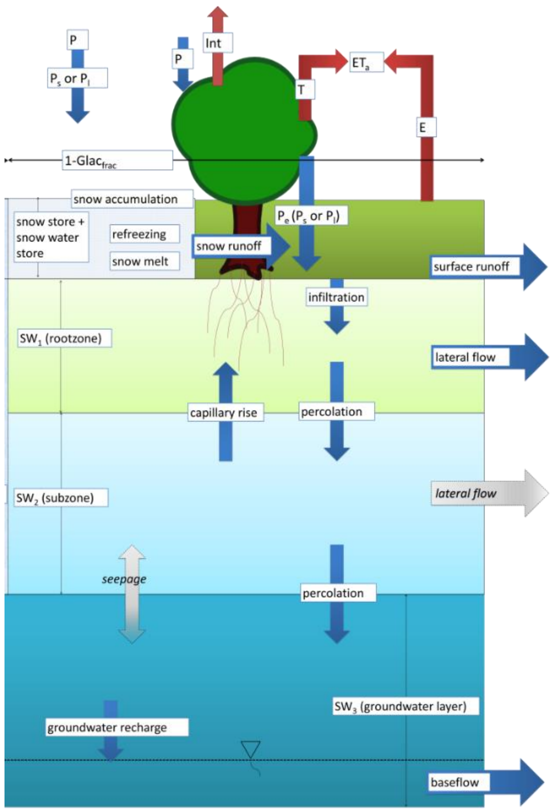

Figure 5. SPHY model concepts. Among others, the model calculates daily canopy interception, infiltration to the root zone, and soil water content, which are all factors determining total evapotranspiration.

[1] https://www.nasa.gov/mission_pages/landsat/main/index.html

Table 1. SPHY data requirements and consulted data sources. Crop yield is not required by SPHY but is listed as an essential input for water productivity quantification.

Description	***Data source***
Digital elevation model (DEM)	SRTM[1]
Soil hydraulic properties	HiHydroSoil (De Boer, 2015)
NDVI	Landsat[2]
Rainfall data	Chimoio station, provided by APROVALE.
Temperature data	Chimoio station, obtained from GSOD[3]
Irrigation data	Provided by APROVALE
Crop yield*	Provided by APROVALE

[1] https://lta.cr.usgs.gov/SRTM1Arc
[2] https://www.nasa.gov/mission_pages/landsat/main/index.html
[3] https://data.noaa.gov/dataset/global-surface-summary-of-the-day-gsod

3 Water productivity of APROVALE fields

3.1 Properties of selected fields

The selected APROVALE fields for water productivity assessment are two fields at Ecoteca farm: a soybean field, referred to as “Soja” hereafter, and a cucumber field from now on referred to as “Pepino”. The locations of these fields are indicated in Figure 6 and their main characteristics are summarized in Table 2. Figure 7 shows the weather conditions (rainfall and temperature) prior to and during the Pepino and Soja growing seasons of 2017. Weather data were obtained from Chimoio weather station, which is located approximately 20 km to the east of the fields. Daily rainfall data from Chimoio station was provided by HUB until June 15th, 2017. Rainfall for later dates, and air temperature data for the entire period, was derived from the Global Summary Of the Day database (GSOD)[1]. As can be observed in Figure 7, the start of the growing seasons overlaps with the tail end of the wet season, while the crops reach maturity during the dry months of May and June.

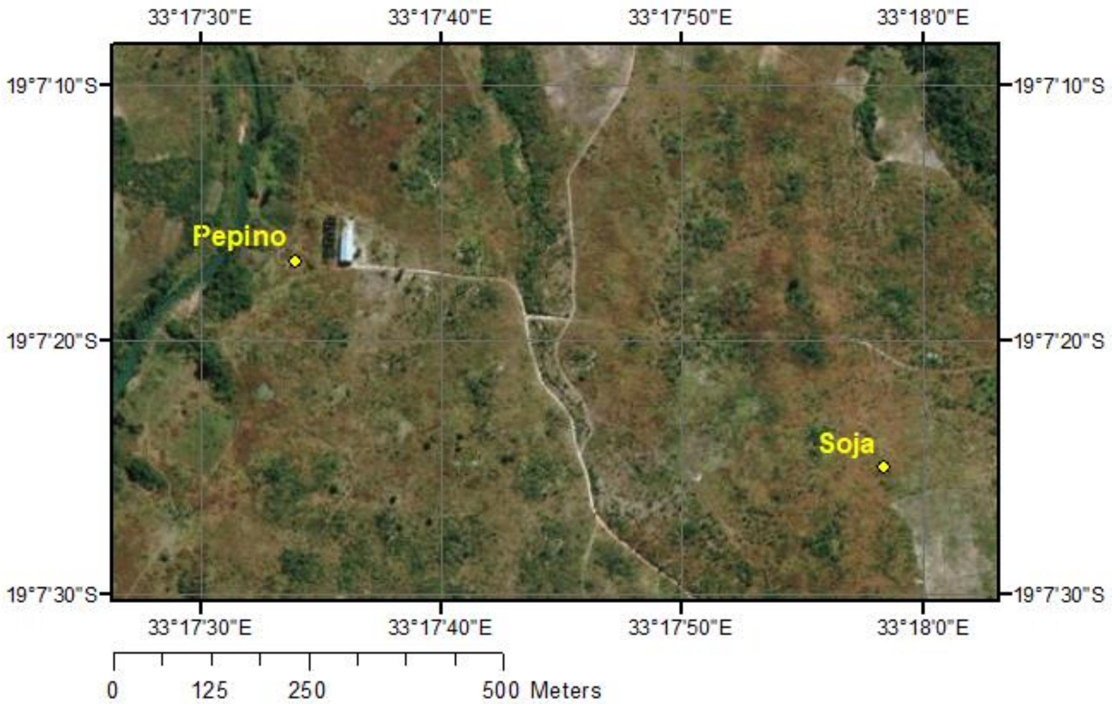

Figure 6. Location of selected APROVALE fields for water productivity assessment, with crops cucumber (“Pepino”) and soybeans (“Soja”).

Table 2. Overview of reported key field information. The Soja harvesting date was not explicitly provided, but derived from reported sowing date and season length (110 days).

Field	*Area (ha)*	*Irrigation type*	*Sowing date*	*Period of harvest*	*Crop yield (kg)*
Pepino	0.1	Sprinkler	April 9th	June 6th - July 10th	3,000
Soja	1.0	Sprinkler	February 18th	June 8th	1,525

[1] https://data.noaa.gov/dataset/global-surface-summary-of-the-day-gsod

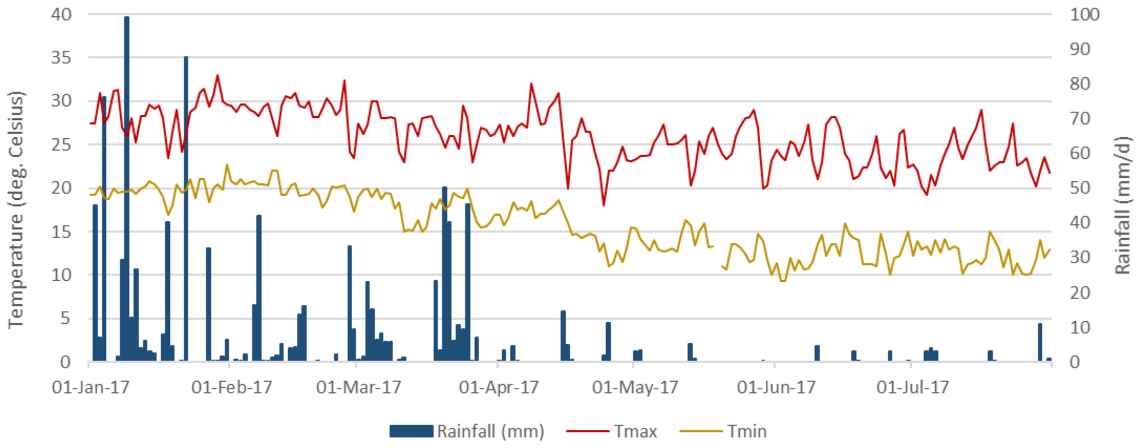

Figure 7. Rainfall, maximum and minimum daily air temperature (T_{max} and T_{min}) as recorded at Chimoio weather station.

The general data requirements for the ET_{act} assessment and the sources used in this study are listed in Table 1. Two essential data types for quantifying water productivity, crop yields and irrigation amounts, were supplied by the APROVALE project. However, a check of the total irrigation amounts during the growing seasons revealed some quality issues. For the Pepino field, 31 irrigation events were reported amounting to 1792 mm of irrigation in total, which is well above the known cucumber water requirements reported in literature. This may partly have to do with large water losses through droplet evaporation from the sprinkler system. However, for Soja the opposite is observed, with 6 irrigation events and a seasonal total of 74.4 m^3 reportedly applied to the field, which would only amount to a seasonal 8.4 mm of irrigation, which seems too low.

Based on these data quality issues, it was decided to derive irrigation amounts in a different way. Seasonal crop water requirements (CWR) were determined based on literature values. For soybeans, the typical range of seasonal CWR is given by FAO as 450-700 mm (Brouwer and Heibloem, 1986). CWR values are known to depend on climate, especially hours of sunshine, temperature, humidity and wind speed. For a semi-arid climate, a value of 531 mm is reported (Yonts et al., 2008). It is therefore reasonable to assume that typical soy CWR in the humid subtropical APROVALE area are around 500 mm. For cucumber, CWR are reportedly around 300 mm in a desert climate (Alomran and Luki, 2012), and crop water use in a semi-arid part of Tanzania was estimated at 150-200 mm for highly efficient irrigation techniques (Pachpute, 2010). Based on these values, it is assumed that seasonal CWR of the Pepino field are 150 mm.

The crop-specific CWR were corrected for seasonal rainfall reported at Chimoio station to determine irrigation water requirements (IWR). These IWR were evenly distributed amongst the irrigation events at the dates reported by the APROVALE project. The full procedure is summarized in Table 3.

Table 3. Calculation of irrigation water requirements (IWR)

Field	*CWR (mm)*	*Seasonal rainfall (mm)*	*Seasonal IWR (mm)*	*No. of irrigation events*	*Irrigation water reaching crop, per event (mm)*
Pepino	150	68	82	31	2.7
Soja	500	364	136	6	22.7

3.2 Quantifying water productivity

Figure 8 and Figure 9 show the NDVI dynamics as observed by the Landsat satellites, for the Pepino and Soja fields respectively. The curves correspond well with the sowing and harvest dates that were reported by the APROVALE period. In its use of dynamic vegetation data (Par. 2.2), the SPHY model uses the crop factor (Kc) concept of FAO Irrigation and Drainage paper 56 to convert reference evapotranspiration to potential evapotranspiration (Allen et al., 1998). For cucumber and soil, maximum Kc (Kc_{max}) values are reported in FAO report 56 as 1.0 and 1.15 respectively. Dynamic Kc values throughout the season were derived by SPHY by coupling these Kc_{max} values to the maximum observed NDVI values of 0.51 (cucumber) and 0.64 (soy).

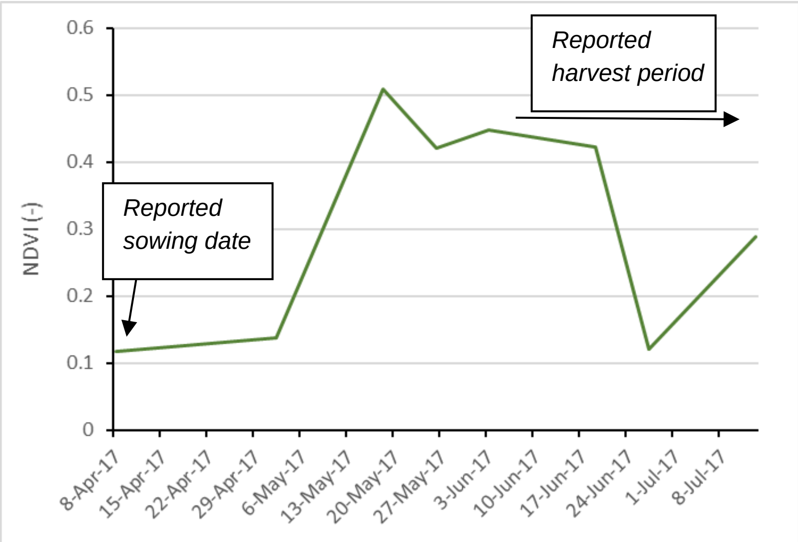

Figure 8. Landsat-based NDVI curve of the Pepino field for the 2017 growing season, including reported sowing and harvest dates.

Figure 9. Landsat-based NDVI curve of the Soja field for the 2017 growing season, including reported sowing and harvest dates.

For both fields, the SPHY model was run daily for calculating ET_{act} during the growing seasons as defined in Table 2. January 23, 2017, was taken as the start date of the model runs, assuming field capacity conditions in the upper soil layer due to heavy rainfall in the preceding weeks (see Figure 7). Figure 10 and Figure 11 show the calculated daily dynamics of ET_{act} for the Pepino and Soja fields respectively, with rainfall and irrigation events indicated.

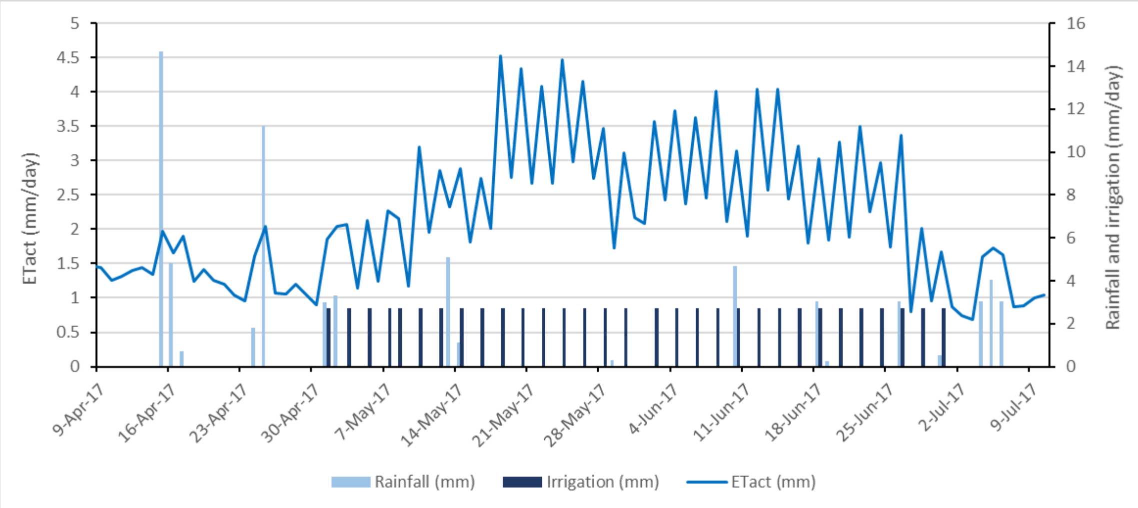

Figure 10. Daily actual evapotranspiration, precipitation and irrigation events for the Pepino field.

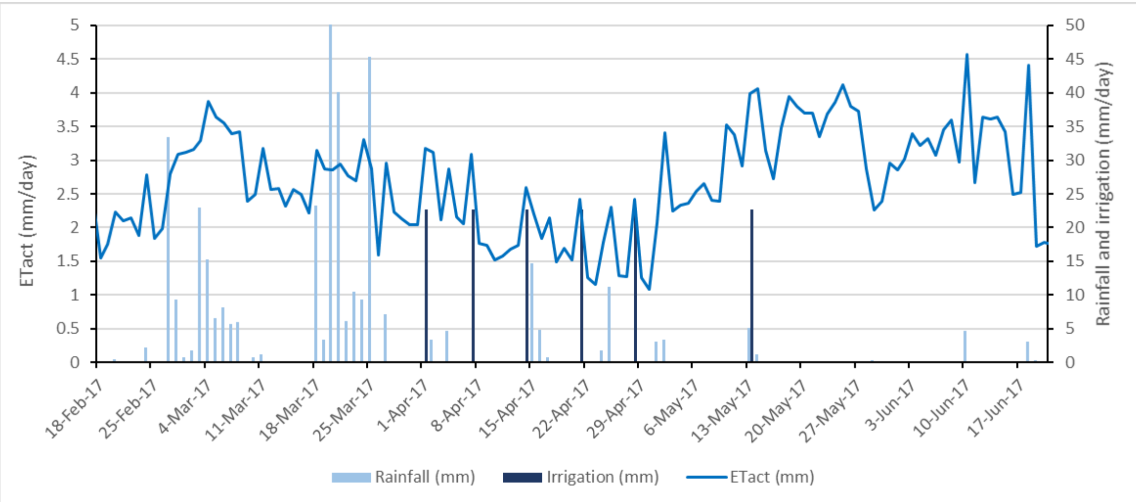

Figure 11. Daily actual evapotranspiration, precipitation and irrigation events for the Soja field.

ET_{act} values were aggregated seasonally for computing crop water productivity of both fields. Based on the NDVI-curve of the Soja field (Figure 9), the final date of the harvesting period is set at June 20th. Using the seasonal ET_{act} and the yield figures reported by APROVALE, crop water productivity of the Pepino field was calculated at 14.9 kg/m^3 and water productivity of the Soja field was found to be 0.46 kg/m^3 (Table 4).

Table 4. Water productivity of both selected APROVALE fields for the 2017 growing cycle.

Field	*Total ET_{act} (mm)*	*Total ET_{act} (m^3)*	*Crop yield (kg)*	*Water productivity (kg/m^3)*
Pepino	201.3	201.3	3000	**14.9**
Soja	330.3	3303	1525	**0.46**

3.3 Comparison with reference data

In order to put the productivity of the APROVALE fields into perspective, it is required to compare the results to reference data. Ideally this reference data is obtained from control fields in the same area, as factors such as climate and soil type play an important role in determining attainable water productivity levels. As no local reference data were available, the results for the APROVALE fields were compared to existing data and literature on other areas. FAOSTAT[1] was used as a source of national yield data for soybean and cucumber (Figure 12 and Figure 13 respectively). The FAOSTAT database does not contain national figures of these crops for Mozambique. Compared to countries in the region, the APROVALE soybean yield in 2017 (1,525 kg/ha) is lower than the average 2010-2014 yield in South Africa (-8%) and Zambia (-25%), though yields are higher than in Kenya (13%) and Zimbabwe (17%). Though it should be noted that the periods of comparison are not equal, this is a preliminary indication of a moderate performance in terms of crop yield and thus a clear scope for improvement.

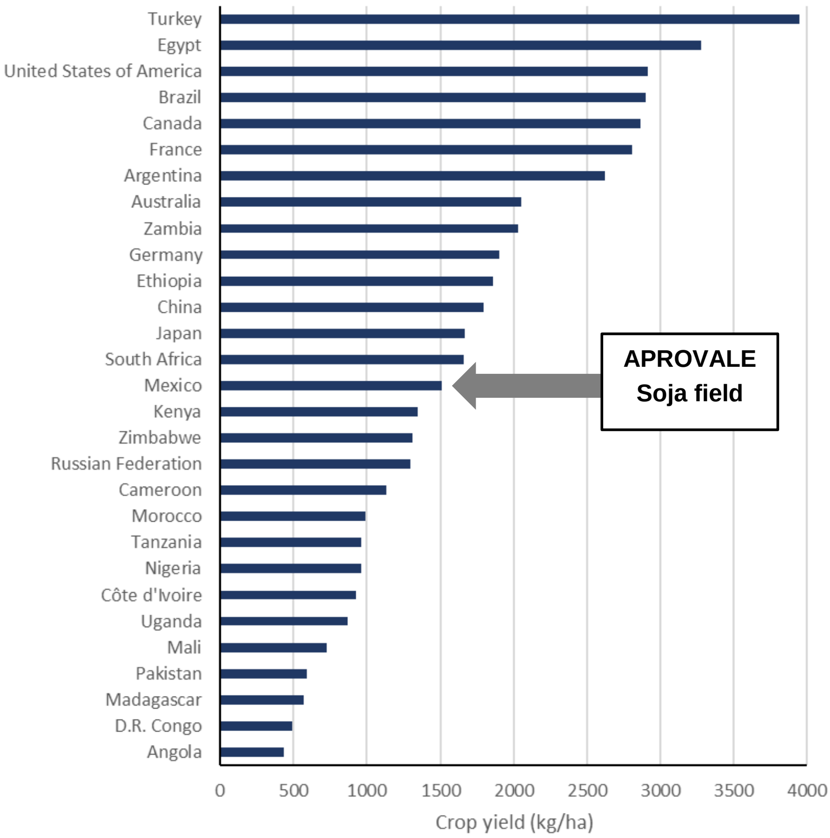

Figure 12. Soybean crop yield for selected countries, as reported by FAOSTAT. Values are averaged over the last five years with data (2010-2014).

[1] http://www.fao.org/faostat/en/

The APROVALE Pepino crop yield in 2017 was 30 tonnes/ha. Figure 13 shows that this cucumber production is well above national averages for South Africa and Kenya (2010-2014), though it should be noted that only data for the very small selected field (0.1 ha) was available. For a true assessment of productivity in the APROVALE study area and monitor project impact, it is required to evaluate a larger number of fields. The large range of cucumber yields in Figure 13 is related to different growing conditions, from controlled greenhouse environments in The Netherlands and the UK to open fields with limited resource input in many African and Asian countries.

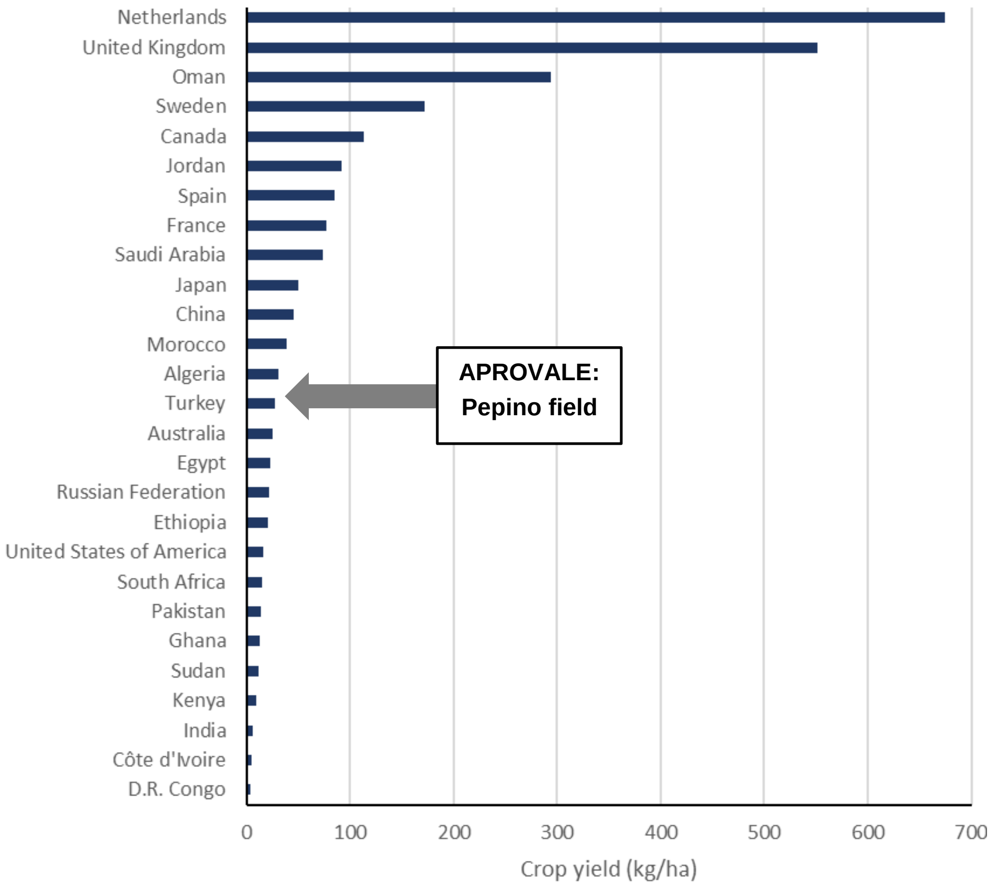

Figure 13. Cucumber crop yield for selected countries, as reported by FAOSTAT. Values are averaged over the last five years with data (2010-2014).

As discussed in Paragraph 2.1, crop yield is only one side of the water productivity equation. Therefore, a brief literature search was conducted to collect water productivity values for soybeans and cucumber. Results from a study of water productivity of soybean under irrigated circumstances in Nebraska (USA) show a water productivity of 0.89 kg/m^3 (Irmak et al., 2014). Typical soybean water productivity numbers according to FAO, based on various studies, lie between 0.6 and 1.0 kg/m^3 (Sadras et al., 2012). These values differ substantially across the world, but it is clear that the APROVALE water productivity of 0.46 kg/m^3 is below this range and shows potential for improvement.

For cucumber, being a less important crop worldwide in terms of cultivated area, less water productivity data is available from existing sources. Most data that is available, e.g. 22.9 kg/m^3 for a drip-irrigated system in Mediterranean circumstances (Buttaro et al., 2015), apply to clearly different conditions than the APROVALE Pepino field. For future water productivity assessments, it is advised to monitor local control areas for appropriate reference data to evaluate project impact.

4 Conclusions and recommendations

This report provides a first-order quantification of water productivity values of two selected APROVALE fields for the 2017 growing season. A monitoring approach based on satellite remote sensing information and hydrological modelling was applied. Water productivity values found for the two APROVALE fields in 2017 are:

- **0.46 kg/m^3** for soybean. This value can be considered as average in the context of the biophysical settings of Mozambique. Substantial increases might be possible.
- **14.9 kg/m^3** for cucumber. This value can be considered as reasonably high in the context of the biophysical settings of Mozambique. Still, improvements in agricultural and water management might be considered to increase this value somewhat further.

The main variables to quantify in water productivity assessments are crop yield and actual evapotranspiration. There are several ways to approach this, dependent on available data and time. The current approach was selected to provide a reasonable first-order quantification of water productivity of the selected fields, given the available resources. There are however several opportunities to enhance water productivity monitoring in a second phase:

- As demonstrated in this report, remotely sensed information is highly valuable for quantifying water productivity. In this study, Landsat satellite images were used (30x30m) to monitor vegetation growth. However, for small fields such as the Pepino field, there is a scale mismatch between this pixel size and the field size, likely causing the occurrence of “mixed pixels”, with different types of land use in a single pixel. This can be solved in the future by using satellite data with a higher level of spatial detail (e.g. ESA Sentinel 2 at 10x10 m). Another limitation is the fact that a single point coordinate was now taken to be representative for the entire field. If field boundaries are provided by the APROVALE team, these could be combined with high-resolution imagery to assess spatial variability of water productivity within a field.

- Since project APROVALE is working with small commercial farmers, the above point is especially valid. To further enhance the level of spatial detail, and allow for data collection on-demand without problems during cloudy days, it is suggested to monitor biomass production with flying sensors[1] during critical stages of the crop development. This information can function as input for the Water Productivity calculation procedure.

- This assessment was based as much as possible on data provided by the APROVALE project. However, a quality issue was observed with regards to the irrigation data. High-quality data will undoubtedly lead to a higher accuracy in calculated water productivity. In the second phase of project APROVALE, FutureWater could provide HUB Lda with checklists and calculation procedures for fieldworkers.

- Another suggestion regarding data collection is the monitoring of control fields to gather reference data. As water productivity is highly variable in space and time, it is important to monitor water productivity of local fields during the same growing season.

[1] The Flying Sensor monitoring service could be supplied by the operational project ThirdEye. Prior to the growing season, flight missions can be planned in the different APROVALE districts and fields.

- As demonstrated, with the SPHY simulation model it is possible to calculate actual evapotranspiration, taking into account crop development with NDVI satellite indices obtained through Landsat. The SPHY methodology is very flexible and strongly focused on the water component of water productivity. Other simulation models, such as Aquacrop[1], explicitly take biomass production into account. In a more elaborate assessment in a second phase, it is possible to setup a model ensemble that allows for scenario analyses to determine appropriate farm management interventions to enhance water productivity. This is a crucial step in going from monitoring water productivity a true 25% improvement.

This report showcases the available techniques and expertise FutureWater has to offer to project APROVALE. In a second phase of the project, it is proposed to jointly define a methodology to monitor crop development and water productivity at the end of the growing season, building on the material presented in this report. To this end, we propose an integrated approach of using field data, remote sensing (UAV"s and satellites) and agro-hydrological models.

[1] http://www.fao.org/aquacrop/en/

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