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Water productivity analysis of sand dams irrigation farming in northern Ethiopia

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Abstract: Water scarcity is the main problem to be tackled to meet regional food security in drylands. A large number of studies is calling to focus efforts to enhance Water Productivity (WP), and one of the most promising option is represented by water harvesting, the collection and storage of runoff water to be used for beneficially uses. Among the available technologies, sand dams are experiencing a renovated interest because of their relative simplicity and their potential. This research aims to deepen the knowledge about WP of water harvesting systems studying a sand dam irrigation system in Tigray, north Ethiopia, where farmers are getting used to this new technology. The research was carried out in the period March-April 2017, when farmers use sand dams water to irrigate maize, during the Ethiopian dry season. We analysed a representative plot irrigated through a shallow well drilled in the sand dam aquifer, in terms of yield, Crop Water Productivity (CWP), Crop Water Productivity based on Evapotranspiration (CWP(ET)) and Economic Water Productivity (EWP), through field data analysis and a validated Aquacrop model. CWP(ET) was found to be low (1.12 kg of grain per m^3 of water), due to both inefficient water application and low soil fertility. Aquacrop model results showed that changing the irrigation schedule can increase CWP(ET) up to 1.35 kg/m^3 and EWP up to 3.94 $birr/m^3$, but yield gap is mainly due to the low soil fertility. Interventions on soil fertility can raise yields from the observed 3.3 kg/ha up to 8.5 kg/ha, and thus CWP(ET) and EWP up to 2.94 kg/m^3 and 9.54 $birr/m^3$ respectively. To enhance the effect of sand dams in northern Ethiopia, a set of measures, including conservation agriculture, is then proposed.

Keywords: drylands, water scarcity, water harvesting, Aquacrop, Ethiopia

Introduction

Despite the common imagine of drylands, the semi-arid agro-ecological zone is characterized by a sufficient annual rainfall amount for growing rainfed crops; it is its extreme variability, with high intensities, few events and poor spatial and temporal distribution that strongly limits crop production (Rockström *et al.*, 2010, Kijne 2003, Oweis and Hachum, 2006). In this agro-ecological zone, meteorological droughts occur on average once or twice every decade, while dry spells (short periods of lack of rainfall during the rainy season) occur more frequently (Rockström *et al.*, 2010).

Although some of the effects of climate change are still uncertain, almost every model predict that the frequencies of extreme events will increase (IPCC, 2014). Direct consequences will be an increase in water scarcity and, in general less, favourable conditions for crop growth, worsening the conditions of vulnerable communities.

Considering the future impacts that developing economies will have on water resources, as well as the effects of climate change and the expected increase of population, water security will continue to be one of the main challenge of institutions working in developing countries.

Concerning agricultural systems, the main focuses that have been addressed by water governing institutions in the last decades were the development of irrigation schemes and in-situ moisture management, while poor attention has been dedicated to water management in rainfed agriculture (Rockström *et al.*, 2010, Kijne, 2003). Some researchers and practitioners are convinced that to develop and to improve rainfed agriculture, major efforts should be on securing water to bridge dry spells and to increase agricultural and Water Productivity (WP) (Rockström *et al.*, 2010).

In dry areas, it is water, and not land, the most limiting factor in agriculture. Therefore, maximizing WP, namely the yield per unit of water used, and not yield per unit of land, represents a more appropriate strategy (Hengsdijk *et al.*, 2010; Molden *et al.*, 2010; Oweis and Hachum 2006). Agricultural production and livelihoods in dry areas can be sustained only if priority is given to improving WP and enhancing the efficiency of water procurement (Oweis and Hachum, 2006) and, according to Foley *et al.* (2011), improving the use efficiency of resources (also water) is indicated as one of the five actions that must be done to achieve food security.

In the last 40 years, WP doubled especially because of the yield increase. In this new context, practices of water harvesting, defined as "the process of concentrating precipitation through runoff and storing it for beneficial use" (Oweis and Hachum, 2006), are experiencing a new interest and, if the trend continues, they will become of primary importance among researchers and practitioners in the near future. In the history of many civilization, various examples of water harvesting systems can be found, developed to cope with water shortage; most of them are now being studied and in some cases reintroduced (Rockström and Falkenmark, 2015; Mekdaschi Studer and Liniger, 2013).

In dry marginal environments, water harvesting is the main solution for economic, agricultural and environmental protection, representing an effective way to improve rain-WP (Oweis and Hachum, 2006). However, socio-economic assessments are not often realised after water harvesting implementation projects. Sustainable increase in WP through water harvesting systems can only be achieved with a general improvement of the agricultural practices and with the involvement of different stakeholders, including both farmers and institutions (Kijne, 2003).

Among the technologies for runoff water harvesting in arid areas, sand dams represent one of the most suitable. A sand dam consists in a concrete wall built in the riverbed of sandy ephemeral rivers onto bedrock or an impermeable layer; the sedimentation of the transported sand in the upstream of wall in a few years is able to create an artificial aquifer. In the sand the water is accumulated and in the dry season people can access to it by digging scoop holes in the accumulated sand or wells, directly in the riverbed or close to it (Hoogmoed, 2007).

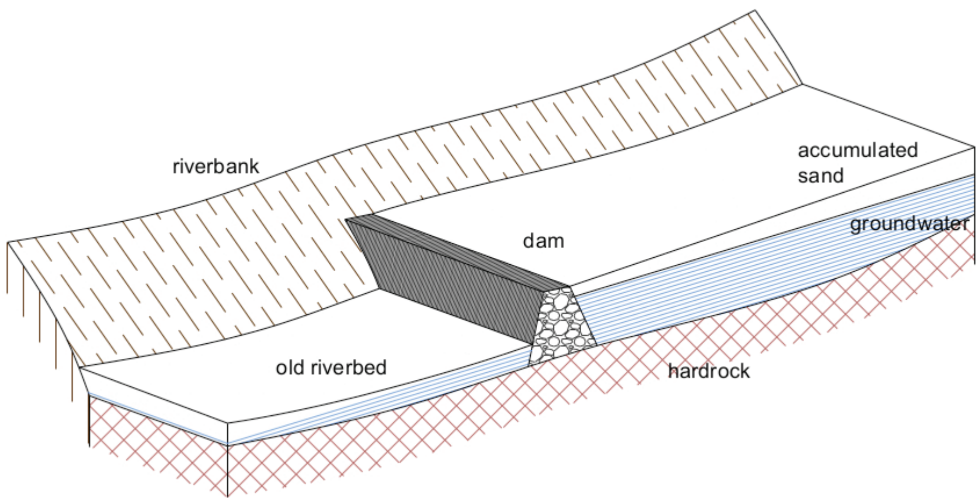

Figure 1 - Principle of a sand storage dam. Source: Borst and de Haas (2006)

The water collected is generally used for domestic use, livestock watering, small-scale irrigation or collected for environmental services (Oweis and Hachum, 2006), but it can also be used for different activities such as brick making (Pauw *et al.*, 2008). Each activity requires different amounts of water; while domestic use and livestock watering can be considered less demanding activities, irrigation and brick making require high amounts of water (Pauw *et al.*, 2008), and the utilization of the stored water for these activities is (or should be) questioned in some cases. Of course, everything depends on the amount of water stored by the dam and by the numbers of users, but future research should assess the sustainability of high-consuming water practices such as off-season irrigation for fully-irrigated crops.

Examples of sand dams can be found in very ancient times in Italy, where Romans build some similar structures in Sardinia, and Tunisia. More recently, the technology has been adapted by U.S. and several other countries like India, Brazil, Pakistan, South and East Africa (Borst and de Haas, 2006, Pauw *et al.*, 2008). Kenya is now the country where more studies have been conducted on the effects of sand dams, that are in most of the cases positive (Pauw *et al.*, 2008, Ryan and Elsner, 2016, Maddrell and Bown, 2017). In Ethiopia, where many water harvesting systems are traditionally used by farmers, the few sand dams that exist have been built in isolated projects. However, good examples in Kenya have raised the interest among practitioners working in Ethiopia and large-scale implementation of sand dams is being considered. In the last years, the NGO Relief Society of Tigray (REST) started many projects to tackle the problems of soil erosion and water scarcity, achieving in some cases astonishing results (REST Mekelle Team, 2011, Tuinhof *et al.*, 2012*)*. In 2012 the construction of some sand dams was undertaken, for introducing the technology in Tigray.

The framework of this research is the Arid African Alluvial Aquifers - A4labss project, funded by the Dutch Ministry of Foreign Affairs and coordinated by IHE Delft - http://A4labss.un-ihe.org/arid-african-alluvial-aquifers-A4labss. The project aims to co-develop, test, share and compare, with farmers and partners, methodologies to create a reliable and sustainable source of water for agriculture in semi-arid regions of three Sub-Saharan countries (Mozambique, Zimbabwe and Ethiopia) using water underlying dry river beds.

The present work was conducted in May Gobo site of the Ethiopian A4labs, where a sand dam and some shallow wells were built in 2012 by REST. After the construction of the sand dam, 53 households were provided with diesel pumps, fruit trees and seeds to improve agriculture and livelihoods. The main utilization of water made available is represented by off-season irrigation of trees, maize and vegetables, like tomato, pepper and onion. In the period of the research (March and April 2017) farmers were complaining a lack of water in the sand dam and organized a fixed reduced irrigation schedule to cope with water lacking. The study has been conducted on a pilot maize plot irrigated with the sand dam's water to obtain results regarding the water withdrawal and the productivity. Crop Water Productivity (CWP) and Economic Water Productivity (EWP) have been calculated based on the collected data and utilized as input for the crop simulation model Aquacrop (Hsiao *et al.*, 2009, Steduto *et al.*, 2012), that was used again to estimate CWP and to analyse the irrigation system.

This study wants to contribute to the general research about sand dams evaluating the results in terms of productivity in May Gobo and propose possible improvements.

Materials and methods

Study Area

The Ethiopian A4labs research site is in the May Gobo *Tabia* (municipality), Hawzen *Woreda* (district), in Tigray Region, Ethiopia, at an altitude of 1714 m a.s.l. Coordinates are 13.89° N and 39.28° E. Hawzen climate is semi-arid and is classified as BSk according to the Köppen and Geiger classification. Mean annual temperature is 17.4 °C; the mean minimum temperature of 5.8 °C occurs in December, while in April the maximum temperature of 27.7 °C is reached. Total rainfall is 611 mm, and roughly half of it is (330 mm) concentrated in the months of July and August, the *Kiremt* season.

May Gobo is within the Tekeze river sub-basin; the Tekeze river is a tributary of the Nile river. The basin is located in northern Ethiopia and it covers a total area of 59,808 km^2. The basin drains parts of the north western highlands of Ethiopia and contributes to about 14% of the Nile river flow. The sand dam height is about 2 m and width about 24 m (Figure 1). REST promoted the plantation of fruit trees such as mango, papaya and oranges after the construction of the sand dam to increase and differentiate the income. In the study plot, these trees were recently planted and still unproductive in comparison to most of the other plots. For this reason, they have not been considered in the study. The well from where water was pumped to irrigate the plot was very close, so that it was possible to avoid considering delivery losses. The representative plot was characterized by maize uniformity.

The plot has an area of 435 m^2, at the beginning of the visiting period maize was already established and sufficiently uniform. Maize (*Zea mays* L. var. Melkassa-1) was sown the 4th of February 2017, emerged 5 days later and flowered a couple of months later. It is a very early variety, and the harvesting day was the 1st of May, after 87 days from sowing. Maize density varies from 8 to 10 plants/m^2, within the field since thinning has not been done.

The irrigation method is traditional and can be roughly defined as a mixed basin/furrow method. The farmer with the pipe reaches two different points of the plot, and from there water is distributed through furrows.

Water Productivity

WP is defined as the ratio of the net benefits from crop to the amount of water consumed to produce those benefits (FAO, 2016 and cited references). As different studies have different objectives, the numerator and the denominator might change according to different focus, scale and point of view, as well as the kind of data available (Kijne, 2003). Regarding the numerator, common choices to estimate WP

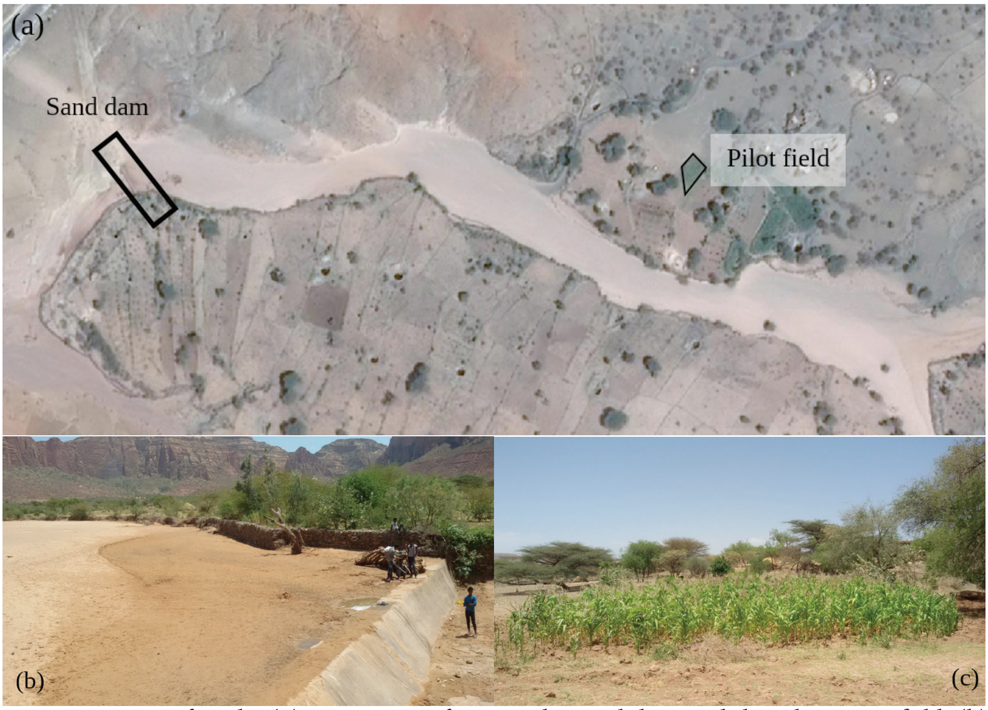

Figure 2 - Area of study: (a) positioning of May Gobo sand dam and the pilot maize field; (b) May Gobo sand dam; (c) pilot maize field

are grain yield, biomass, nutritional value, jobs created and economic return (Kijne, 2003).

A common form of WP is the so-called "crop per drop" approach that focuses on the amount of product per unit of water used (Kijne, 2003). WP expressed as kilogram per drop is a useful concept since it can be used to compare different systems efficiencies and also compare different uses of water. Since it is the most common method to measure WP and there are many data available, it is possible to compare obtained results with the ones of other research.

In comparison to the choice of the numerator, the choice of the denominator can be more difficult as the concept of water used may change among different researchers. Various epistemic groups define the word 'drop' in different ways such as kg per unit of transpiration by breeders and kg per unit of water by agronomists and agricultural engineers (Temesgen, 2007). In some cases, it can also be considered the non-productive water for beneficial use such as cover crops, water used to favour germinability of the seeds, etc. (Kijne, 2003).

The question of considering water losses from seepage and percolation as consumption does not receive a unique response (Kijne, 2003, Temesgen, 2007). Here, the issue is rather to consider the water used by the plant or the water applied to the field. In general, if the water lost for percolation is used downstream, it isn't considered in the denominator. Again, the focus and the scale of the specific study might change decisions.

We can distinguish a physical water productivity, namely the Crop Water Productivity (CWP), defined as the ratio of mass of product (either the grain or the biomass) to the amount of water consumed, and Economic Water Productivity (EWP), defined as the value (usually the economic return) derived per unit of water used (Sadras *et al.*, 2012). According to the research objectives, the value can be also nutritional values, jobs created, etc. (Kijne, 2003).

The choice of the parameters to be considered has been the focus of the first weeks of the research. After visiting the site, the plot and identified which data were collectable and its accuracy, we decided to consider CWP defined as the grain yield in kg per m^3 of water applied to the field and EWP defined as net return in birr per m^3 of water applied to the field. Since rainfall was a very small percentage (the season was dry) respect to the total water applied with irrigation, we decided to neglect it.

As we used also the Aquacrop software to calculate WP, it was also estimated as yield in kg per m^3 of water evapotranspired. In this research we will refer to this kind of WP as CWP(ET).

More specifically, CWP helps us to evaluate the water use efficiency at the irrigation level, while CWP(ET) gives us information regarding the yield gap and if water is limiting production.

CWP and EWP evaluation

CWP is calculated through the formula

$$CWP=Y/I \qquad (1)$$

where:
Y = the maize grain yield [kg/ha]
I = the water applied with irrigation [m^3/ha]

EWP is calculated through the formula

$$EWP=NR/I \qquad (2)$$

where:
NR = the net return, calculated as the difference between gross return and costs [birr/ha]
I = the water applied with irrigation [m^3/ha]

Most of the data have been collected during visits to the site between March and

April 2017 through direct measurements and interviews to the owner of the plot, other farmers and local experts. These months of the year belong to the season that is locally known as *Belg*. *Belg* precedes the real rainy season known as *Kiremt* (or *Meher*), thus it is the period with less water in the dam, especially if the season is dry as in 2017. In the period of study, there has been no significant rainfall and maize growth was supported mostly by irrigation water.

Aquacrop model

WP was also calculated with the FAO software Aquacrop, version 5.0, a software for estimating biomass production directly from actual crop transpiration, through a water productivity parameter (Steduto *et al.*, 2012). Specifically, the model converts daily transpiration directly into daily biomass production, using daily reference evapotranspiration and normalized WP, a conservative (virtually constant) parameter specific to a crop species. Yield is derived directly from biomass with the harvest index (Hsiao *et al.*, 2009). The location and cultivar-dependent parameters, as well as inputs such as weather data, irrigation schedule, soil fertility and planting density are to be supplied by the user. The model demonstrated to be reliable and has been successfully calibrated and evaluated for several common crops, including maize (Hsiao *et al.*, 2009).

The software has been proven to be a valid simulation tool, with good performances for the evaluation of WP in different contexts and for different crops (Jin *et al.*, 2018; Karunaratne and Azam-Ali, 2013). In the current version, the model exhibit not fully satisfactory performances in extreme conditions such as strong water stress (Greaves and Wang, 2016) or the simulation of irrigation of saline water (Kumar et al., 2016), conditions not present for the analysed case study.

Among the numerous applications of the software, the most common in scientific papers are the study of the impact of climate change on crop yields and of scenario simulations under different management practices. For this work, it has been used to analyse the irrigation schedule and to estimate CWP(ET).

Aquacrop allows different options for irrigation according to different objectives. It is possible to provide an irrigation schedule and test it, to make the software calculate net irrigation requirements and also to generate an optimal irrigation schedule.

Four different simulations have been prepared: (1) considering actual irrigation method (AI), (2) calculating the net irrigation requirements (NI), (3) generating an optimal irrigation schedule (OI) and (4) testing the OI irrigation schedule without soil fertility stress (NS). Data were the same for all the inputs except for the irrigation file, that was changed according to the objective of each simulation, and for the soil fertility stress of the NS simulation that was set to zero. Results of AI were compared with data collected with interviews to validate the Aquacrop model.

For the model, climatic data were taken from the National Climatic Data Center (NCDC) database, for the Mekelle station. For all the other inputs, we used data collected through interviews and assessments on the field.

The default maize of Aquacrop has been modified to adjust it to the variety used by the farmer. The stages and the total cycle length have been changed, and root deepening was decreased to 1.5 m to take into account the lower height of this maize. 80000 plants/ha have been considered. Sandy-loam default soil has been used. To consider the soil fertility stress the input in the software regarding biomass production was "poor", corresponding to 60% of soil fertility stress, that corresponds to a 60% biomass reduction. To consider the reduced evaporation due to the intercropped trees, a little amount of organic mulches has been put (10%). 10 cm of soil bunds have been considered too to take into account also the particularity of the irrigation method. No groundwater table was considered since it was too deep to influence the root zone. The input for the initial condition of the soil was 15% of water at 30 cm depth and 30% of water at 90 cm depth. Irrigation was simulated as follows:

AI: The input used in the first simulation to consider the irrigation method was furrow irrigation, with a wetted surface of 90%. The first irrigation was done 2 days after the emergency, that is the 11^{th} of February, and one irrigation per week was applied. Considering that the total irrigation events applied to the field plot in the period of analysis were 11, each one of 60 m^3, and given the area of 435 m^2, the gross irrigation depth for each event was calculated as 137,9 mm. Estimating an efficiency of 50%, the net irrigation depth considered for the simulation was 69 mm for each event. Water quality was considered as excellent, as for the other simulations.

NI: For the second simulation the tool was used to calculate the net irrigation water requirements, and the simulation was built to keep the soil moisture constantly at field capacity, in every calculation step.

OI: The irrigation file has been set to generate an irrigation schedule. Furrow irrigation was the method considered with 80% of the surface wetted; the irrigation event when 80% of the readily available water was depleted, to reach the field capacity.

NS: The irrigation schedule generated in the OI simulation was tested in the same conditions a part for the soil fertility parameter, to assess its performance without fertility stress.

Results

CWP and EWP evaluation

In the representative plot, and in general in May Gobo, the irrigation distribution uniformity is low, and it was estimated as 50%. The pump used provided by REST was a diesel pump with a discharge of 60 m^3/h.

The lack of rainfall from the previous rainy season caused sand dam refilling capability to be low. Farmers were complaining a general lack of water and the community organized fixed and limited irrigation turns: farmers could irrigate once per week for one hour. Total amount of water applied in the irrigation season was 660 m^3.

In May Gobo, farmers apply traditional practices to prepare the soil: three different tillage operations have been done, to mix the soil and make it softer. Fertilization has been done with 25 kg of DAP (di-ammonium phosphate). Weeding has been done manually by family members. No thinning was done. The soil was described as sandy both by the farmers and the experts interviewed. The qualitative analysis test resulted in a sandy-loam texture soil.

The soil organic content has not been measured, but considering the sandy soil texture, the high amount of rainfall concentrated in few months that cause land degradation (Temesgen, 2007), the high number of tillage operations, the lack of rotation (and in particular the use of leguminous species) and the lack of organic fertilization, it is most likely that the fertility of the soil is low.

The farmer sowed a maize variety provided by REST almost a year before. After the first cycle, he saw some of the harvest, and this cycle of cultivation was the third. Experts from REST said that this variety could reach, in optimum conditions, 6 t/ha.

The observed yield in the test plot was 0.15 t, correspondent to 3.448 t/ha. In the season 2015/2016 average maize yield in Ethiopia was 3.387 t/ha (Cochrane and Bekele, 2017), in line with the yield collected. Potential maize yields reported by Tesfaye in the Global Yield Gap Atlas (2018) reach 6.0 to 8.0 t/ha for on-farm trials.

Considering the 150 kg of maize grain production and the 660 m^3 of water applied with irrigation on the same plot area, the resulting CWP calculated through the formula (1) is 0.23 kg/m^3.

Maize was for self-consumption and it wasn't sold; anyway, if the farmer would have sold it, the price of maize according to FAO data obtained in the GIEWS database in Makale in May 2017 would have been of 640 birr/q.

Table 1 - Calculation of the gross return

Production (q)	Price (birr/q)	Gross return (birr)
1.5	640	960

The costs for this maize cultivation cycle were only those afforded to buy the diesel to run the pump and the fertilizer di-ammonium phosphate (DAP). No other direct costs have been afforded by the farmer; seed was self-produced and labour was provided by family members. 25 kg of DAP have been paid 400 birr.

Net return is calculated through the difference between gross return and total costs and equal to 507.40 birr. Considering the 507.40 birr of net return and the

660 m^3 of water applied with irrigation, the resulting EWP calculated through the formula (2) is 0.77 birr/m^3.

Table 2 - Cost calculation for diesel use

Irrigation time (h)	1
Number of irrigations	11
Total irrigation time (h)	11
Pump consumption (l/h)	0.33
Diesel consumption (l) (Pump consumption x Total irrigation time)	3.63
Diesel price (birr/l)	14.49
Total diesel cost (birr) (Diesel consumption x Diesel price)	52.60

Table 3 - Calculation of the total cost

Diesel cost (birr)	DAP cost (birr)	Total cost (birr)
52.60	400	452.60

Aquacrop results

With the inputs used to simulate the AI simulation, the results of the model were in line with the results obtained by elaborating field data. The model yield was 3.316 t/ha, very similar to the yield actually harvested of 3.448 t/ha. The model is thus considered appropriate as base for the other NI, OI and NS simulations.

As we used Aquacrop to analyse the irrigation system and not to make future predictions for which appropriate calibration is suggested, we considered this as a sufficient validation of our inputs and of the response of the software for the other three simulations. Potential yield calculated by the software, without any kind of stress, is 8.42 t/ha, a little higher than the potential yield reported in the Global Yield Gap Atlas and to what experts from REST told us for the maximum production of the variety.

According to the software, of the 61% of biomass reduction only 1% was caused by water stress, while the other 60% was caused by soil fertility stress. Therefore, water wasn't a constraint and the maize was sufficiently irrigated. Water in the soil was always close to the field capacity.

Regarding the AI simulation, with a daily evaporation of 2.2 mm/day, the total evaporation is 107.5 mm, and with a daily transpiration of 0.6 mm/day, the total transpiration is 188.4 mm. The CWP(ET) calculated by the software is 1.12 kg/m^3. It's important to remember that Aquacrop measures WP referred to ET and not to the total water applied to the plot. Total net irrigation is an input provided by our simulation of the irrigation schedule since we created it, and it is 759 mm.

NI results showed that the crop needs 341.5 mm. Water needs calculated as net irrigation requirements (without considering the efficiency of the system) are therefore less than the half respect to the total water applied by the farmer. Total evaporation predicted is 148.9 mm, and transpiration 190.5 mm. The CWP(ET) achieved would be of 0.98 kg/m^3, that is a lower value than the one obtained in AI simulation. This is mainly due to the higher volume of water transpired by the plant, given the maximum water availability. Predicted yield was 3.332 t/ha.

OI simulation showed that only three irrigations were needed: the first one on the first day of 23.9 mm, the second one at day 36 with 57.8 mm, while the third and last one on day 57, with 78.5 mm. Total net irrigation was 160.1 mm. With this schedule, total evaporation would drop to 58.3 mm, while transpiration remain constant at 185.7 mm. The CWP(ET) would raise to 1.35 kg/m^3: this is the best value attainable with this kind of management but with an optimal irrigation schedule. Predicted maize yield is 3.301 t/ha.

NS simulation showed that the irrigation schedule generated in the OI simulation was sufficient to provide enough water to the maize not limited by soil fertility, and achieve the highest yield attainable, equal to 8.491 t/ha. The lack of soil fertility stress drastically increased the biomass produced and therefore also transpiration increased (245 mm). Instead, evaporation decreased due to a higher canopy cover (40.9 mm). CWP(ET) reached the value of 2.97 kg/m^3, while net irrigation requirements remained the same as OI simulation, 160.1 mm.

For the OI simulation, considering the equalized production of 143.6 kg and the total water applied of 139 m^3, CWP calculated through (1) is 1.033 kg/m^3. To pump 139 m^3 of water with a discharge of 60 m^3/h it takes 2.32 hours. Referring to data reported in Table 2, with a pump consumption of 0.33 l/h the total diesel consumption would drop to 0.77 l. With the diesel price of 14.49 birr/l, total diesel price would be of 11.16 birr. With a net return of 548.84 birr and with the total water applied of 139 m^3, EWP calculated through (2) would be 3.94 birr/m^3.

In the NS simulation the production is 369.4 kg while water applied remain 139 m^3. CWP calculated through (1) is 2.655 kg/m^3. EWP for the NS simulation was estimated considering a proportional increase in costs of fertilizers to the yield. Gross return is 2361 birr, total costs are 1035.16 birr. EWP calculated through (2) is 9.54.

Results of the four simulations are shown in Tables 4 and 5.

Table 4 - Comparison of the results of the Aquacrop simulations

	Yield (t/ha)	Water stress (%)	Soil fertility stress (%)	Evaporation (mm)	Transpiration (mm)	Net irrigation requirements (mm)	Gross irrigation requirements (m^3)
AI	3.316	1%	60%	107.5	188.4	759.0	660
NI	3.332	0%	60%	148.9	190.5	341.5	297
OI	3.301	0%	60%	58.3	185.4	160.1	139
NS	8.491	0%	0%	40.9	245	160.1	139

Table 5 - Comparison of the results of Aquacrop simulations in terms of CWP and EWP

	CWP (ET) (kg/m^3)	CWP (kg/m^3)	EWP (birr/m^3)
AI	1.12	0.218	0.74
NI	0.98	0.488	
OI	1.35	1.033	3.94
NS	2.97	2.655	9.54

Discussion

The results of the Aquacrop model, validated based on the comparison of the calculated and modelled yield, showed that the current irrigation schedule (AI simulation) represents a misuse of water, since the same yield can be produced with a net water application of 160.1 mm, as shown in OI simulation, far below the 759.0 mm applied in AI. With refence to the inaccuracy of the software (Greaves and Wang, 2016) discussed in the "Materials and Methods" section, Aquacrop simulations have been considered valid for the scope of the study, since severe crop stress induced by water scarcity is not evident.

Analysing CWP(ET) and its components, evaporation and transpiration, we assess the homogeneity of the transpiration parameter and huge differences regarding evaporation, apart from NS simulation, where maize shows higher transpiration, due to nutrients availability.

Interesting is the situation of the NI simulation, where evaporation was the highest and CWP(ET) the lowest. If field capacity can be considered as the ideal situation for plant growth, it can be concluded that the best situation for plant growth doesn't correspond to the highest result in CWP(ET). AI simulation shows also CWP(ET) higher than NI, mainly due to the fact that most of the water applied percolates to the shallow aquifer, and does not transpires, and it is not considered as water lost as ET.

As expected, CWP(ET) was higher in OI simulation, where an optimal irrigation schedule was generated. The value of 1.35 kg/m³ can be considered as the best CWP(ET) result available with these conditions if water management would be optimized.

Values of actual and potential CWP(ET) calculated with Aquacrop respectively in AI and OI simulations have been compared to data reported in two different reviews of studies of CWP(ET) at global scale (Kijne, 2003, Zwart and Bastianssen, 2004) and with a similar study carried out for maize carried out by Erkossa *et al.* (2011) for Upper Nile basin in Ethiopia, as shown in table 6.

Table 6 - Comparison of actual and potential CWP(ET) calculated through Aquacrop with ranges reported by Kijne (2003), Zwart and Bastianssen (2004) and Erkossa et al. *(2011)*

Actual CWP(ET) (kg/m³)	1.12
Potential CWP(ET) (kg/m³) - OI simulation	1.35
Potential CWP(ET) (kg/m³) - NS simulation	2.97
Potential CWP(ET) with fertilization (Erkossa *et al.*, 2011) (kg/m³)	2.6
Range of CWP(ET) (Kijne, 2003) (kg/m³)	1.2 – 2.3
Range of CWP(ET) (Zwart and Bastianssen, 2004) (kg/m³)	1.1 – 2.7* (0.22 - 3.99)

*defined as the 5 and 95 percentiles of the entire range

Considering simulations in which no fertilisation improvement was modelled (AI, OI), actual and potential CWP(ET) lie around the lowest in the world. This has partial meaning since in this range are considered more favourable agro-ecological zones and also advanced management practices. However, a substantial increase should be pursued.

Aquacrop results were used to detect possible sources of yield reduction. One of the characteristics, and possibly a limit, of Aquacrop is semi-quantitative approach for the soil fertility parameter (Van Gaelen *et al.*, 2015). Aquacrop doesn't give the opportunity to provide detailed data about fertilization and soil quality; everything is included in the soil fertility parameter that must be estimated as a reduction of biomass produced. We decided to consider soil fertility "poor", that means a stress causing 60% of biomass reduction, and yield results confirmed that our estimation was close to reality.

In particular for AI, of the 61% of biomass reduction only 1% was caused by water stress, while the other 60% was caused by soil fertility stress, that is shared with the other simulations. Therefore, water wasn't a constraint and maize was sufficiently irrigated. This confirms the findings of other studies, in particular to the common behaviour, especially in drylands, to overuse water when it is available for irrigation (Oweis and Hachum, 2006, Kassu *et al.*, 2017), underestimating other causes that limit production.

Thus, both the analysis of CWP and yield calculated on the field and modelled CWP(ET) and yields show that, given the possibility of irrigating maize, the gap yield could be mainly connected by soil fertility stress. Nevertheless, the analysis of different irrigation schedules shows that substantial water saving can be obtained if irrigation schedule is changed. It also should be pointed out that, with actual irrigation schedule, most of the water returns to the aquifer to percolation. However, there is no certainty that water will come back to the artificial aquifer generated by the sand dam and further research on the hydrology of the sand dams is suggested.

Considering the results of the simulations, and their correlation with the field data-based analysis, we strongly suggest further analyses and research-action focused on soil quality assessment and soil fertility management for the pilot study area of May Gobo and similar case studies in Ethiopia, to validate and support an integrated soil-water management strategy.

In addition, the coherence between results of NI, OI and NS simulations with data available in literature, reinforced the assumption of low soil fertility. In this sense, as NS simulation demonstrated, substantial increases in yield and CWP(ET) can be reached if soil fertilization will be improved, almost triplicating CWP(ET). Results, in line with other scholars that deal with the same issue (Erkossa *et al.*, 2011), shows that water harvesting can decisively contribute to the gap yield if conjunctive soil fertilization is applied (Rockström *et al.*, 2003).

In addition, reduced water application will result in economic saving, given the lower need of pumping water to the field, and thus to a higher value of EWP, enhanced by the less water applied. Results showed that EWP could raise from a value of 0.74 birr/m^3 to 3.94 birr/m^3 utilizing the modelled results of the OI simulation, and up to 9.54 birr/m^3 in the NS simulation.

With reference to the discussed results, the following section presents a general overview of possible strategies to increase CWP and EWP. The main literature sources have been selected and discussed for the specific context of Ethiopian arid regions.

Potential strategies to improve CWP and maize yield

CWP and CWP(ET) can be increased by several methods, the majority of which can affect both of them at the same time. All these methods also affect directly or indirectly EWP and in the last part of the section, further methods peculiar to increase it are suggested.

The only method to increase CWP without affecting CWP(ET) is the increase in irrigation efficiency to reduce the total water applied, in particular to reduce runoff and percolation losses. This water is considered in the calculation of CWP as calculated in this research, while doesn't sum up in the denominator for the calculation of CWP(ET).

Irrigated farms in Tigray show significant inefficiencies, and there is considerable potential for increasing outputs by improving the efficiency of irrigation (Gebregziabher *et al.*, 2012).

An improvement in irrigation efficiency can be achieved modifying or changing the actual irrigation system. Traditional knowledge is a treasure that should be respected and studied since it has been modelled throughout the centuries to achieve an efficient use of the usually poor resources available. But when relatively new technologies, such as irrigation with pipes, are implemented, relying only on this knowledge may be time consuming, since it usually takes a lot of time to learn to adopt these new technologies efficiently (Gebregziabher *et al.*, 2012).

Considering the major advantages and disadvantages of the various irrigation methods that could be used, the one that should best fit is the furrow irrigation. This irrigation method is characterized by a high volume of water for each irrigation as all the other surface methods. Moreover, the sandy texture of the soil is not the most appropriate; it has, specifically, high infiltration rate and a reduced water holding capacity, and especially in the young stages when root zone is very short, the amount of water applied to reach the whole plot is too high. On the contrary, the small size of plots (the maximum furrow length would be less than 25 m) and the low need of technologies and expertise make this method the one that should bring greater advantages increasing drastically irrigation efficiency, without any significant increase in costs. Most importantly, the adoption of an improved scheme of furrow irrigation would be similar to the method now adopted, and this will probably be better accepted by farmers (Gebremedhin, 2017), that could oppose to the adoption of pressurized systems such as drip or sprinkler irrigation. Particularly interesting is the method called "alternate furrow irrigation" that gave good results in Tigray, decreasing water used and increasing CWP (Gebremedhin, 2017).

The evaporation component is to be lowered to increase both CWP and CWP(ET). It is usually a big issue in drylands, since radiation is high, and the low surface coverage doesn't interfere with it. Possible solutions to reduce it, not always easy to be implemented, aim to modify the microclimate with practices such as mulching, intercropping and agroforestry. Another action to reduce evaporation is to irrigate when radiation is minimum (early in the morning or late in the afternoon).

Practices that increase soil organic content like mulching and organic fertilization improve the structure of the soil increasing its capacity to retain water. This would benefit the crops and of course also CWP and CWP(ET).

As we made for traditional irrigation, a similar assumption can be made about the traditional tillage system. Experience lead farmers to this kind of soil management that optimized resources and tools available. With the introduction of new technologies, the agricultural context changes, and farmers need time to adapt.

Temesgen *et al.* (2007) questioned the Ethiopian traditional tillage system and tried to find an alternative with the development of new tools and testing conservation agriculture practices. Traditionally, in Ethiopia first tillages are made, in rainfed agriculture, early in the *Belg* season, and if rainfall amount is enough, farmers sow a long cycle variety. If the rainfall is not enough, they keep ploughing until the right sowing time. Eventually, they arrive at the start of the main rainy season, the *Kiremt.* Another reason for the several tillages is that the specific plough adopted by Ethiopian farmers (the *Maresha* plough) needs more than one passage to complete the work (Temesgen *et al.*, 2007).

In our case, the introduction of irrigation deeply changed the agriculture context in May Gobo; agricultural management partially chased these modifications (e.g. with the introduction of improved seeds and trees), while tillage practices didn't change.

Since water application now depends on the farmers' will, they can plan a different tillage calendar, possibly reducing tillage operations, adapting new tools and new practices such as conservation tillage. Of course, every change must be tested and approved especially by the main stakeholders, that are the farmers themselves.

For maize in Ethiopia, strip tillage system seems to be a good option that could both increase yields and save water (Rockström *et al.*, 2010), while no tillage is not feasible for smallholder farmers, because of difficulties in maintaining soil cover due to low rainfall and communal grazing and because of high costs of herbicides use (Temesgen *et al.*, 2007). Another suitable option could be the recharge pits use.

Every practice that has to be introduced should be tested in a representative plot, with an analysis of pros and cons. Although we haven't explicitly mentioned it yet, most of these proposed practices belong to Conservation Agriculture. There will never be a definitive practice to be adopted widely, but principles of Conservation Agriculture should be kept in mind especially when dealing with contexts with poor resources and low inputs, such as Sub-Saharan Africa.

Lastly, it's obvious that an increase in yield would lead to a proportional increase in CWP and CWP(ET). Thus, all the practices that aim to fill the gap yield will contribute to this objective.

Since from the results, it came out that water wasn't a limiting factor for production, seed was genetically good, and maize didn't suffer of any particular disease or pest, the problem most likely concerns soil nutrients. The applied DAP fertilization (18N and 46P) should be enough to cover nitrogen and phosphorus removal, even if in an inefficient and unbalanced way. The most realistic hypothesis is that other nutrients are limiting production, as demonstrated by NS simulation, and in accordance with similar Aquacrop simulations discussed by Erkossa *et al.* (2011). It is a characteristic of smallholder agriculture in Sub-Saharan Africa to have soil fertility problems, especially in cases of poor farmers with few or no livestock producing manure, like the case that we analysed. In our case, maize mono-succession probably worsened the situation leading to a degraded soil, unable to sustain high production. Soil analysis should be done to confirm this hypothesis, but it seems clear that attention should be posed on increasing organic content in the soil. Another possible improvement to achieve higher yields is related to an enhanced homogeneity of maize through the thinning practice.

Increasing yield and reducing water applied will have a positive impact also on EWP. The other method to enhance EWP is to increase the net return, that can be achieved with a reduction of costs or an increase in gross income. Costs are already very low and can hardly be reduced; with an improvement in the efficiency of irrigation, diesel cost can be reduced but it wouldn't really have a strong impact. Plus, since to achieve higher yields more inputs will have to be used, it is likely that costs will have to increase. On the other hand, increasing the gross return is a viable strategy and can be achieved increasing yield or switching to cash crops. Suggestions to improve yield have already been discussed, and the intercropped trees that will become productive in the next years represent a good example to increase income. Improvements in trading of production are also needed.

Conclusion

The present work deals with the analysis of the Economic and Crop Water Productivity (EWP and CWP) of an irrigation system through the water coming from a sand dam in the Tigray Region, northern Ethiopia. The analysis has been carried out on a pilot maize plot, irrigated through a shallow well, draining the sand dam aquifer. The analysis was carried out by the calculation of yield, CWP and EWP realised basing on field data collection and a validated Aquacrop model, used for modelling yield, CWP, CWP(ET) – the Crop Water Productivity based on evapotranspiration and EWP.

Results showed that the current irrigation schedule, with net water application of 759.0 mm, represents a misuse of water, since the same yield can be obtained with a net water application of 160.1 mm. Aquacrop simulation showed that current CWP and EWP are not limited by water availability but could be related to low soil fertility. Aquacrop modelling of alternative irrigation schedules showed that CWP and EWP can be increased by applying a different irrigation management, reducing both the number of irrigation interventions and the amount of water applied. Nevertheless, simulated scenarios show that low soil fertility represents the main factor limiting yields, and thus CWP and EWP.

The result of the present work suggests performing a detailed soil quality assessment at field level to identify potential issues connect with soil fertility and suitable soil fertility management strategies.

Agricultural improvements can be obtained if soil fertilization and conservation agriculture will be jointly applied. Suggested improvements should be tested by farmers and the context of the A4labs project fits perfectly to this aim. Focusing on WP lead us to good results, and we advise to continue with this approach to evaluate the system from the water's point of view and to compare future results with the ones obtained in this research.

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