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The influence of shallow groundwater on the actual transpiration flux of irrigated fields using satellite observations

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ABSTRACT

Irrigation requirements are mostly determined by estimating the atmospheric evaporative demand, in combination with precipitation data to estimate the irrigation need per field. However, in case of a high groundwater table, the contribution of capillary rise is often not taken into account. Nevertheless, this flux can contribute significantly to the actual evaporation. Ignoring this flux in irrigation practices might lead to over-irrigation and reduced yields. The significance of the groundwater flux in a furrow irrigated sugarcane plantation in Mozambique with a shallow groundwater table is presented here.

Groundwater levels in a sugarcane plantation in Xinavane in Mozambique were recorded in several fields for a duration of six months. The groundwater recordings, potential evaporation estimates from satellite remote sensing, and field data were combined in the Vegetation-AtMosPhere-Soil water model (VAMPS) that was set up to understand the effect of groundwater contribution on the actual evaporation of a sugarcane field. With the hydrological field representations set up, we analyzed whether the current furrow irrigation requirement in the plantation, of 1350 mm/year for furrow irrigation, is efficient.

The results show that groundwater contribution to the transpiration flux reduces the need for irrigation in the study area. As such, we conclude that the current irrigation requirement is leading to over-irrigation. The incorporation of the groundwater contribution is needed to provide adequate estimations for irrigation. A reduction in irrigation for these fields will lead to a higher water productivity in the study area.

Keywords: irrigation, field water balance, shallow groundwater, evaporation

1. INTRODUCTION

In many agricultural lands groundwater is shallow, either occurring naturally or resulting from poor subsurface drainage in irrigation and drainage systems.[1–4] Shallow groundwater poses both a threat, as well as an opportunity to irrigation.[5] To clarify, the groundwater level should balance between optimizing the use of groundwater flux and keeping the groundwater level low enough to prevent secondary negative effects resulting from deficit aeration in the root zone. Additionally, capillary rise as a result of shallow groundwater can also pose secondary salinization which should be prevented.[5] The opportunity of shallow groundwater to irrigation arises in case of adequate groundwater management. In this case irrigation depths and/ or frequency can be decreased, which will consequently lead to an improved water productivity.

With current irrigation advice methodologies, the groundwater flux is often not taken into account, because of the absence of simple methodologies to estimate the groundwater contribution to transpiration on a plot scale.[6] Conventional methodologies to estimate irrigation depth is often assisted by computing crop water demand with the help of meteorological based transpiration estimates.[7] With the arrival of satellites we are able to estimate irrigation need spatially with evaporation algorithms. However, in case of stress linked to water-logging or

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salinization, irrigation advice will falsely prescribe more irrigation is needed, as transpiration in these cases is detected below potential transpiration.

In order to improve understanding of the observed evaporation with satellite remote sensing and add value to irrigation decision making support, satellite evaporation estimates would benefit from a link to groundwater estimates to understand the transpiration flux better and improve irrigation prescriptions. In irrigated areas where groundwater is shallow, the evaporation estimates could be linked to groundwater measurements in a unsaturated root-zone model. In such a model the effect of shallow groundwater to the transpiration could be better understood, consequently adjust irrigation depth and/ or frequency accordingly.

In this research an example from the field is examined where shallow groundwater is often present and irrigation is applied. The area of interest is a large sugarcane plantation in Xinavane, southern Mozambique, located along the Incomati river bank. Here, shallow groundwater occurs naturally, but is also human-induced due to bad subsurface drainage. Currently, however, the groundwater flux is not taken into account in the irrigation scheduling. Therefore, in this experiment we aim to estimate the influence of the shallow groundwater flux in specific furrow-irrigated areas in the plantation to transpiration. This, in order to advise the agricultural department on how to improve the water productivity.

2. METHODOLOGY

2.1 Study area and field measurements

Within the analysis we focus on several fields within a large sugarcane plantation in Xinavane, Mozambique, see Figure 1. The plantation contains a total of approximately 18.000 hectares of irrigated sugarcane and is located along the banks of the Lower Incomati. The irrigation is sustained by the flow of the Incomati and to sustain all stakeholders with water throughout the year, the flow is regulated by a dam upstream of the plantation, the Corumana dam. Since 2016 southern Mozambique faces a drought, and the Corumana dam has not been filling up to capacity needed to sustain demand in the dry season.

The majority of the plantation is assumed to require irrigation to sustain sugarcane crop growth in the semi-arid conditions. Average yearly potential evaporation rates lie around 1600 mm/ year (Meteorological data plantation). The irrigation interval is approximately 10-12 days, and the net irrigation application depth aimed by the agricultural department is approximately 1,350 mm/year. The average precipitation in the area since 2016 is approximately 590 mm/year (Meteorological data plantation).

It is observed that low fields with a shallow groundwater table perform less good than areas with a higher elevation in the study area (Agricultural department of Xinavane, personal communication, 31 November 2018). For the analysis in this paper we focus on two adjacent fields: XNE21 and XND21. While the fields are located next to each other, XNE21 performs significantly better in terms of yield. Looking at harvest data since 2011 until now in Fig. 2, a number of differences between the fields can be observed. The yield of XNE21 is increasing over time, with relatively lower yields in the last two years, 2017 and 2018. XND21 was replanted in 2010 and 2017, after replanting in 2010 the yield was high, but decreased soon after. Replanting in 2017 did not effect the yield positively, as the yield in 2018 was only 70 tonne cane per hectare [TCH].

The fields have a similar growing season and a ratoon* above four years: XND21 is harvested in June and XNE21 in August. However, the mean elevation and soil profile is different. See Table 1 for more characteristics of the two fields under study. As can be observed from Fig. 2, especially in the last years, the yield in field XND21 deteriorated. A phenomena observed frequently in other furrow-irrigated areas in the plantation (Agricultural department of Xinavane, personal communication, 31 November 2018).

*sugarcane is often grown as a ratoon crop. Which means the sugarcane is cut, but the roots remains intact. After harvest new shoots start to arise from the old rooting system, producing sugarcane for a new season.

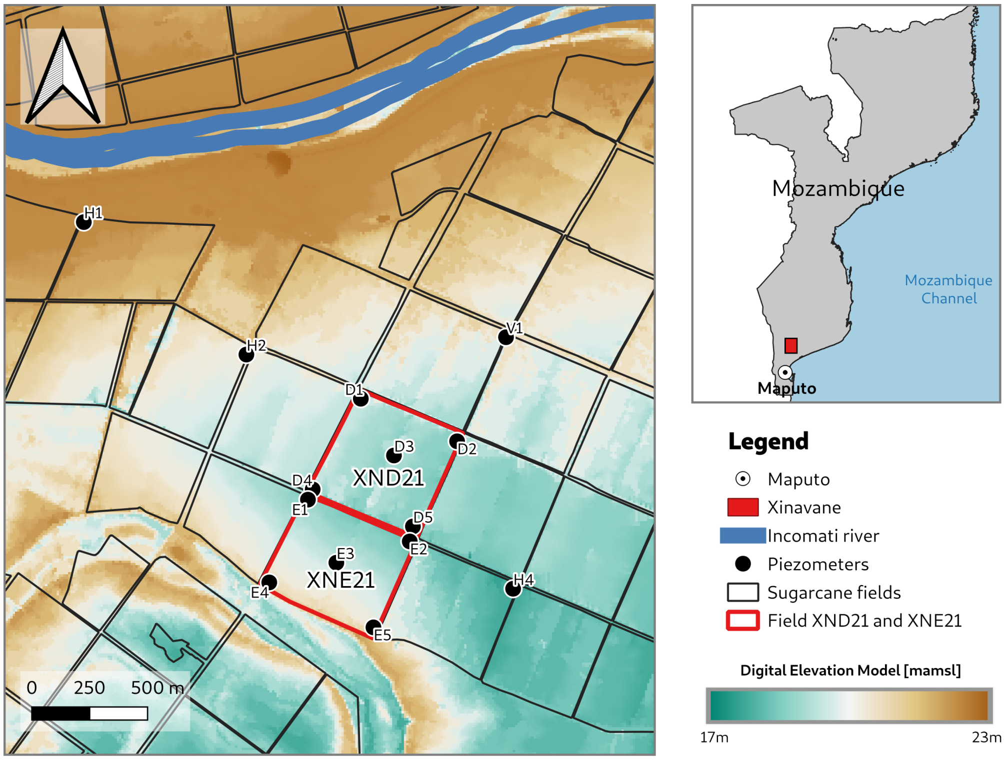


Figure 1: The study area (Xinavane) is located in Southern Mozambique, nearly 200 kilometres north of Maputo. The underlying Digital Elevation Model visualizes the topology. The points indicate the location of the different piezometers that were recorded on a weekly basis.

2.2 Data description and workflow

Data of all different components of the water balance were collected or derived for both fields, including groundwater level and quality data, irrigation data, soil evaporation, and transpiration. The piezometers in Figure 1 were checked every week from the 26th of November 2018 until June 2019. Groundwater levels and Electrical Conductivity (EC, microS/cm) values of the groundwater were recorded and documented. The groundwater levels were converted to hydraulic head by choosing a reference of the soil profile at 2 meters depth, see Fig. 2.

The irrigation policy in both fields is the same, the agricultural department aims to apply 1350mm/year, but a clear record of irrigation depth is not present. Therefore we impose an irrigation time-series based on the irrigation requirement and frequency set by the agricultural department, as mentioned in section 2.1 Study area and field measurements.

The plantation has a meteorological station located near the study site, which records short wave incoming solar radiation (MJ/hr), temperature (^oC), relative humidity (%), rainfall (mm/hr), and wind speed (m/s). The air temperature and shortwave incoming radiation data of this station were used in combination with Sentinel-2 satellite data and MODIS LST and Albedo products to calculate spatial evaporation estimates[8] using a Priestley and Taylor formulation.[9]

Additionally, to derive the potential soil evaporation and transpiration flux, underlying principles of the Aquacrop model were used.[10] The FAO crop model, Aquacrop, simulates the crop growth as a function of water availability and uses a crop growth module to simulate the development of the canopy and canopy cover to differentiate between soil evaporation and transpiration. The principles behind the crop growth model in Aquacrop were used in this research to simulate transpiration and soil evaporation adequately.[11] In the Fig. 3 the workflow of the calculations are displayed. The eventual crop factors [Ktc] were retrieved with the help of NDVI.[8] The soil factor [Ksc] was set at 0.3.[12]

Table 1: Overview of selected field characteristics of fields XNE21 and XND21. The σ sign stands for the standard deviation of the sugarcane yield.

	XNE21	XND21
Average yield [TCH] 2002-2018	97 (σ 20)	78 (σ 28)
Last two harvest dates	24 September 2017 8 August 2018	19 November 2016 2 June 2018
Ratoon ['18-'19]	13	5
Soil profile [2m]	[0 - 0.5m] Sandy clay [0.5 - 1.5m] Sand	[0 - 0.25m] Sandy clay loam [0.25 - 0.75m] Sandy clay [0.75 - 1.25m] Sand [1.25 - 2m] Sandy clay
Average groundwater level [cm]	128	75
Field size [ha]	24	25
Average EC groundwater [microS/cm]	590	510

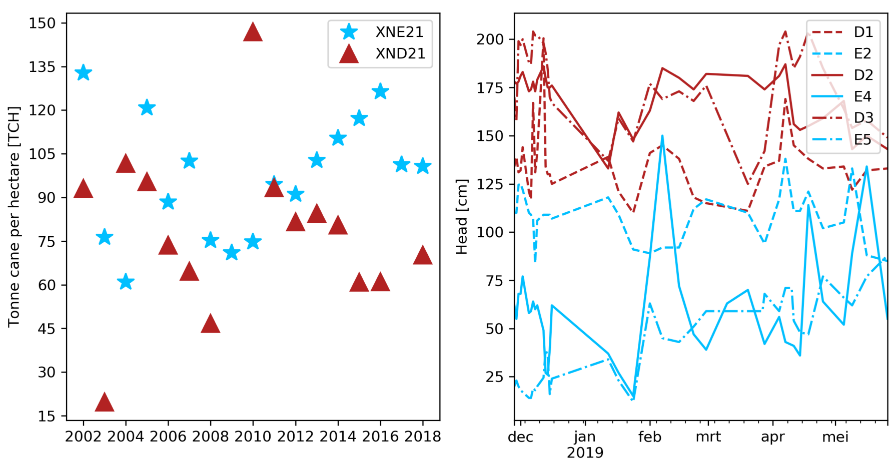


Figure 2: Left panel: yield of the fields XNE21 and XND21. XNE21 performs significantly better than field XND21. Note that in 2009 and 2017 there is no yield data for XND21, because the field was replanted in that year. The right panel shows the hydraulic head [cm] recorded in different piezometer placed in the fields. Note that the groundwaterlevels in field XND21, D1-D3, are confined by a shallow clay layer at approximately 75 centimeters depth.

2.3 Sugar cane root-water uptake model

To understand the plant-water interaction in the root zone, a one-dimensional solution model that combines an solution of the unsaturated zone water dynamics with water uptake stress functions was set up [13,14, VAMPS]. VAMPS' main module is the module that calculates the unsaturated flow of water through the soil by solving Richard's equation, and is, therefore, a very useful tool to analyze the effect of different different groundwater and irrigation scenarios on sugarcane transpiration.

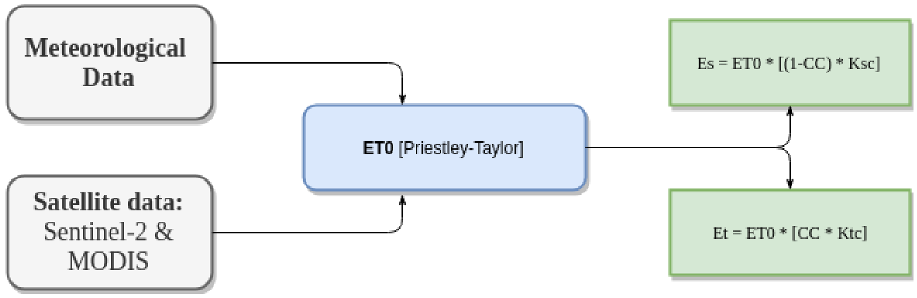


Figure 3: Atmospherically corrected Sentinel 2a, MODIS LST and Albedo products, and meteorological data have been used to construct potential evaporation estimates for the study area. Within the evaporation framework the canopy cover [CC] is used to derive between potential soil evaporation and transpiration.

To run the model, data on potential evaporation, groundwater level or head, precipitation, rooting depth, and information on the soil profile is required. The parameterization within VAMPS was done by adjusting the stress response function[15] to sugarcane specific parameters [cm] hlim1 = -15, hlim2u = -30.0, hlim2l = -30.0, hlim3h = -345.0, hlim3l = -600.0, hlim3 = -600.0, hlim4 = -8000.0.[5] Additionally, for both fields the rootzone was set at 60 centimeters below surface, because 85 percent of the root biomass can be found in that depth range.[16] Information on soil profile was constructed while installing piezometers, see Table 1 for the chosen profiles.

It should be mentioned that some piezometers were drilled in a layer under pressure, therefore the heads at these sites were set at the border of the confining layer Fig. 2 for the modelling procedure with VAMPS. VAMPS was parametrized and simulated for field XNE21 and XND21.

3. RESULTS AND DISCUSSION

Figure 4 displays soil moisture simulation results at different depths in the first 100 centimeters of the soil profile in XND21. The first 50 centimeters responds visibly to incoming rainfall and irrigation fluxes from the top of the profile. These fluxes infiltrate into the profile and are then extracted by the roots to transpire. At high irrigation and precipitation depths the first 50 centimeters of the profile quickly reaches maximum water holding capacity. At 60 centimeters, which is the end of the root zone, the layer is saturated throughout the simulated period. From 25 centimeter until 75 centimeters below the surface there is a sandy clay layer, with a porosity of 0.42. At 75 centimeter depth a sandy layer starts, therefore a drop in soil moisture is visible at 100 centimeter in Figure 4. As the sandy layer is confined by the overlying clay layer, the groundwater is held at 75 centimeters below the surface. The dotted grey line in Figure 4 indicates the hydraulic head of this confining layer, at 125 centimeter, to be read from the right axis. At the end of April the dry-off of sugarcane started, which means irrigation is turned off. Therefore no irrigation is visible during this period, and no rainfall was recorded.

The simulated situation illustrated in Figure 5 represents a different situation. Here, a field with a more sandy profile and fluctuating groundwater table results in a more fluctuating profile. The first 50 centimeters of the profile contains a sandy clayey soil, most activity is happening in this layer due to the presence of the root-zone. After each rainfall event, the simulation shows there is insignificant drainage to layers below the first 50 centimeter (brown line in Figure 5). Below this layer a sandy soil shows a steep drop in soil moisture due to a different soil texture. The porosity of the sandy soil is set at 0.395.

To continue, the incoming irrigation and precipitation fluxes are held and used within the first 50 centimeter of the profile. Additionally, as one can see from Figure 5, the soil moisture level in the sandy layer increases with depth. Towards the groundwater level the layers increasingly saturate: at 100 centimeter below the surface the sandy layer is saturated. The groundwater level fluctuates over the simulated period between 180 centimeter (head is 20 centimeter) and 120 centimeter (head is 80 centimeter).

By observing the evolution of the soil water content over time in the two fields under study, the difference between the root zone storage capacities is visible. In Figure 5 the soil water content in the first sixty centimeters

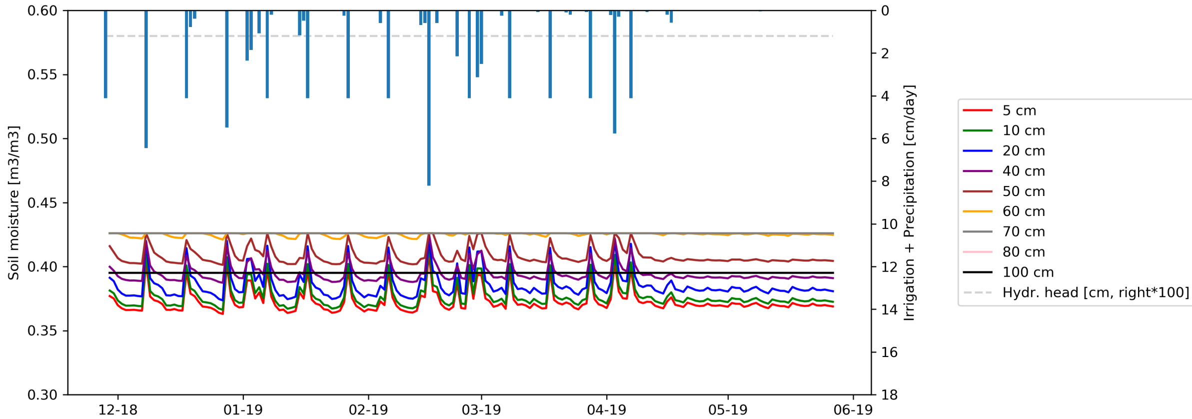


Figure 4: Simulation of the soil moisture status in field XND21 (poor field) under irrigation. The colored lines indicate the soil moisture fluctuation over time at different depths in centimeter below the surface. The dotted grey line in Figure 4 indicates the hydraulic head of this confining layer, at 125 centimeter, to be read from the right axis. The blue hanging bars represent the incoming irrigation and/or precipitation flux [cm/day].

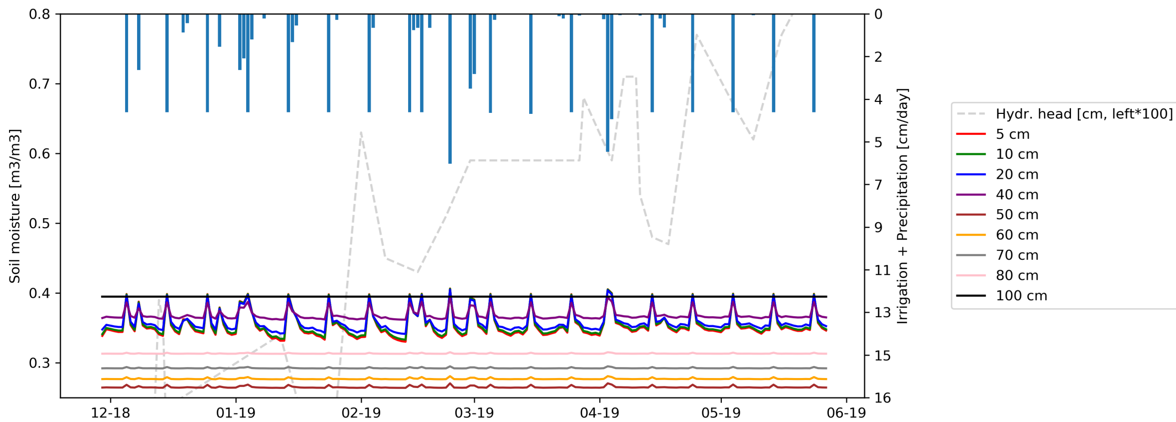


Figure 5: Simulation of the soil moisture status in field XNE21 (good field) under irrigation. The colored lines indicate the soil moisture fluctuation over time at different depths in centimeter below the surface. The dotted grey line indicates the hydraulic head. The head can be read from the left axis when multiplied by a hundred, resulting in the head in centimeters. The blue hanging bars represent the incoming irrigation and/or precipitation flux [cm/day].

is compared. The root zone water content of the poor performing field XND21 is higher than the average root zone water content of the better performing field XNE21. Moreover, the status of the root zone of field XND21 is continuously near-saturated. Potential effects following from poor drainage of the root-zone, in combination with high evaporation rates like in Xinavane, are accumulation of salts in the root-zone and poor aeration.[17,18] These effects can consequently lead to salinization and/or sodification of the soil, which can cause an inability of the roots to take up water and nutrients and can lead to severe crop losses.[19]

Figure 6 shows NDVI timeseries and soil water content for field XND21 and XNE21. In the average NDVI value it can be observed that field XND21 is under significantly more stress than the neighboring field XNE21.

However, the stress observed in XND21 does not result from water-deficit, but the field observations and simulations point out to stress linked to excess water in the root-zone, or secondary effects resulting from waterlogging.

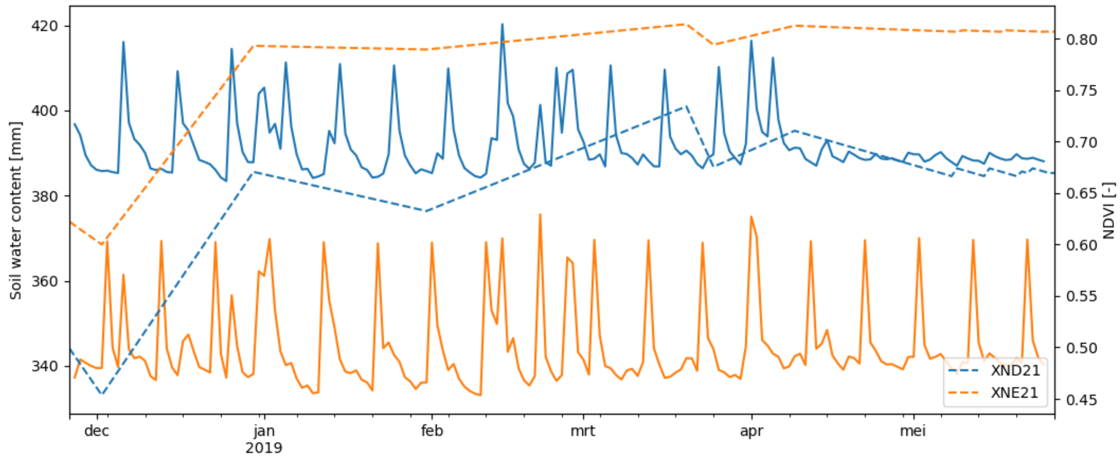


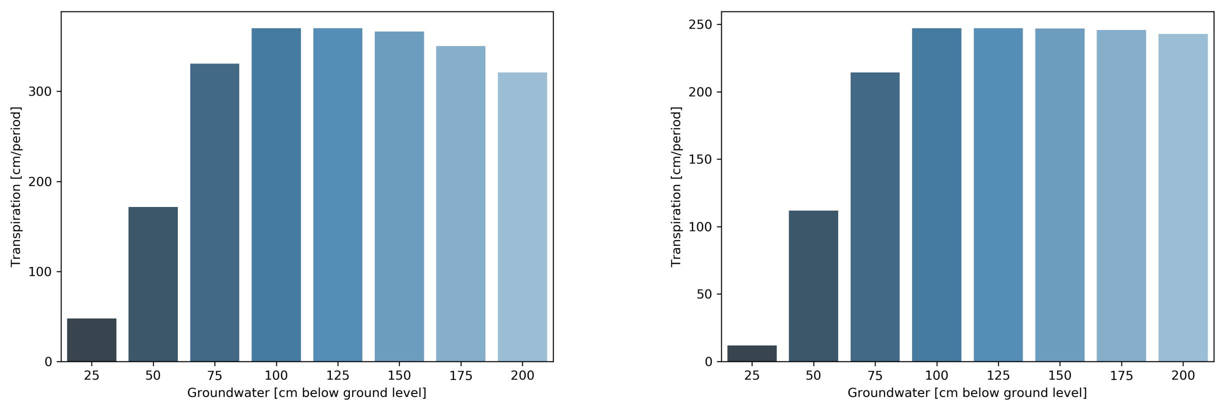
Figure 6: A comparison between the soil water content in the first sixty centimeters and NDVI in XND21 (poor performing) and XNE21 (well performing). The blue lines correspond to field XND21, the orange lines represents XNE21. The dotted line gives an evolution of the NDVI over time, where the lines represent the soil water content. The soil water content in the top sixty centimeters is consistently higher in the poor performing XND21.

In the methodology section Table 1 indicated the Electrical Conductivity of the groundwater is on average 590 and 510 microS/cm, for field XNE21 and XND21 respectively. Which suggests the enrichment of salts are low in the groundwater[20] and, therefore, the groundwater can be valued as a source of irrigation, rather than continuing irrigation without accounting for a groundwater flux. Considering the shallow groundwater table present in different parts of the plantation we assess the effect of different shallow groundwater scenarios to the transpiration in the different plots.

The outcome of the simulations considering different groundwater scenarios are visualized in Figure 7a and 7b. In all these groundwater scenarios irrigation is completely halted, in order to observe what happens to the transpiration of sugarcane. The simulation period for XNE21 is from the 24th of September 2017 end of May 2019 (612 days). Potential transpiration during this period was 248cm. The simulation of field XND21 starts at the 19th of November 2016 until the end of May 2019 (921 days). Potential transpiration during this period was 371cm.

From Figure 7a it is evident that a saturated root-zone has detrimental effect on the crop growth of the sugarcane. If groundwater levels throughout the season are at 25, 50, and 75 centimeters below ground level, transpiration is affected negatively. The root zone is in the first 60 centimeters, and an increasing transpiration can be observed in Figure 7a when groundwater is below the root zone. After the groundwater reaches a level of 150 centimeters the contribution of groundwater to replenish the soil moisture is increasingly insufficient to meet transpiration demands, hence a decline in transpiration is visible with increasing groundwater depth.

In Figure 7b the transpiration response to groundwater levels in field XNE21 shows a similar response as in field XND21. In the scenarios where groundwater levels are at 25, 50, and 75 centimeter below the surface, transpiration is lower than the potential and faces stress. After the groundwater level reaches 175 centimeter a small decrease in transpiration is visible. Looking at the soil water fluxes beneath the root-zone the gradient between the root-zone and underlying layers is maintained until a groundwater level of 200 centimeter. Meaning that there is a constant flux from below the root-zone to replenish the root-zone in XNE21. Whereas in XND21, the gradient between the flux of the root-zone and underlying layers diminish after 150 centimeters. Meaning



(a) Poor field (XND21) (b) Good field (XNE21)

Figure 7: In figure (a) and (b) the effect of different groundwater scenarios to transpiration are displayed.

less water is drawn to the root-zone through capillary rise. The difference can be explained by the more complex and stratified soil profile in XND21, which hampers groundwater moving freely through the profile, as compared to XNE21. In XNE21 the sandy uniform layer underneath the root-zone can transport groundwater from below without blockages due to additional clay layers.

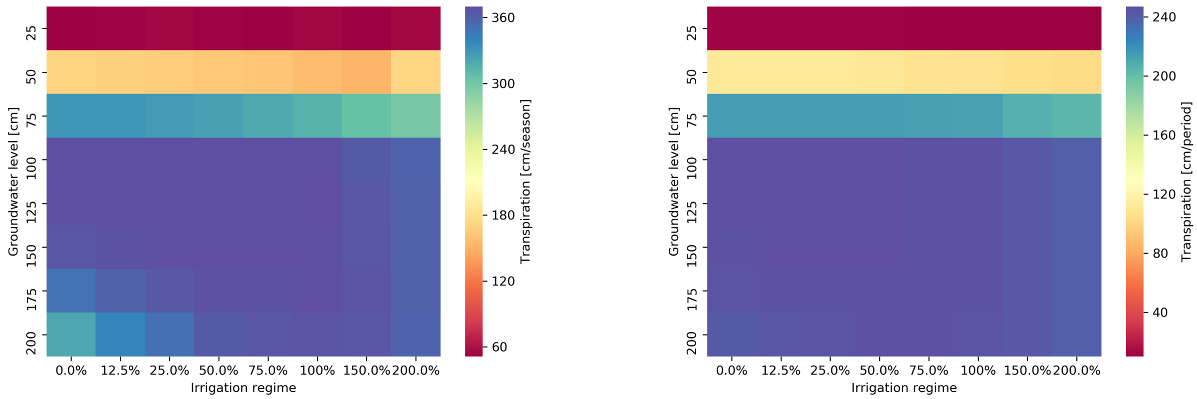
The section 2 explains that the plantation-wide irrigation strategy for furrow irrigation in the plantation is to irrigate every 10-12 days, and reach a reach a net irrigation depth of 1350mm/year. In Figure 8a and 8b we assess a combination of different irrigation and groundwater level scenarios for the two different fields. The current irrigation regime is visualized in the 100% irrigation column. As noted earlier and also visible in Figure 8a and 8b, in all irrigation scenarios, a groundwater level in the root-zone will result in an undesirable transpiration flux. However, when the groundwater level is below the root-zone, and no or little irrigation is applied, transpiration is still sustained by groundwater until a depth of 125 cm in Figure 8a. For field XNE21 the moment transpiration is affected significantly by a decreasing groundwater depth is postponed. This, due to the less complex soil profile, as explained in the previous paragraph.

From Figure 8a and 8b it is evident that under current irrigation practices the same transpiration rates are sustained when no irrigation is applied, if groundwater levels are around 100-125 centimeter. The irrigation depth and frequencies can be adjusted in areas where groundwater is below 125 centimeters. And the irrigation can be postponed if groundwater is above 125 centimeters. Note that the groundwater is presumably recharged by irrigation, hence postponing or cancelling irrigation will lower the groundwater level. Therefore, it is of importance to measure the groundwater level frequently, in order to balance between optimizing the use of groundwater through capillary rise and keeping the groundwater low enough to prevent water-logging and accumulating salts in the root-zone.

4. CONCLUSION

In this research we aim to combine satellite data with groundwater data in a unsaturated zone model to understand the influence of groundwater to the sugarcane transpiration flux. The study area lies in a sugarcane plantation in southern Mozambique, where current irrigation decision making does not take into account the effect of shallow groundwater to the transpiration of sugarcane. In order to make an attempt to incorporate all relevant fluxes, the focus on this research lies on two fields. The adjacent fields differ significantly in performance. We asses for each example the contribution of groundwater to transpiration and the need for irrigation in different groundwater and irrigation scenarios.

Simulations showed the root-zone water content of the poor performing field was consistently higher than the good performing field. In the analysis we demonstrated that an extreme shallow groundwater table, within the root-zone, has detrimental effect on the growth of sugarcane. The irrigation applied in the study area can be



(a) Poor field (b) Good field

Figure 8: In figure (a) and (b) the effect of different groundwater scenarios and irrigation regimes to the transpiration are displayed. The simulation period for XNE21 is from the first of August 2018 until the end of May 2019. The simulation of field XND21 starts at the 2nd of June 2018 until it was harvested at the end of May 2019.

reduced and can lead to a higher water productivity. The analysis shows that if groundwater levels are between the end of the root-zone and 125 centimeters depth, irrigation can be cancelled. Presence of shallow groundwater fluxes should be taken into account in irrigation systems to prevent over-irrigation and water-logging.

This study exemplifies the importance of integrating field measurements with satellite remote sensing in assisting irrigation in wetlands or poorly drained irrigation schemes. Understanding the groundwater flux to transpiration is vital to prevent tenacious problems as salinity and sodicity of the soil. Further efforts to assist irrigation with the help of satellite remote sensing should take into account other effects than water deficit related stress, in order to signal issues related to over-irrigation and water-logging.

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