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Evaluation of Crop Water Use and Rice Yield Using Remote Sensing and AquaCrop Model for Three Irrigation Schemes in Sri Lanka

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Civilingenjörsprogrammet i miljö- och vattenteknik

Abstract

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With a changing climate and an increased competition over water resources for agricultural irrigation, the need to improve crop water productivity using time and cost-efficient methodologies have become critically important. The Malwathu Oya river basin in Sri Lanka is struggling with water scarcity, which threatens food security and the income of farmers. In this study, freely available remote sensed land- and water productivity data from FAO's WaPOR database was evaluated. The evaluation consisted of a comparison of the WaPOR data and primary collected field data using the crop water model, AquaCrop, for three irrigation schemes in the Malwathu Oya river basin. Additionally, the spatio-temporal variability in crop water use within and across these three irrigation schemes was assessed using indicators derived from the WaPOR portal. The evaluation was conducted for the main cultivation season, called Maha, between 2010 and 2021.

The WaPOR and AquaCrop actual evapotranspiration (ET_a) values were found to be in relatively good agreement (312–537 and 400–465 mm respectively). WaPOR yield values (2.5–2.9 ton/ha) were however lower compared to the AquaCrop simulated yield values and historical yield data (4.6–5.7 and 4.4–5.6 ton/ha respectively). Difference in calculation methodology, possible sources of error in WaPOR conversion calculations and limitations in accuracy caused by cloud coverage when collecting satellite data could be explanations for this. Prior knowledge and accurate allocation of the crop type and parameters used in conversion calculations in WaPOR is therefore of significant influence. From the spatio-temporal variation assessment with WaPOR indicators, a fair uniformity of the water distribution within the irrigation schemes was shown (CV 11–19 %). The beneficial water use (BWU) in the irrigation schemes showed lower values (50–90 % allocated to T) for years when the available water amount was higher, which could be explained by the higher rate of water lost through soil evaporation. Crop water productivity (CWP) values showed higher values (about 0.70 kgDM/m^3) when the available water amount was higher, indicating that yield production is sensitive to water-scarce environments. Applying a yield boundary function, representing the best attainable yield in relation to water resource, showed that there is potential to achieve the same yield with less amount of water. There are thus possibilities for improved water productivity in the three irrigation schemes investigated. For future research it is recommended to perform a sensitivity analysis for WaPOR and ground truth with yield data to obtain a better understanding of potential limitations. To obtain more precise site descriptions it is also recommended to ground truth AquaCrop with yield and soil data.

Keywords: WaPOR, remote sensing, evapotranspiration, crop water productivity, irrigation scheme, AquaCrop, Malwathu Oya, Sri Lanka, paddy rice, humid tropical climate

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Referat

Utvärdering av vattenanvändning i risodling med hjälp av fjärranalys och AquaCrop modell för tre bevattningssystem i Sri Lanka
Veronika Widengren

Med klimatförändringar och en ökad konkurrens om vattenresurser inom jordbruksbevattning har behovet av ökad vattenproduktivitet med hjälp av tids- och kostnadseffektiva metoder blivit kritiskt viktigt. Malwathu Oyas avrinningsområde i Sri Lanka kämpar med vattenbrist, som hotar bönders inkomst och livsmedelssäkerheten. I denna studie utvärderades fritt tillgängliga fjärranalyserad mark- och vattenproduktivitetsdata från FAO:s WaPOR-databas. Utvärderingen bestod av en jämförelse mellan WaPOR-data och insamlade fältdata som användes i AquaCrop-modellen för tre bevattningssystem i Malwathu Oyas avrinningsområde. Dessutom utvärderades rums- och tidsvariationer i grödans vattenanvändning inom och över dessa tre bevattningssystem med hjälp av indikatorer härledda från WaPOR-portalen Utvärderingen genomfördes för den huvudsakliga odlingssäsongen, Maha, mellan 2010 och 2021.

WaPOR- och AquaCrop ET_a-värden överensstämde relativt väl (312–537 respektive 400–465 mm). WaPOR-skördevärden (2.5–2.9 ton/ha) var däremot lägre jämfört med AquaCrop simulerade skördevärden och historiska skördedata (4.6–5.7 respektive 4.4–5.6 ton/ha). Skillnad i beräkningsmetodik, möjliga felkällor i konverteringsberäkningar i WaPOR samt begränsningar i tillförlitlighet till följd av molntäckning vid insamling av satellitdata, kan vara förklaringar till detta. Kunskaper och noggrann allokering av gröda och parametrar som används vid konverteringsberäkningar i WaPOR är därför av stor betydelse. Från bedömningen av rums- och tidsvariationer visades en relativt enhetlig vattenfördelning inom bevattningssystemen (CV 11–19 %). Den fördelaktiga vattenanvändningen (BWU) i bevattningssystemen visade på mönster av lägre värden (50–90 % tilldelad T) när den tillgängliga vattenmängden var högre, förklarat av en högre andel vatten förlorad via evaporation från marken. Vattenproduktiviteten (CWP) visade på mönster av högre värden (cirka 0.70 $kgDM/m^3$) när den tillgängliga vattenmängden var högre, förklarat av skördeproduktionens känslighet för miljöer med vattenbrist. Från produktionsfunktionen, som representerade bästa möjliga skörd i förhållande till vattenresurs, kunde slutsatsen dras att det finns potential att uppnå samma skörd med mindre mängd vatten. Det finns således möjligheter till förbättrad vattenproduktivitet i de tre undersökta bevattningssystemen. För framtida forskning rekommenderas det dock att utföra en känslighetsanalys för WaPOR, och göra jämförelser med direkt observerade skördedata för att få en ökad förståelse av potentiella begränsningar i databasen. För att erhålla mer precisa miljöbeskrivningar rekommenderas det även att jämföra AquaCrop med direkt observerad skörde- och jorddata.

Nyckelord: WaPOR, fjärranalys, evapotranspiration, vattenproduktivitet, bevattningssystem, AquaCrop, Malwathu Oya, Sri Lanka, ris, fuktigt tropiskt klimat

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Preface

This MSc thesis comprises 30 credits at the Master's Programme in Environmental and Water Engineering at Uppsala University and the Swedish University of Agricultural Sciences, SLU. It contributed to the project KnoWat (Knowing Water better: towards fairer and more sustainable access to natural resources), carried out by the International Water Management Institute, IWMI, in collaboration with national partners such as the Irrigation Department of the Ministry of Mahaweli and the Irrigation Department of Sri Lanka. The KnoWat initiative is funded by the German Federal Ministry of Food and Agriculture, led by FAO (Food and Agriculture Organization of the United Nations).

This MFS is twinned with the MFS "Improved Understanding of Water Balance in the Malwathu Oya River Basin Using SWAT and Remote Sensing". The two MFS are complementary, where this MFS focuses on crop water use on an irrigation scheme level and the other on water balance on a basin level of the Malwathu Oya river basin, Sri Lanka.

I acknowledge financial support by SIDA (Swedish International Development Agency) through an MFS (Minor Field Study) scholarship.

First, I would like to express my gratitude to my subject reviewer Prf. Jennie Barron at the Department of Soil and Environment, Swedish University of Agricultural Sciences, for all your valuable advice and support throughout this project, and for supporting me prior to my travel to Sri Lanka. A big thank you to my supervisor Dr. Karthikeyan Matheswaran at IWMI for always taking time to help and support me throughout my work. I would also like to thank IWMI for giving me the opportunity to come and perform my work in Sri Lanka, and for all the guidance during my stay in the country. I would also like to give a special thanks to Dr. Nirman Shrestha at IWMI for always finding time to support me in the AquaCrop model work.

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Finally, thank you to my friend Alexander Fors for being a supportive and valuable travel and study companion and to my family and friends for being there for me throughout my studies.

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Populärvetenskaplig sammanfattning

På grund av pågående klimatförändringar och en ökande världsbefolkning har vatten blivit en bristvara, speciellt i fattiga delar av världen. Det är därför av betydande vikt att ta vara på jordens vattenresurser. Den största delen av vattenanvändningen idag går till livsmedelsproduktionen, och för att kunna säkra vattentillgången och förse folk med mat, är det därav väsentligt att vattenproduktiviteten, det vill säga producerad skörd per vattenmängd, ökar. För att möjliggöra detta är en utveckling av tids- och kostnadseffektiv teknik av stor vikt. Förenta nationerna (FN) uppmärksammar detta i sina globala mål för hållbar utveckling, och jobbar för att öka den globala vattenproduktiviteten. FAO, som är FN:s organisation för agrikultur har utvecklat en dataportal, WaPOR, som gör det möjligt att fritt kunna tillgå vatten- och landdata uppmätt via fjärranalys. Sri Lanka, som är ett utvecklingsland med en lång historia av bevattningssystem, där mycket av landets odling idag påverkas av vattenbrist till följd av klimatförändringar, är det nödvändigt att kunna utvärdera vattenproduktiviteten på ett effektivt sätt. Omkring 25 procent av landets befolkning arbetar inom jordbrukssektorn, och att ha ett välfungerande bevattningssystem är därav av stor betydelse.

I denna studie undersöktes vattenanvändningen inom livsmedelsproduktionen med hjälp av WaPOR-portalen och fältmätningar använda i en modell, AquaCrop, som kan uppskatta skörd och vattenanvändning. Förhoppningen var att kunna utvärdera WaPOR-portalen och hitta möjliga förbättringar med hjälp av jämförelser med AquaCrop modellen. Studien utfördes i tre bevattningssystem i Malwathu Oyas avrinningsområde i Sri Lanka, beläget i den torra zonen av landet. Studien utfördes under odlingssäsongen Maha (den huvudsakliga odlingssäsongen under året), mellan åren 2010 och 2021. Genom att bedöma evapotranspiration, som är summan av avdunstning från marken och vattenupptag via växter, och även titta på skördenivå i förhållande till evapotranspirationen, kunde inblick i vattenproduktivitet fås.

Studien påvisade liknanden värden för evapotranspiration från WaPOR-portalen och AquaCrop modellen (312–537 och 400–465 mm respektive). Skördevärdena var dock lägre hos WaPOR i jämförelse med AquaCrop modellens värden och uppmätt historiska data (2.5–2.9, 4.6–5.7, 4.4–5.6 ton/ha respektive). Detta kan

förklaras av att WaPOR och AquaCrop använder sig av olika beräkningsmetoder, samt av att felkällor kan förekomma i konverteringsberäkningarna som kan komma att påverka slutvärdet. En annan möjlig förklaring är att molntäckning vid insamling av satellitdata i WaPOR kunde ha kommit att medföra luckor i data, vilket medför begränsningar tillförlitlighet.

Med hjälp av indikatorer, som utvärderade hur jämn vattenupptagning var i områdena, samt hur effektivt vatten tas upp av grödor, kunde inblick fås i hur väl WaPOR producerar data. Resultaten som erhölls överensstämde med förväntade mönster. Med hjälp av en produktionsfunktion, som representerade bästa möjliga skörd i förhållande till vattenresurs, som jämfördes med erhållna WaPOR och AquaCrop värden, kunde slutsatsen dras att det finns potential för en ökad vattenproduktivitet för de undersökta bevattningssystemen i Sri Lanka. För framtida forskning rekommenderas det dock att utföra en känslighetsanalys för WaPOR, och göra jämförelser med direkt observerade skördedata för att få en ökad förståelse av potentiella begränsningar i databasen. För att erhålla mer precisa miljöbeskrivningar rekommenderas det även att jämföra AquaCrop med direkt observerad skörde- och jorddata.

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Abbreviations and Acronyms

AOT	Above ground Over Total biomass ratio [Fraction of 1]
AquaCrop	FAO’s crop water productivity model
BWU	Beneficial Water Use [Fraction of 1]
c_p	Specific heat of dry air [J $kg^{-1}K^{-1}$]
CC	Canopy Cover [%]
CV	Coefficient of Variation
CWP	Crop Water Productivity [$kgDM/m^3$]
e_a	Actual vapour pressure of air [Pa]
e_s	Saturated vapour pressure of air [Pa]
ET	Evapotranspiration [mm]
ET_a	Actual Evapotranspiration [mm]
ETI	Evapotranspiration and Interception [mm]
ETI_a	Actual Evapotranspiration and Interception [mm]
ET_0	Reference Evapotranspiration [mm]
FAO	Food and Agriculture Organisation of the United Nations
fAPAR	Fraction of photosynthetically active radiation absorbed by the vegetation canopy [Fraction of 1]
FC	Soil moisture content at field capacity [%]
G	Soil heat flux [W/m^2]
GIS	Geographic Information System
HI	Harvest index [Fraction of 1]
I	Interception [mm]
IWMI	International Water Management Institute
KnoWat	Knowing Water better: towards fairer and more sustainable access to natural resources (project implemented by FAO)
K_{sat}	Saturated hydraulic conductivity [mm/day]
LAI	Leaf Area Index [Fraction of 1]
LUE	Light Use Efficiency correction factor [Fraction of 1]
$MC_{biomass}$	Moisture content in fresh biomass [Fraction of 1]
MC_{soil}	Moisture content in soil [%]
NDVI	Normalized Difference Vegetation Index [Fraction of 1]
NPP	Net Primary Production [Cg/m^2]
PWP	Soil moisture content at Permanent Wilting Point [%]

r_a	Aerodynamic resistance [s/m]
r_s	Bulk surface resistance [s/m]
R_n	Net radiation [W/m^2]
RS	Remote Sensing
SA	Sensitivity Analysis
SAT	Soil moisture content at saturation [%]
SLU	Swedish university of agricultural sciences
SDG	Sustainable Development Goal
T	Transpiration [mm]
TBP	Total biomass production [kgDM/ha]
WaPOR	Water Productivity through Open access of Remotely sensed derived data (FAO developed database)
λ	Latent heat of evaporation [J/kg]
ρ_a	Air density [kg/m^3]
Δ	Slope of the saturation vapour pressure vs. temperature curve [Pa/K]
γ	Psychrometric constant [Pa/K]

1. Introduction

With a changing climate and an increased competition over water resources between users, water scarcity is increasing and is expected to continue doing so (FAO 2020a; Pörtner et al. 2022). Global food production systems, particularly in the developing countries dominated by smallholder farmers, are especially vulnerable to this problem of water scarcity (FAO n.d.a). This can in turn threaten farmer income, food production and security, functioning ecosystems, and equal water access (FAO 2020a). Irrigation makes up about 70% of the total global freshwater extractions, and there is thus a need to identify ways to save water in existing irrigation systems and, consequently, of importance to increase water productivity, i.e. production per unit of water applied, and promote technology to improve this (Molden et al. 2010; Grafton et al. 2018; Giordano et al. 2021). The United Nations emphasizes this in the Sustainable Development Goal (SDG) indicator 6.4.1., addressing sustainable water withdrawals and supply to help reduce water scarcity (United Nations n.d.).

In Sri Lanka, the irrigation sector plays an important role, and has been impacting the country's culture since ancient times with its rainfed interconnected system of tanks, called tank cascade system (Shah et al. 2013; FAO n.d.c). Today, 36% of the total land area of Sri Lanka is cultivated and 31% of that area is irrigated (FAO n.d.b), which is equal to about 700 000 ha of cultivated irrigated land. The agricultural sector makes about 7.9% of the GDP in the country (FAO n.d.b), and approximately 25% of the country's population works within this sector (World Bank n.d.a). Thus, having a sustainable and well-functioning irrigation system is of great importance for the population of Sri Lanka.

Crop water use is one of the largest sources of water use and a critical component in the hydrological cycle (Morison et al. 2007). By estimating crop water productivity (CWP), insight in crop yield in response to water can be obtained (Steduto et al. 2012). This can be measured by assessing the yield in relation to actual evapotranspiration (ET_a). ET_a is an essential part of the hydrological cycle as it indicates how much of the water that is being absorbed by the plant and thereby contributing to the production of crop yield (Molden et al. 2010; Dhungel & Barber 2018). Hence, by assessing the ET_a, crop water productivity can be evaluated and the potential to close water yield gaps (difference between the actual attainable and the potential yield), can be investigated.

Previous studies measuring ET_a have however often shown to be expensive, time consuming, vary in accuracy and complexity and lack in spatial representation (Dhungel & Barber 2018; Sobrino et al. 2021; Parsinejad et al. 2022). With the use of remote sensing, RS, techniques, these limitations can potentially be overcome. Using RS, time and cost-efficient ET_a measurements can be obtained across large spatio-temporal scales (Dhungel & Barber 2018; Giordano et al. 2021; Sobrino et al. 2021; Parsinejad et al. 2022).

1.1. Aim

This study aims to evaluate the crop water use in three irrigation schemes in the Malwathu Oya River Basin in Sri Lanka, using freely available remote sensed data (RS) from the WaPOR database, and primary collected field data validated using the crop water model AquaCrop. The study was conducted for the Maha cultivation seasons between 2010 to 2021 for paddy rice. It is the first study to contribute to an assessment of WaPOR data accuracy in an Asian monsoon climate.

1.2. Research Questions

- How does the crop water use, and yield estimate from remote sensing-based measurements compare with field and model estimates?
- How does the water use vary spatio-temporally within and across three selected irrigation schemes dominated by rice paddy crop?

The project combined field data collection, farmer survey and modelling with an open-source crop water productivity model, AquaCrop, for comparison with the remote sensed data of the WaPOR database. The activities were carried out under the KnoWat project (FAO n.d.a).

2. Background

2.1. Remote Sensed Data

Remote sensing, RS, is used to collect data from distance by satellite imagery. The geospatial database of WaPOR (Water Productivity through Open access of remotely sensed derived data) (FAO 2020b) developed by the United Nations Food and Agricultural Organization (FAO) provides freely available datasets on land and water productivity indicators collected through remote sensing. These datasets are available at three spatial levels, where level 1 is on a continental level and has a spatial resolution of 250 m, level 2 is on a national level and has a spatial resolution of 100 m and level 3 is on a sub-basin level and has a spatial resolution of 30 m (FAO 2020b). In this study, Level 2 WaPOR data covering the whole of Sri Lanka were used. The temporal resolution of the data in WaPOR is available on a dekadal, monthly or annual scale depending on the type of data. Dekadal refers to a period of 10 days, splitting the month into three parts, where the first two parts of the month are 10 days and the last is the remaining days of the month (FAO 2020b). In this study dekadal and monthly data were used, according to availability.

2.1.1. Evapotranspiration

The actual evapotranspiration, ET_a, is one of the major processes in the water balance and is an essential component of plant growth (Blatchford et al. 2020b; FAO 2020b; Parsinejad et al. 2022). Evapotranspiration is a joint term including the evaporation from the soil, E, and the transpiration that occurs with the release of water from the stomata in the leaves, T. Interception, I, i.e. the evaporation from the surface of the leaves, can also be included, then with the denotation ETI (Allen et al. 1998).

A range of techniques are used to estimate and measure actual evapotranspiration, ranging from conventional field scale measurements using lysimeters, eddy covariance, Bowen ratio system, pan measurement etc. derived from energy balance or crop water balance to spatial measurements using remote sensing (Allen et al. 1998; Abtew & Melesse 2013; Dhungel & Barber 2018; Sobrino et al. 2021).

The Penman-Monteith equation has been one of the most widely used methods for estimating ET_0, the reference evapotranspiration, describing the evapotranspiration from a standardized vegetative surface (Allen et al. 1998). With input from meteorological and crop data collected from ground-based meteorological stations, this equation has become the FAO standard equation for reference- and actual evapotranspiration calculations (Allen et al. 1998; FAO 2020b). To estimate evapotranspiration from conventional ground-based measurements can however often be expensive, time consuming, vary in accuracy and complexity and not be spatially representative enough (Dhungel & Barber 2018; Sobrino et al. 2021; Parsinejad et al. 2022). Remote sensing techniques have overcome these limitations, allowing for large-scale ET_a measurements to obtain spatio-temporal variations of ET_a (Dhungel & Barber 2018; Giordano et al. 2021; Sobrino et al. 2021; Parsinejad et al. 2022).

WaPOR uses the Penman-Monteith (P-M) equation with the input data obtained from using multiple RS datasets and global meteorological data (FAO 2020b). The P-M equation (Equation 1) combines the surface energy balance equation and the aerodynamic equation, two fundamental approaches to estimating the evapotranspiration (FAO 2020b).

$$\lambda \mathrm{ET} = \frac{\Delta(R_n - \mathrm{G}) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad (1)$$

Where λ is the latent heat of evaporation [J kg^{-1}], ET is the evapotranspiration [kg m^{-2}s^{-1}], R_n is the net radiation [W m^{-2}], G is the soil heat flux [W m^{-2}], ρ_a is the air density [kg m^{-3}], c_p is the specific heat of dry air [J kg^{-1}K^{-1}], e_a is the actual vapour pressure of the air [Pa], e_s is the saturated vapour pressure [Pa] which is a function of the air temperature, Δ is the slope of the saturation vapour pressure vs. temperature curve [Pa K^{-1}], γ is the psychrometric constant [Pa K^{-1}], r_a is the aerodynamic resistance [s m^{-1}] and r_s is the bulk surface resistance [s m^{-1}] (FAO 2020b).

The method to calculate E and T separately in WaPOR is made using the ETLook model (Bastiaanssen et al. 2012; FAO 2020b), which solves two parallel P-M equations for E and T respectively, based on fractions of vegetation and bare soil (Blatchford et al. 2019). The ratio of E and T respectively in ET gives insight into the amount of water beneficially used by plants (Sadras 2015). Input data components used for calculating E, T and I are presented in Figure 1 (FAO 2020b).

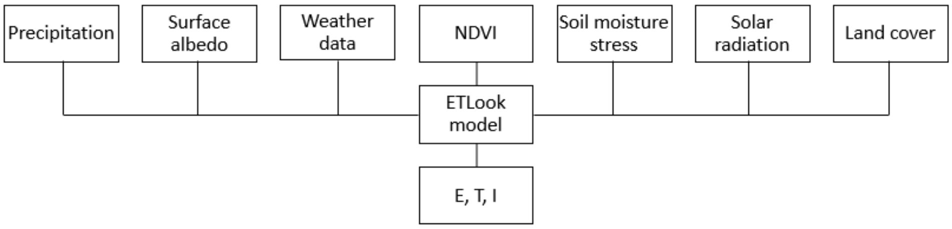

Figure 1 *Input data components affecting E, T and I in the WaPOR database (FAO 2020b).*

Where precipitation is derived from an external data source combining satellite observations, global model, and station measurements. Surface albedo is obtained from the surface albedo intermediate data component. Weather data refers to air temperature, specific humidity, and wind speed and are derived from an external global atmospheric model producing hourly grids, which are then aggregated to an average daily value. Normalized difference vegetation index, NDVI, (photosynthetically active vegetation based on the spectral reflectance of the red and near-infrared wavelengths), is an intermediate data component that also contains information on the quality of the remote sensing observations (FAO 2020b). Soil moisture stress, which indicates the water deficiency in the root zone, is an intermediate data component that uses weather data, NDVI and external land surface temperature, as input data. Solar radiation is also an intermediate data component that requires surface downwelling solar radiation to be calculated. The land cover uses NDVI, phenology and external data such as multispectral satellite imagery and other external datasets to be calculated (FAO 2020b). The data, with their sensors and data products, used to calculate E, T and I from level 2 in WaPOR are presented in Table 1 (FAO 2020b).

Table 1 *Sensors and data products used for input data components at level 2 (FAO 2020b).*

Input Data Component	Sensor	Data Product
Precipitation		CHIRPS v2 CHIRP
Surface albedo	PROBA-V	
Weather data	MERRA/GEOS-5	
NDVI	PROBA-V	
Soil moisture stress	MODIS	MOD11A1, MYD11A1
Solar radiation	MSG	SRTM
Land cover		WaPOR LCC product

In previous research, assessing the accuracy of remotely sensed WaPOR data, has shown to overestimate ETI_a values for dry irrigated areas (Blatchford et al. 2020b). The causes can be due to parameters such as relative soil moisture content, input of quality layers and local advection effects (Blatchford et al. 2020b). Although overestimation can occur, ETI_a values are, according to Blatchford et al., of enough quality to monitor water management. The study was carried out in 13 countries in Africa, for different climatic zones and crop types. There has however not yet been any research assessing the accuracy of WaPOR data in countries with monsoon climate in Asia. This study will be the first to contribute to this.

2.1.2. Crop Water Productivity

Net primary production (NPP), denoting the generation of biomass by photosynthesis, is a fundamental characteristic of an ecosystem (FAO 2020b). The WaPOR database derives NPP from satellite and meteorological data through the ETLook model. Input data required to calculate NPP in WaPOR are daily weather data and solar radiation, dekadal fAPAR data (fraction of photosynthetically active radiation absorbed by the vegetation canopy) and soil moisture stress, as well as light use efficiency, LUE, given from land cover data (FAO 2020b). Total Biomass Production (TBP), expressing the sum of the dry matter (DM) produced during the season, is derived from NPP using a scaling factor (converting gC/m^2 to kgDM/ha). TBP can thereafter be used to derive yields with information on the harvest index (HI), which is describing how much of the biomass production is contributing to the harvestable fraction of a crop (yield) (FAO 2020b).

The Crop water productivity (CWP), expresses the relationship between yield and water consumption, here defined as grain yield per ETI_a. As crop water use is one of the largest sources of water use (Morison et al. 2007), estimating CWP can give valuable insight into yield gaps, and increase the potential to close these gaps (Sadras 2015).

2.2. Crop Water Productivity Model

To address food security and assess crop production response to environment and management, numerous crop models have been developed. However most of them require high detail in the input data that can be hard for users to obtain (Vanuytrecht et al. 2014a; Foster et al. 2017). The freely available AquaCrop model (Raes et al. 2009), developed by the FAO, simulates water-limited crop production under a wide range of environmental- and agronomic conditions and requires a relatively small number of explicit input data (Vanuytrecht et al. 2014a; Foster et al. 2017).

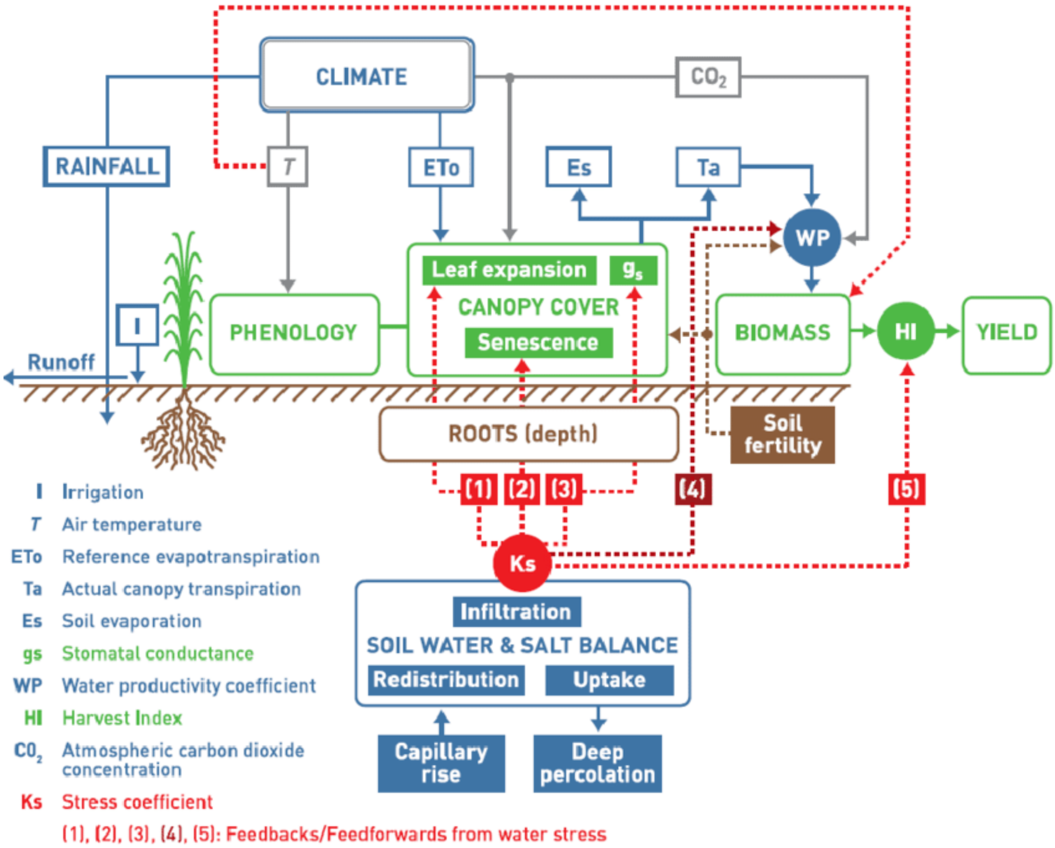

Figure 2 *Flowchart of the AquaCrop model with dotted lines indicating the process affected by water stress (Steduto et al. 2008).*

The mechanism of the AquaCrop model and how water stress (dotted red lines) affect plant development is presented in Figure 2. In the figure, the functional relationships between the different model components are shown. The canopy expansion and senescence, the root deepening of the crop, the stomatal conductance and transpiration, as well as the harvest index are all affected by the water stress in the AquaCrop model (Steduto et al. 2008). The model is dynamic in its approach to crop development and is balanced between accuracy, robustness and simplicity (Hsiao et al. 2009; Shrestha et al. 2013). Calculation processes in the model are based primarily on fundamental and complex biophysical processes to provide a realistic simulation of crop responses to the environment (Vanuytrecht et al. 2014a), and have been tested and applied worldwide to derive irrigation schedules, improve irrigation management, simulate yield response, and improve decision support in crop production (Geerts & Raes 2009; Abedinpour et al. 2012; Shrestha et al. 2013).

In this study, the AquaCrop model was validated with field data, collected specifically to fine-tune the model to the environment of the studied irrigation schemes in the Malwathu Oya river basin in the dry zone of Sri Lanka for the rice crop. To detect how input parameters affected the output value, a sensitivity analysis (SA) was conducted. This was done to detect which of the parameters were more sensitive, and hence impacted the model output sensitivity.

2.3. Spatio-temporal Patterns of Land- and Water Productivity Indicators

Monitoring irrigation scheme crop performance with remote sensing techniques can help compare spatial and temporal crop performance which can lead to a better understanding of the state of the scheme and to introduce remedial measures for e.g., improved water productivity. The crop performance of the scheme can be evaluated using different indicators. Previous studies have assessed indicators related to water, crop production and finances (Molden et al. 1998; Blatchford et al. 2020a; Chukalla et al. 2021). In this study only indicators related to water and crop production have been included.

The land- and water productivity indicators evaluated in this study were uniformity, beneficial water use (BWU) and crop water productivity (CWP). Where uniformity describes the uniformity of the water distribution within the scheme, indicated by the coefficient of variation (CV) of ETI_a. The beneficial water use describes the generation of biomass per water resource and was calculated by the ratio of transpiration (T) over ETI_a. The crop water productivity describes crop yield production per water resource and was calculated by yield over ETI_a (Molden et al. 1998; Blatchford et al. 2020a; Chukalla et al. 2021). These indicators were set based on available data in the WaPOR database (FAO n.d.d), which can be seen in Table 2 together with their temporal resolutions.

Table 2 *Overview of WaPOR level 2 (100 m) data components used to calculate land- and water productivity indicators and their temporal resolution used in this study (FAO 2020b).*

Data Component	**Temporal resolution**
ETI_a	Monthly
T	Dekadal
NPP	Monthly

3. Methods and Materials

This study evaluated the crop water use in three selected irrigation schemes in the Malwathu Oya river basin in Sri Lanka, assessing RS level 2 data (spatial resolution of 100 m) from the WaPOR portal. Dekadal and monthly data were aggregated to seasonal data using QGIS. A cross comparison of the WaPOR data was then made with AquaCrop model outputs (validated with primary collected field data), and historical yield data from the Anuradhapura region (where the field study was conducted) (Department of Census and Statistics n.d.). Additionally, spatio-temporal variability in crop water use were assessed using indicators derived from the WaPOR portal.

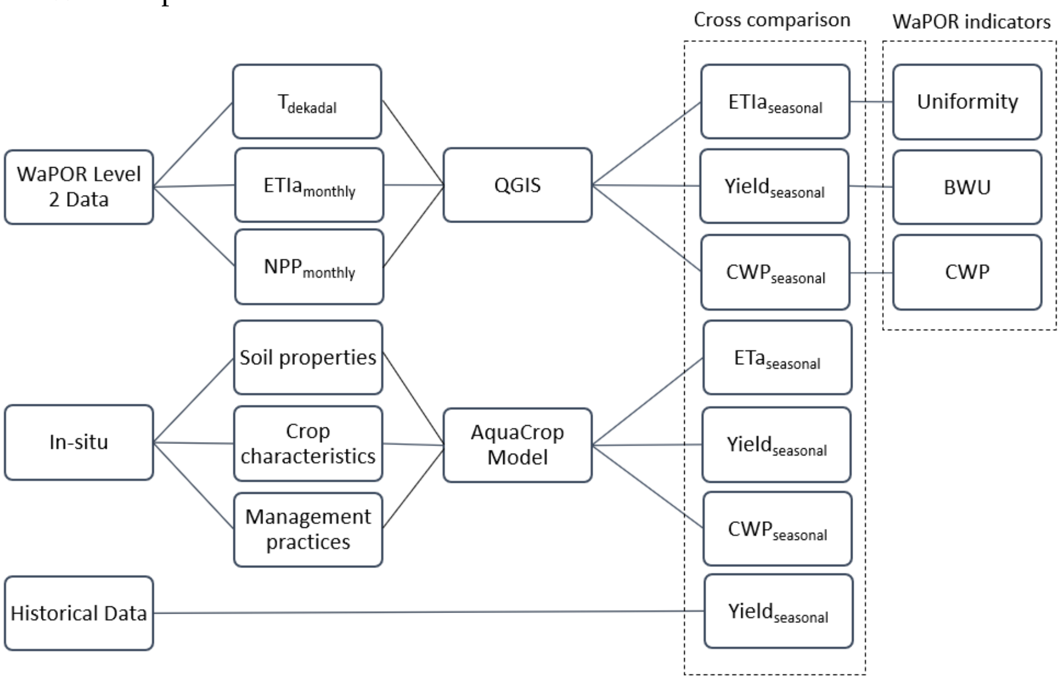

Figure 3 *Flowchart of the work process methodology.*

An overview of the work process methodology illustrated with a flowchart can be seen in Figure 3.

3.1. Site Description

Sri Lanka is a country of 22 million people (World Bank n.d.b). Its climate is characterised as tropical, and has a mean annual rainfall between 900 (southeast and northwest) to 5000 mm (western slopes and central highlands), which originates mainly from monsoonal, convectional and depressional rain (Department of Meteorology n.d.). Maha and Yala are the two monsoon seasons in Sri Lanka. The Maha season (the north-east monsoon) is effective from September to March the following year and the Yala season (the south-west monsoon) is effective from May to August (Department of Census and Statistics n.d.). The mean annual temperatures in the country vary between 16 to 27 °C depending on the altitude. The central southern parts are highlands, with a topography of 300-2500 m, and have the lowest temperatures and the highest amount of rainfall (Department of Meteorology n.d.). Tea is cultivated in these parts and is the major source of import to other countries. In the lowlands, rice, the major crop in Sri Lanka, is grown together with fruits, vegetables and other types of crops (Ministry of Agriculture n.d.).

3.1.1. Malwathu Oya River Basin with Irrigation Schemes

The Malwathu Oya river basin, is the second largest river basin in Sri Lanka and has a catchment area of about 3000 km^2. It is located in the north-west part of the country around the city Anuradhapura, in the dry zone in the lowlands, with a mean annual precipitation rate of less than 1750 mm (Punyawardena 2021). About 15 % of the basin consists of agricultural land (Fors 2022), where paddy rice production is the main source of livelihood. The two cultivation seasons, Maha and Yala, corresponds to the two main monsoon seasons in the country. In this study the duration of the Maha cultivation season (the main cultivation season) was determined by the field survey conducted, (see section 3.2.1. Table 7), starting from the beginning of October and lasting to the end of February. The river basin is one of Sri Lanka's major agricultural areas and the Malwathu river is one of the most important irrigation sources in the North Central Province (FAO n.d.c). The irrigation systems of the river are legacy of the Sri Lankan ancient hydraulic revolution, with hundreds of interconnected rainwater tanks and reservoirs, and with a range of different water users still today (FAO n.d.c). Due to climate change, the basin is however prone to water scarcity, and has limited available adequate data and information for proper planning and management of water resources (FAO n.d.c).

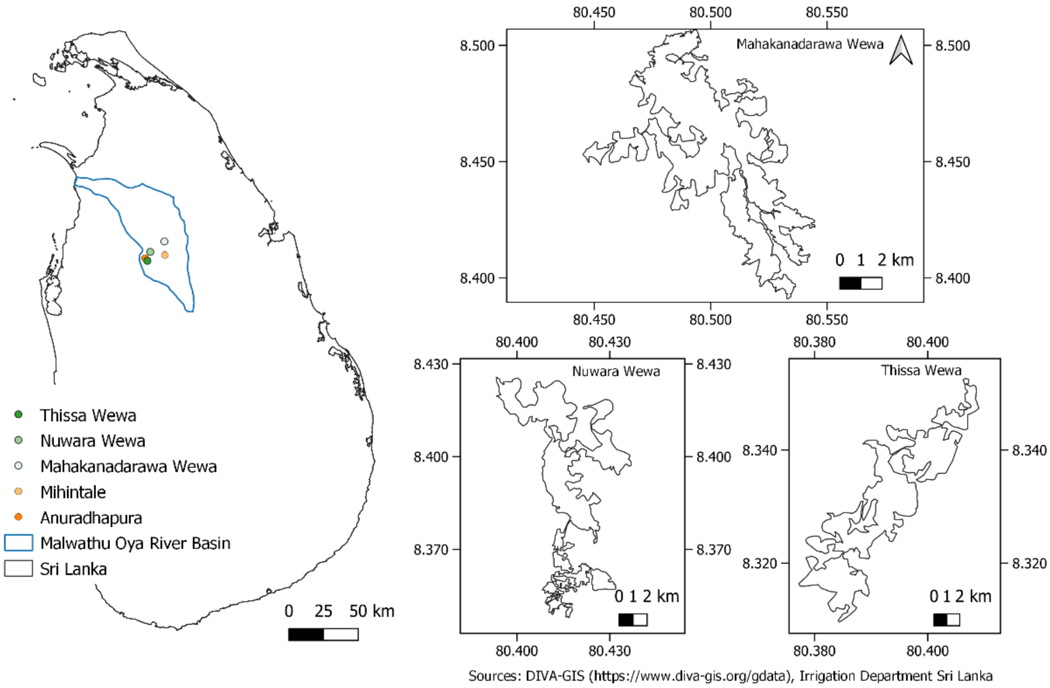

Figure 4 *The Malwathu Oya river basin in Sri Lanka with the location and area of the three irrigation schemes Mahakanadarawa, Nuwara and Thissa Wewa.*

The study area of the Malwathu Oya river basin, where the field measurements were performed, were the three irrigation schemes Mahakanadarawa, Nuwara and Thissa Wewa (Figure 4), with areas of 39.2 km^2, 10.2 km^2, 3.64 km^2 respectively. They are located between the latitude 8.3165 and 8.5069 and longitude 80.377 and 80.545 (WGS84). The schemes use basin irrigation with water collected from inter-connected rainwater storage tank cascade systems, and larger reservoirs (FAO n.d.c).

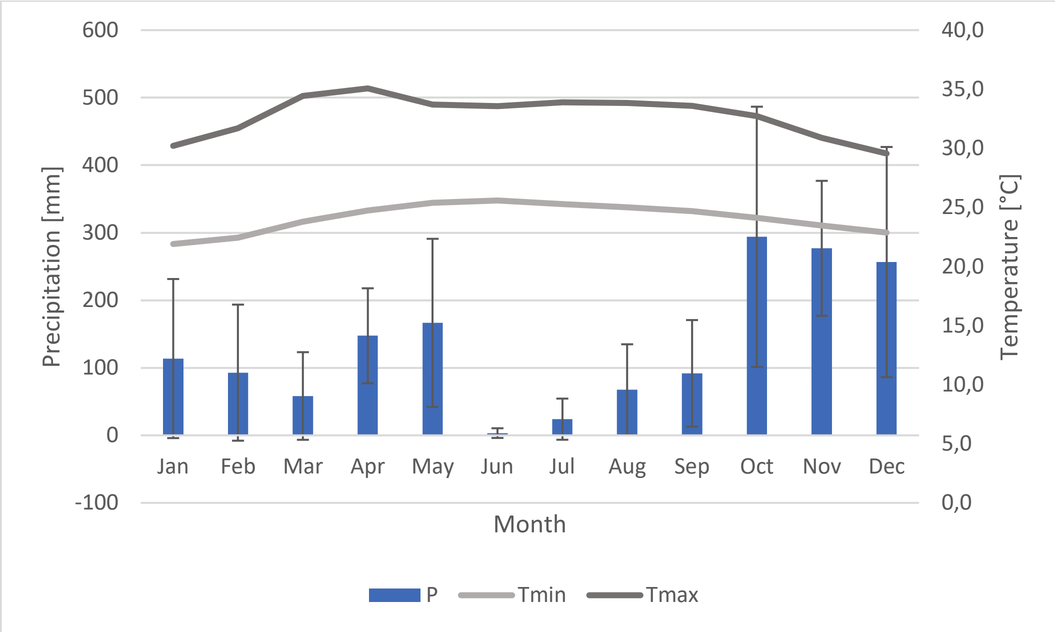

Figure 5 *Mean monthly precipitation (P) [mm] with standard deviation for Mihintale (latitude: 8.37, longitude: 80.51 (WGS84) and elevation: 107 m) maximum and minimum temperature (Tmax and Tmin respectively) [°C] for Anuradhapura (latitude: 8.35, longitude: 80.38 (WGS84) and elevation: 92 m) over the period of 2010–2020 (Department of Meteorology n.d.).*

Monthly precipitation and temperature values for the study area can be seen in Figure 5. Where mean monthly temperature values varied between 22 and 35 °C, mean monthly precipitation rates varied between 3 and 294 mm and the mean annual precipitation rate was about 1600 mm. Temperature values were lower and precipitation values were higher at the beginning and at the end of the year. The standard deviation of the monthly precipitation rates had values up to 170 mm, giving insight in the magnitude of the variation in rainfall during these 10 years.

3.2. AquaCrop Modelling

3.2.1. Field Data Input

The AquaCrop model requires input data on climate, crop, soil and field management parameters to be able to model outputs accurately. The climatic data used as input in the model was collected from the closest weather station, in Anuradhapura, located at latitude 8.35, longitude 80.38 (WGS84) and at an elevation of 92 m. The weather data consisted of data time series on daily maximum and minimum temperature, daily maximum and minimum relative humidity, monthly solar radiation, monthly wind speed, and daily ET_0 calculated from the climatic data using the P-M equation (Equation 1). Daily precipitation data was collected from the closest rain station, in Mihintale, located at latitude 8.37, longitude 80.51 (WGS84) and at an elevation of 107 m.

Primary collected field data, on soil properties (Table 3, 4 and 5), crop characteristics (Table 6) and management practices (Table 7) were used as inputs in the AquaCrop model. Details on how these parameters were measured and calculated as well as measurement locations can be found in Appendix A.

Table 3 *Sand and clay content and the textural class for the 6 samples with mean values. The mean values were used as inputs for the AquaCrop model.*

Sample no	Sand content [%]	Clay content [%]	Textural class
1	84.4	13.3	Sandy Loam
2	85.5	9.63	Loamy Sand
3	78.1	11.9	Sandy Loam
4	87.1	5.70	Loamy Sand
5	80.6	7.59	Loamy Sand
6	87.1	6.99	Loamy Sand
Mean	**83.8**	**9.18**	**Loamy Sand**

Table 4 *Mean, minimum (Min), maximum (Max) and standard deviation (SD) of the water content at permanent wilting point (PWP), field capacity (FC) and saturation (SAT). The mean values were used as inputs for the AquaCrop model.*

Variable	PWP [%]	FC [%]	SAT [%]
Mean	7.5	13.7	44.7
Min	5.6	11.7	43.5
Max	9.7	15.5	45.8
SD	1.7	1.6	0.92

Table 5 *Hydraulic conductivity (K_{sat}) per hour and per day. The value per day was used as input for the AquaCrop model.*

K_{sat} [mm/hour]	K_{sat} [mm/day]
104	2469

Table 6 *Mean, Minimum (Min), Maximum (Max) and standard deviation (SD) for LAI, CC and HI values and the maximum rooting depth for rice paddy crop. The mean values were used as inputs for the AquaCrop model.*

Variable	LAI	CC	HI	Maximum rooting depth [m]
Mean	7.128	0.988	0.324	0.11
Min	5.704	0.966	0.280	0.060
Max	9.910	1.002	0.350	0.14
SD	1.968	0.0167	0.0316	0.020

In Table 7 the mean value from the conducted field survey (Appendix B) answered by 15 farmers and irrigation managers can be seen. The survey followed IWMI research ethics policy (IWMI n.d.) and the data was exclusively used as input for the AquaCrop model.

Table 7 *The most frequently occurring answers from the field survey and literature values that were used as inputs for the AquaCrop model.*

Phenology	
Transplanting	Not occurring
Sowing date	Beginning of October
Flowering start date	December
Full canopy cover date	January
Harvest date	End of February
Irrigation management	
Irrigation type	Basin
Irrigation frequency	Every 7 days
Irrigation depth	75 mm per irrigation event (RRDI n.d.)
Height of soil bunds [m]	0.43
Fertilizer management	**Before 2021**
Fertilizer	Inorganic fertilizers (urea, TSP, MOP)
Frequency of application	Beginning + every 15 days
Application amount [kg/ha]	275
General recommendations of application for fertilizers [kg/ha]	225 (DOA n.d.)
Field control	
Weed control	Chemicals
Tillage	Mechanical (with tractor)
Frequent pest/disease	Insects
Frequent soil problem	No problem/sedimentation
Crop rotation	Not occurring

3.2.2. Sensitivity Analysis

A sensitivity analysis (SA) was conducted for three parameters in the model. These were determined by compiling previous studies evaluating the sensitivity of the AquaCrop model using Morris method and extended Fourier amplitude sensitivity method (Shrestha et al. 2013; Vanuytrecht et al. 2014b; Jin et al. 2018). Parameters that were found to have a higher sensitivity for the rice crop were those describing the maximum effective rooting depth (rtx), canopy decline rate and maximum canopy cover (cdc and ccx respectively), and the reference water productivity and harvest index (wp and hi respectively) having simulated yield as the target function for their analyses (Shrestha et al. 2013; Vanuytrecht et al. 2014b; Jin et al. 2018). From these parameters, hi and rtx were chosen, describing the production and the canopy development respectively. The parameter fc was also chosen, to have one parameter representing the soil water condition. By varying the field capacity and keeping the permanent wilting point at the same value, the total available soil water level accessible for plants varies in the model (Lopez & Barclay 2017).

These parameters were then tested by running the model for each parameter set to its minimum, mean and maximum value (Table 8), and with the rest of the model parameters unchanged. Ranges for the three selected parameters were set to ± 15% according to the standard deviation from the calibrated parameters from the field (Shrestha et al. 2013), or set based on literature review (Raes et al. 2016) such that the ranges would be physically plausible (Vanuytrecht et al. 2014b).

Table 8 *The three chosen parameters of the AquaCrop model SA with their description, minimum, mean and maximum value.*

Parameter	**Description**	**Minimum value**	**Mean value**	**Maximum value**	**Unit**
rtx	Maximum effective rooting depth	0.3		0.6	m
hi	Reference harvest index (HI_0)	0.28	0.32	0.37	Fraction of 1
fc	Moisture content at field capacity (FC)	11.7	13.7	15.8	%

3.3. Assessment of Spatio-temporal Patterns of Land and Water Productivity Indicators Using WaPOR Approach

Spatio-temporal variability in crop water use within and across the three irrigation schemes, Mahakanadarawa, Nuwara and Thissa Wewa, were assessed using indicators derived from WaPOR level 2 data. These indicators were uniformity, beneficial water use (BWU) and crop water productivity (CWP). Calculations were done for each scheme for the years 2015–2021 for the Maha cultivation season, starting from the beginning of October to the end of February (determined by the field survey, see section 3.2.1. Table 7).

3.3.1. Uniformity

The uniformity of the irrigation distribution in the schemes was described using the coefficient of variation (CV) of seasonal ETI_a. Monthly ETI_a values were derived from the WaPOR database and then aggregated to seasonal ETI_a values in QGIS. The CV of ETI_a was calculated by first computing the standard deviation (SD) and the mean value of the seasonal ETI_a values. Thereafter, the ratio of SD and mean of ETI_a was calculated (Equation 2).

$$CV = \frac{SD}{mean} \times 100 \tag{2}$$

3.3.2. Beneficial Water Use

The beneficial water use (BWU) was calculated by deriving monthly ETI_a and dekadal T values from WaPOR database and then aggregating them to seasonal values in QGIS. The ratio of T over ETI_a was then calculated (Equation 3).

$$BWU = \frac{T}{ETIa} \tag{3}$$

Where BWU is beneficial water use, T is transpiration [mm], ETI_a is evapotranspiration and interception [mm].

3.3.3. Crop Water Productivity

Crop water productivity (CWP) was calculated by deriving monthly net primary production (NPP) from WaPOR database and then aggregating them in QGIS to seasonal values. It was then calculated into total biomass production (TBP) (Equation 4) and thereafter calculated into yield (Equation 5). Monthly ETI_a values were aggregated from WaPOR and converted into seasonal values in QGIS. The CWP was then calculated by the ratio of yield over ETI_a (Equation 6).

$$TBP = AOT \times LUE \times \frac{NPP \times 22.222}{1 - MC_{biomass}} \tag{4}$$

Where TBP is the total biomass production [kgDM/ha], AOT is above ground over total biomass ratio, LUE is the light use efficiency correction factor, NPP is the net primary production [gC/m^2], 22.222 is a conversion factor for dry matter (DM) converting gC/m2 to kgDM/ha (FAO 2020b) and $MC_{biomass}$ is the moisture content in fresh biomass. Assuming paddy is the dominant crop, AOT is set to 0.75, LUE is set to 1 and $MC_{biomass}$ is set to 0.15 (FAO n.d.d).

$$Yield = TBP \times HI \quad (5)$$

Where yield is dry matter grain yield [kgDM/ha], HI is the harvest index. Assuming rice is the main crop cultivated in the area, the HI value is set to 0.32 from field data measurements, (details in measurement and calculation procedure on HI can be seen in Appendix A).

$$CWP = \frac{Yield}{ETIa} \quad (6)$$

Where CWP is the crop water productivity [kgDM/m^3], yield is dry matter grain yield [kgDM/ha] and ETI_a is the actual evapotranspiration and interception converted from [mm] to volume of water per unit area [m^3/ha].

4. Results

4.1. Sensitivity Analysis of the AquaCrop Model

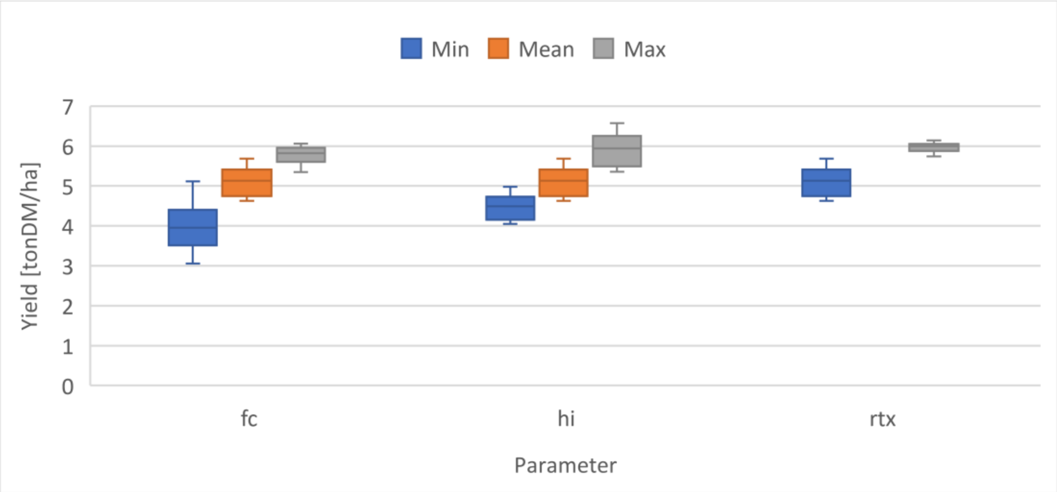

Figure 6 *The AquaCrop model SA with yield output for the minimum, mean and maximum value for the selected parameters (fc, hi and rtx), indicated with blue for the minimum value, orange for the mean value and grey for the maximum value.*

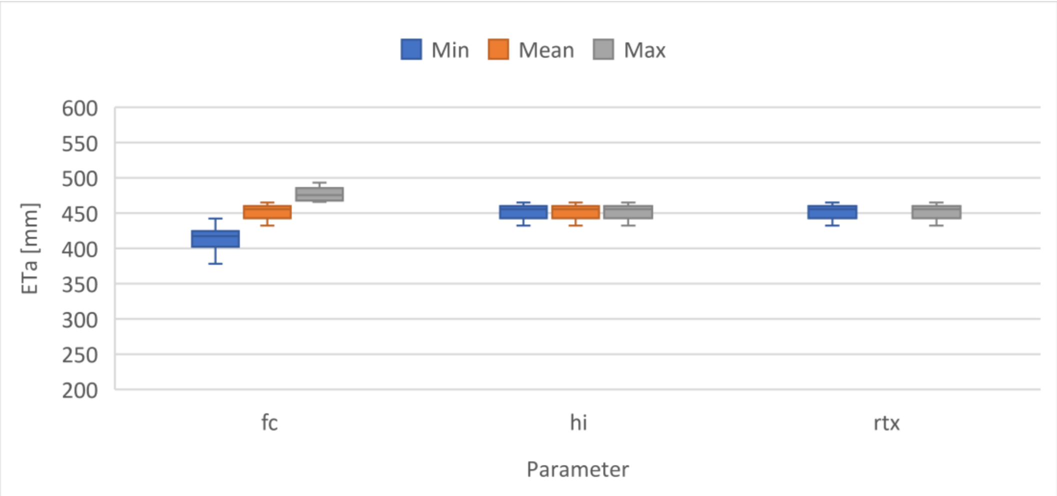

Figure 7 *The AquaCrop model SA with ET_a output for the minimum, mean and maximum value for the selected parameters (fc, hi and rtx), indicated with blue for the minimum value, orange for the mean value and grey for the maximum value.*

In Figure 6 and 7 the sensitivity analysis for the yield and the ET_a AquaCrop model outputs are presented for the three selected parameters: field capacity (fc), reference harvest index (hi) and maximum effective rooting depth (rtx). Where a larger range for the min, mean and max value respectively indicates a higher sensitivity to that particular value, while a larger difference between the min, mean and max value indicates a higher sensitivity to changes in that parameter value.

For the AquaCrop model yield output (Figure 6), there was shown to be a variation in the range for each min, mean and max value, with lowest range being 0.4 kgDM/ha and highest being 2.1 kgDM/ha. There was also a difference between the values, lying between 4.0–6.0 kgDM/ha for the mean values. This indicates that there is a sensitivity for the yield output for the fc, hi and rtx input parameters.

For the AquaCrop model's ET_a output (Figure 7), the variation in the range for each min, mean and max value was low, with lowest range being 27 mm and highest range being 64 mm. This indicates that the value of each parameter does not affect the ET_a output to a larger extent. A difference between the values can be seen for the fc parameters min, mean and max value, lying between 413 and 471 mm for the mean values. This indicates that there is a sensitivity for the ET_a output for fc input parameter. For the hi and rtx input parameters, having the same mean values of 448 mm, the ET_a model output does not show any sensitivity.

4.2. WaPOR and AquaCrop Comparison

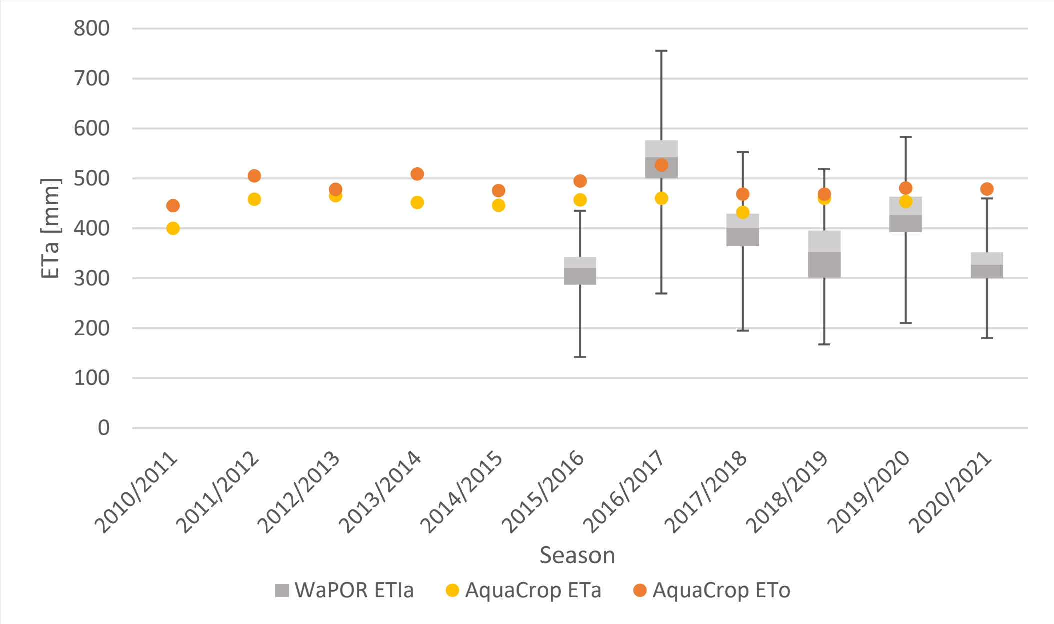

Figure 8 *WaPOR ETI_a cell values for Mahakanadarawa, Nuwara and Thissa Wewa presented with boxplots for Maha season 2015/2016–2020/2021, AquaCrop ET_a outputs for Maha season 2010/2011–2019/2020 and AquaCrop ET_0 outputs for Maha season 2010/2011–2020/2021 presented with yellow and orange points respectively.*

In Figure 8, the WaPOR ETI_a, AquaCrop ET_a and AquaCrop ET_0 outputs are shown. AquaCrop ET_a outputs are relatively consistent, lying between 400–465 mm throughout the study period, close to the ET_0 value, lying between 446–527 mm. WaPOR ETI_a mean values show more variation, lying between 312–537 mm for the study period. The AquaCrop values are lying in the upper part of the WaPOR ETI_a value ranges for the majority of the Maha seasons studied. However, for the Maha season 2016/2017 the WaPOR ETI_a value is higher than the AquaCrop ET_a value. This year is reported as a drought year (Department of Meteorology n.d.), explaining the higher values of actual evapotranspiration for WaPOR.

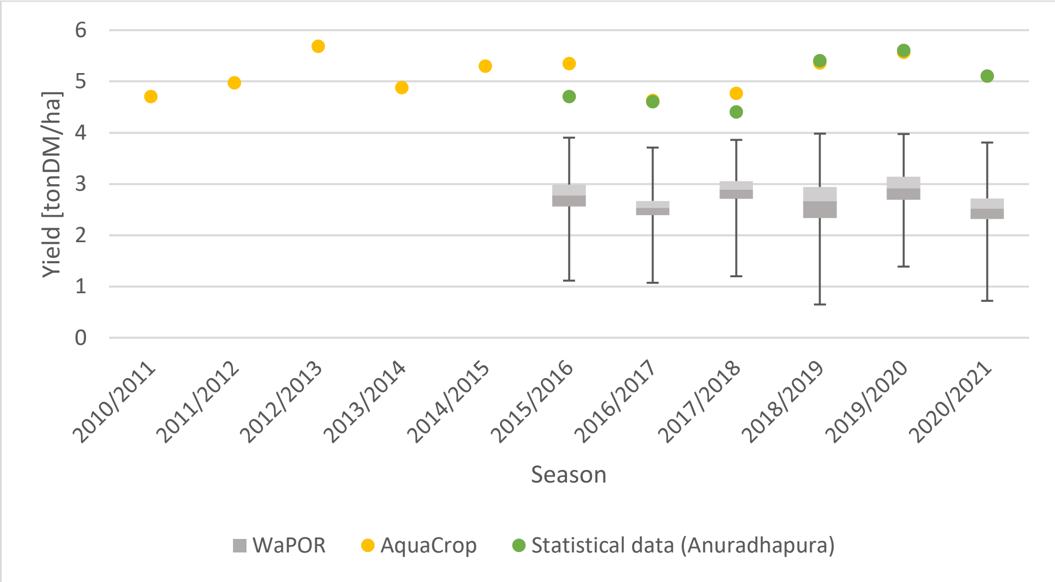

Figure 9 *WaPOR yield cell values for Mahakanadarawa, Nuwara and Thissa Wewa presented with boxplots for Maha season 2015/2016–2020/2021, AquaCrop yield outputs for Maha season 2010/2011–2019/2020 and historical yield data (from the Anuradhapura region) for Maha season 2015/2016–2020/2021 (Department of Census and Statistics n.d.) presented with yellow and green points respectively.*

In Figure 9, the WaPOR, AquaCrop and historical yield values are shown. The AquaCrop yield output is lying at 4.6–5.7 ton/ha for the observed period, corresponding well, both by trend and value, with the historical yield data, lying at 4.4–5.6 ton/ha. WaPOR show consistently lower yield values, with the mean values lying between 2.5–2.9 ton/ha per season for the study period, relative to historical data.

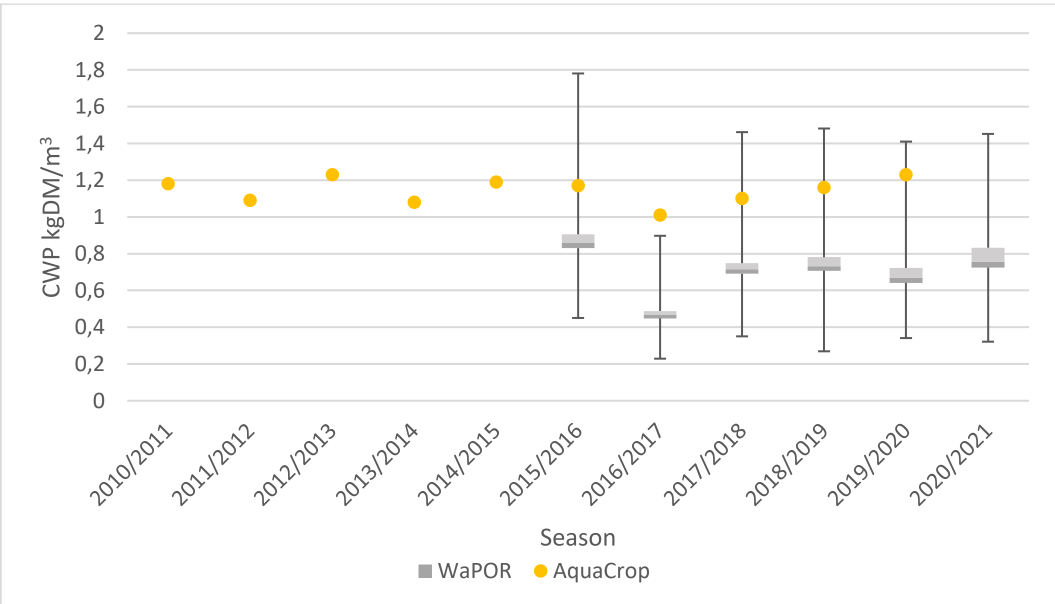

Figure 10 WaPOR CWP cell values for Mahakanadarawa, Nuwara and Thissa Wewa presented with boxplots for Maha season 2015/2016–2020/2021 and AquaCrop CWP outputs presented with yellow points for Maha season 2010/2011–2019/2020.

In Figure 10, the WaPOR and AquaCrop crop water productivity (CWP) outputs are shown. The AquaCrop CWP output show values of 1.01–1.23 kgDM/m^3, whereas WaPOR CWP show lower values, between 0.48–0.90 kgDM/m^3 for the mean values. As the CWP values are calculated by taking the ratio of yield over ET_a, the lower WaPOR CWP values are results of the lower WaPOR yield values noted in Figure 8.

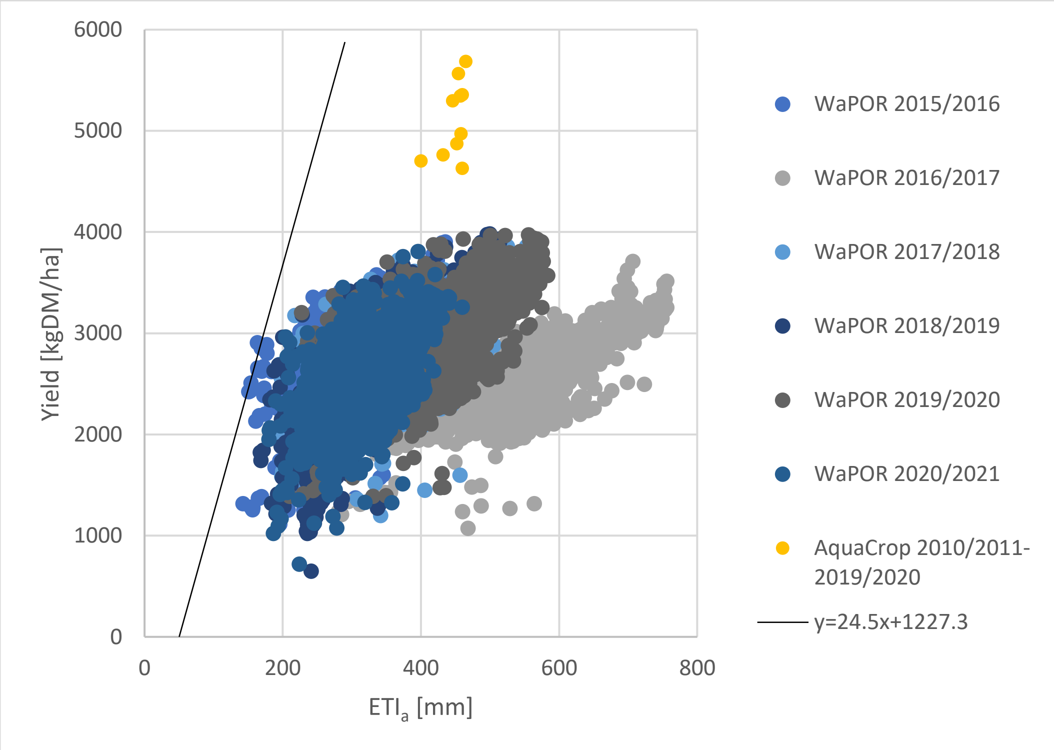

Figure 11 *Yield in relation to ETI_a for WaPOR scheme cell values for Mahakanadarawa, Nuwara and Thissa Wewa irrigation schemes for the Maha season from 2015/2016 to 2020/2021 and for AquaCrop model simulated yield and ET_a for Maha season from 2010/2011 to 2019/2020 (yellow points). A boundary function is illustrated with a black line with the slope 24.5 kg/ha mm and x-intercept 50.09 mm (Bastiaanssen & Steduto 2017).*

Yield was plotted against ET_a for WaPOR scheme cell values for the three irrigation schemes and for AquaCrop model simulated values (Figure 11). A boundary function was plotted as a reference to help benchmark the best yield in relation to water resources, in this case ETI_a. The yield gap is represented by the difference between actual yields and the boundary function (Sadras 2015). The boundary function in Figure 11 was given from previously conducted global research on rice yield and ET_a measured in experimental fields during the period of 2000–2010 in 17 countries (Bastiaanssen & Steduto 2017). The data points outer edge corresponds well with the boundary line from (Bastiaanssen & Steduto 2017). The distributions and total ranges of yield are similar between the different Maha seasons for WaPOR, only Maha season 2016/2017 (drought year) lie further away from the other total ranges and further away from the boundary line, as a result of severe water stress. ETI_a values are higher for this Maha season because of the drought, with higher temperatures and dryer air. The AquaCrop model simulated values lie over the WaPOR values in the figure, having higher yield values. This trend can also be seen in Figure 9.

4.3. Spatio-temporal Patterns of Land- and Water Productivity Indicators

4.3.1. Uniformity

The uniformity of the water distribution within the schemes are presented with the coefficient of variation (CV) of ETI_a for the three irrigation schemes Mahakanadarawa, Nuwara and Thissa Wewa for the Maha season 2015/2016 to 2020/2021 (Table 9). Low values of ETI_a CV indicate good spatial uniformity within a season, while higher values indicate poor spatial uniformity. In this study, CV values were classified into three groups. Where ETI_a CV < 10 %, 10 % ≤ ETI_a CV < 25 % and 25 % ≤ ETI_a indicate a good, fair and poor uniformity respectively (Sawadogo et al. 2020; FAO 2021). All the CV values are lying within the range 11 to 19 % for the studied period, indicating a fair uniformity of water distribution that is relatively similar for all the irrigation schemes for the different Maha seasons. For the Thissa Wewa, the CV values lie in the upper part of the range, indicating a lower uniformity.

Table 9 *Uniformity of the water distribution, indicated with coefficient of variation (CV) values of ETI_a for the Mahakanadarawa, Nuwara and Thissa Wewa irrigation scheme for the Maha season 2015/2016 to 2020/2021.*

Irrigation scheme	**2015/ 2016**	**2016/ 2017**	**2017/ 2018**	**2018/ 2019**	**2019/ 2020**	**2020/ 2021**
Mahakanadarawa Wewa	15 %	12 %	14 %	17 %	14 %	13 %
Nuwara Wewa	13 %	12 %	14 %	18 %	13 %	11 %
Thissa Wewa	19 %	14 %	16 %	19 %	16 %	13 %

4.3.2. Beneficial Water Use

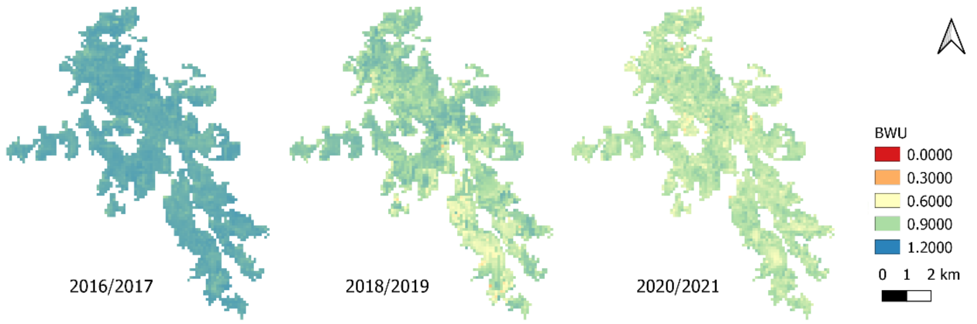

Figure 12 *BWU for the Mahakanadarawa Wewa irrigation scheme for the Maha season 2016/2017, 2018/2019 and 2020/2021.*

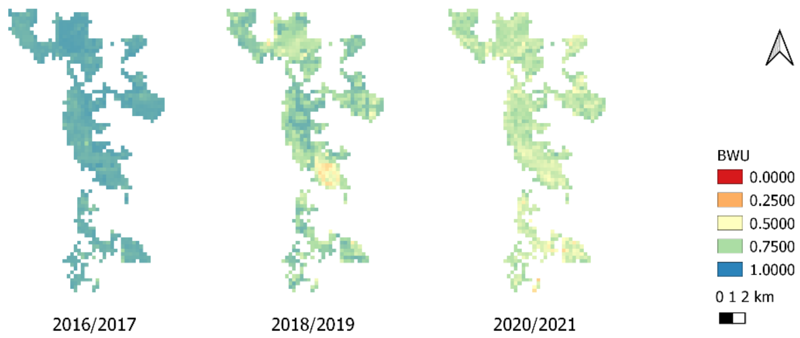

Figure 13 *BWU for the Nuwara Wewa irrigation scheme for the Maha season 2016/2017, 2018/2019 and 2020/2021.*

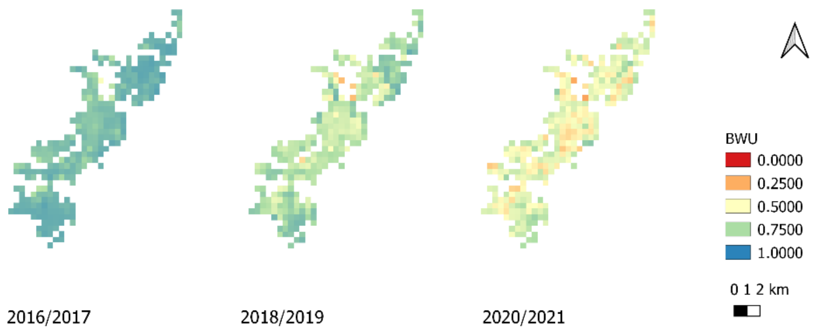

Figure 14 *BWU for the Thissa Wewa irrigation scheme for the Maha season 2016/2017, 2018/2019 and 2020/2021.*

Three Maha seasons are presented in each figure for beneficial water use (BWU) (Figure 12, 13 and 14); one dry year (2016/2017), one average year (2017/2018) and one wet year (2020/2021) (Department of Meteorology n.d.). In the figures, a higher BWU value indicate a higher ratio of T over ETI_a, meaning that there is a higher amount of water being beneficially taken up by the plant to generate biomass. In Figure 12, 13 and 14 higher values of BWU can be seen for the dry year (Maha 20176/2017) and lower values of BWU can be seen for the average and wet year (Maha 2018/2019 and 2020/2021 respectively). This trend can be seen for all the three irrigation schemes and indicates that more water is being lost through soil evaporation in years where more water is available. In a dry season almost 100 % of the ETI_a is allocated to T, whereas in an average and a wet years about 50 to 90 % is allocated to T (Figure 12, 13 and 14).

4.3.3. Crop Water Productivity

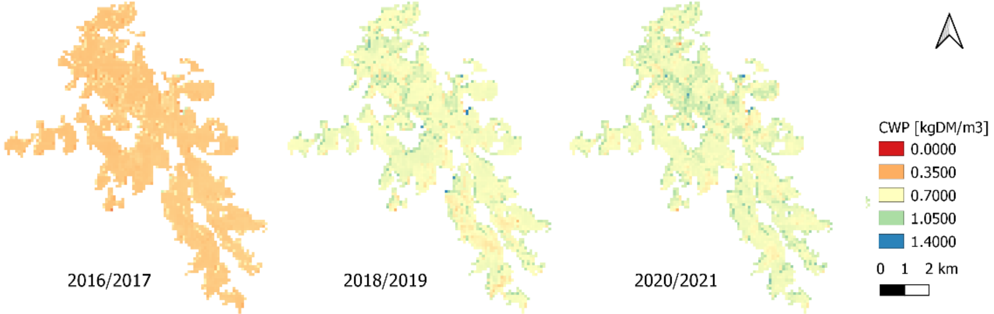

Figure 15 *CWP for the Mahakanadarawa Wewa irrigation scheme for the Maha season 2016/2017, 2018/2019 and 2020/2021.*

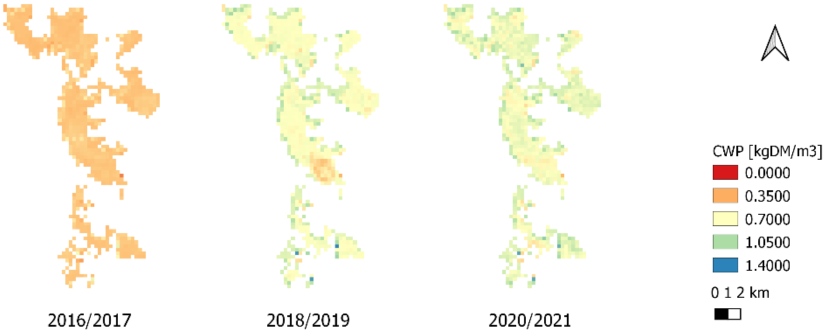

Figure 16 *CWP for the Nuwara Wewa irrigation scheme for the Maha season 2016/2017, 2018/2019 and 2020/2021.*

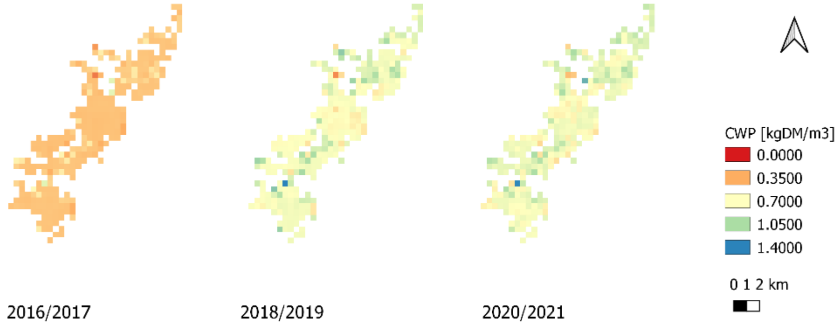

Figure 17 CWP for the Thissa Wewa irrigation scheme for the Maha season 2016/2017, 2018/2019 and 2020/2021.

Three Maha seasons are presented in each figure for crop water productivity (CWP) (Figure 15, 16 and 17); one dry year (2016/2017), one average year (2017/2018) and one wet year (2020/2021) (Department of Meteorology n.d.). In the figures, a higher CWP values indicate a higher amount of grain yield generated per water resource (ETI_a). In Figure 15, 16 and 17 lower values of CWP can be seen for the dry year (Maha 2016/2017), about 0.35 kgDM/m^3, and higher CWP values can be seen for the average and the wet year (Maha 2018/2019 and 2020/2021 respectively), about 0.70 kgDM/m^3. This trend can be seen for all the three irrigation schemes and indicates that less yield per ETI_a is generated during years when water is scarce.

5. Discussion

5.1. WaPOR and AquaCrop Comparison

In section 4.2, Figure 8, the ET_a values obtained from WaPOR and AquaCrop in this study (312–537 and 400–465 mm respectively) were shown to be similar to a previously conducted study in India for lowland rice (290-352 mm) (Chatterjee et al. 2021). The AquaCrop ET_a simulated values were shown to be in the upper part of the WaPOR generated ETI_a values and had more consistent values throughout the study period compared to the WaPOR values. For the reported drought year however, WaPOR showed higher ETI_a values than AquaCrop, which could be explained by that more water is lost through soil evaporation this year because of the hot and dry weather. Both WaPOR and AquaCrop use the P-M equation for the calculations of ET_a, however, there is a difference in input values. WaPOR uses spatial global data from meteorological stations and remote sensing (FAO n.d.d) influenced by various parameters (Allen et al. 1998). AquaCrop uses point data from meteorological stations and primary collected field data. A possible explanation to AquaCrop ET_a outputs being at the upper range of the WaPOR ETI_a values, could be because of unlimited water conditions in the model environment. The frequency of the water application in the model was determined from survey answers (section 3.2.1.) and the irrigation amount was determined from the department of agricultural in Sri Lanka (RRDI n.d.). With these model settings, the water access in the model was non-limiting, leading to higher and more consistent ET_a values.

In section 4.2, Figure 9, the AquaCrop yield output values were shown to be in good agreement with the historical yield data values (4.6–5.7 and 4.4–5.6 ton/ha respectively). WaPOR values were on the lower side (2.5–2.9 ton/ha), indicating a potential underestimation of yield in WaPOR. This could be explained by the difference in the calculation methodology when calculating the seasonal yield in AquaCrop and WaPOR. The WaPOR database uses satellite data and calculates the yield from the total biomass production with help from global crop parameters (FAO 2020b). In previous research, comparing remote sensed and in-situ data, where a comprehensive literature review was conducted, it was concluded that there is a vast difference in reported accuracy to the remote sensing of crop yield. Prior knowledge and accurate allocation of the crop type and parameters such as HI, light use efficiency (LUE) and moisture content (MC) were concluded to be of significant influence (Blatchford et al. 2019). The lower yield values obtained in WaPOR could therefore be due to sources of error in these conversion calculations. For future research, it is recommended to perform a sensitivity analysis to obtain a better understanding of potential limitations in the database. Another explanation to lower yields in WaPOR could be due to cloud coverage and atmospheric variations when collecting satellite data, especially normalized vegetation index data (NDVI). The NDVI quality has shown to be lower in humid tropical environments, than in arid and semi-arid climate (Blatchford et al. 2020b). When data is missing due to these circumstances, gaps and anomalies are filled by smoothing (FAO 2020b), where cells with missing and unreliable values are replaced by more reliable data through a process of interpolation (Swets et al. 1999). This leads to a lower accuracy in the output WaPOR data (FAO 2020b) and should be taken into account when deriving RS data. NDVI data is used as input in the calculations of ETI_a as well as of fAPAR, which is used to determine NPP, used for the yield calculations (FAO 2020b).

The AquaCrop model uses primary collected field data inputs. The model does not take insects and diseases into account, and as there were found to be some problems with these (see survey answers in section 3.2.1), it could be possible that AquaCrop is simulating better growing conditions leading to higher yield than what is actually obtained. Additionally, the lowest value for the maximum rooting depth that could be applied in the model was 0.3 m, however, the maximum rooting depth was measured to 0.11 m in the field. As water is taken up by the roots and transpires, a greater root depth in the AquaCrop model could potentially have led to simulating a rice crop with better ability to take up water in the rootzone. In the sensitivity analysis conducted for AquaCrop model (see section 4.1), it was shown that the yield output was sensitive for the parameters tested with minimum, mean and maximum value. Where the maximum rooting depth (rtx) was one of these parameters. For the same three parameters, the ET output only showed sensitivity for the fc parameter. The fc parameter is indicating the soil water availability for the plant uptake and has therefore a direct connection to the transpiration. The conducted sensitivity analysis did however only consider three parameters (fc, hi and rtx), and is therefore limiting in the representability of the model sensitivity. More parameters should be tested to obtain a better understanding of the sensitivity of the model. It is also recommended to ground truth AquaCrop with yield and soil data to obtain more precise site condition descriptions.

In section 4.2, Figure 10, the crop water productivity (CWP) values were shown to be on the lower side for the WaPOR output (0.48–0.90 kgDM/m^3) compared to the AquaCrop output values (1.01–1.23 kgDM/m^3). The CWP values are calculated by the ratio of yield over ETI_a, and because deviations between ETI_a and yield is different, the compound of CWP seems to decrease divergence between the two methods, leading to an artefact of two opposite trends for ETI_a and yield. As yield values from WaPOR were low, this contributed to lower CWP values. From a previous study, the globally measured average CWP value per unit water depletion for rice gathered from 14 publications for 4 different continents, was 1.09 kg/m^3 with a range of 0.6–1.6 kg/m^3 (Zwart & Bastiaanssen 2004). Both AquaCrop and WaPOR values lie within this range, where WaPOR lie on the lower part of the range.

In section 4.2, Figure 11, the similarities between the boundary function and the outer edge of the data from the cell values for the three irrigation schemes indicate that the line could represent a boundary function for the three irrigation schemes. As a boundary function represents the best yield in relation to water resources (in this case ET_a) (Sadras 2015), points that are located far from the boundary function indicate that the same yield could potentially be achieved with less water. It is thus implied that there are possibilities for improvements in water management to improve the water productivity. However, the boundary function represents a global study conducted for 17 countries (Bastiaanssen & Steduto 2017) and could therefore be limited in accuracy for the studied irrigation schemes. The global constant crop parameters for rice (0.14, 2.5 and 0.55 for MC, LUE and HI respectively), used in the study by Bastiaanssen & Steduto (2017), to construct the boundary function, differ from the values that were used to calculate the WaPOR yield (0.15, 1 and 0.32 for MC, LUE and HI respectively) (FAO n.d.d). The crop parameters used in WaPOR are global parameters for rice and could therefore not be representative for the three irrigation schemes that were assessed. The HI value used in this study was measured in the field taking 3 samples from a small area and might thus not be representative either. The AquaCrop model simulated values lie over the WaPOR values (Figure 11), having higher yield values. As discussed above, there are likely more factors affecting yield in AquaCrop then what is accounted for in the model. The AquaCrop model could thus potentially give decreased yield output values if more of these factors were considered.

5.2. Spatio-temporal Patterns of Land- and Water Productivity Indicators

In section 4.3.1. the uniformity, indicated with CV of ETI_a, showed similar CV values (ranging from 11 to 19 %) for all the schemes for the different Maha seasons throughout the study period. The CV values were classified as fair, according to previous studies (Sawadogo et al. 2020; FAO 2021), but because the schemes observed in this study are relatively small, they would be expected to have lower CV values, as factors such as soil uniformity, land use and distribution of the irrigated water would be expected to be uniform. For the Thissa Wewa, the CV values were in the higher part of this range (11 to 19 %), indicating a lower uniformity. A possible explanation for this could be that this scheme lies close to infrastructure, which could be affecting the outer cell values when interpolating in WaPOR. Because the Thissa Wewa is relatively small, a higher ratio of the total number of cell values could be affected compared to the larger schemes observed.

The beneficial water use (BWU) (section 4.3.2.), showed higher values (about 100 % allocated to T) for the dry year, and lower values (50–90 % allocated to T) for the average and wet year for all the three irrigation schemes. As there is more water available in the average and wet year, and there is only a certain amount of water that the crop can take up, water that is not transpired by the plant is lost through soil evaporation. The BWU value, calculated by the ratio of transpiration over evapotranspiration was therefore lower for the years with higher amount of available water. When comparing the different schemes, it could be concluded that there were lower values for the Thissa Wewa and higher for Nuwara and Mahakanadarawa Wewa. As mentioned above the smaller area and close location to infrastructure could affect Thissa Wewa to show lower values compared to the other two schemes. When instead looking at the values within each scheme, they were relatively uniform, with slightly lower values at the edges of the schemes, explained by the surrounding infrastructure leading to lower T values.

When looking at the BWU values, it is important to be aware of that T is indicating water that is used to produce total biomass, and thereby also includes the parts of the crop that are not directly used for food production. The weed extent in the schemes should also be taken into consideration. Weed is also contributing to the biomass production in the scheme and could therefore give misleading values of BWU. In this study, the weed extent in the field at the end of the growing season was observed to low levels. However, the observations were only done for a relatively small area.

In section 4.3.3., the crop water productivity (CWP) is presented. Where lower CWP values are shown for the dry year (about 0.35 kgDM/m^3) and higher CWP values are shown for the average and wet year (about 0.70 kgDM/m^3) for all the three irrigation schemes. This indicates a higher amount of yield production in years where there is less water limitation. In years when water is scarce the crop faces water stress, leading to lower yields. All the three schemes show relatively uniform values both within and between the schemes.

6. Conclusions

In this study, remote sensed land- and water productivity data from the WaPOR database was evaluated with primary collected field data using the AquaCrop model for three irrigation schemes in the Malwathu Oya river basin in Sri Lanka. The research questions in this study have led to the following results:

- The WaPOR and AquaCrop ET_a values were found to be in relatively good agreement (312–537 and 400–465 mm respectively). However, AquaCrop had more consistent values, explained by the non-limiting water conditions in the model environment leading to a lower sensitivity for weather data. The ET_a values of WaPOR and AquaCrop were also shown to be similar to what has been obtained in previous studies on lowland rice (290–352 mm) (Chatterjee et al. 2021). It could thereby be concluded that WaPOR is a useful tool for estimating ETI_a.

  WaPOR yield values (2.5–2.9 ton/ha) were lower compared to AquaCrop yield values and historical yield data (4.6–5.7 and 4.4–5.6 ton/ha respectively). This could be due to difference in yield calculation methodology for WaPOR and AquaCrop, and possible sources of error in conversion calculations in WaPOR. Prior knowledge and accurate allocation of the crop type and parameters used in conversion calculations in WaPOR is therefore of significant influence. Cloud coverage and atmospheric variability when collecting satellite data, causing data gaps and accuracy limitations, could also affect the seasonal yield calculations in WaPOR. For future research it is recommended to perform a sensitivity analysis for WaPOR, and ground truth with yield data to obtain a better understanding of potential limitations. To obtain more precise site condition descriptions it is also recommended to ground truth AquaCrop with yield and soil data.

  When looking at yield in relation to ET_a and the boundary function, it could be concluded that there is potential to achieve the same yield with less water. There are thus possibilities for improved water productivity in the three irrigation schemes.

- The spatio-temporal variations in crop water use assessed using WaPOR derived indicators showed a fair uniformity of water distribution within the irrigation schemes (11–19 %). The beneficial water use (BWU) in the irrigation schemes showed patterns of lower values (50–90 % allocated to T) for years when the available water amount was higher, explained by the higher rate of water lost from soil evaporation. Crop water productivity (CWP) values showed patterns of higher values (about 0.70 $kgDM/m^3$) when available water amount was higher, explained by yield production sensitivity to water scarce environments. The spatio-temporal patterns obtained in this study were consistent with expectations, and WaPOR could therefore be concluded to be a useful tool for these kinds of evaluations.

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Appendix A. Field Measurements

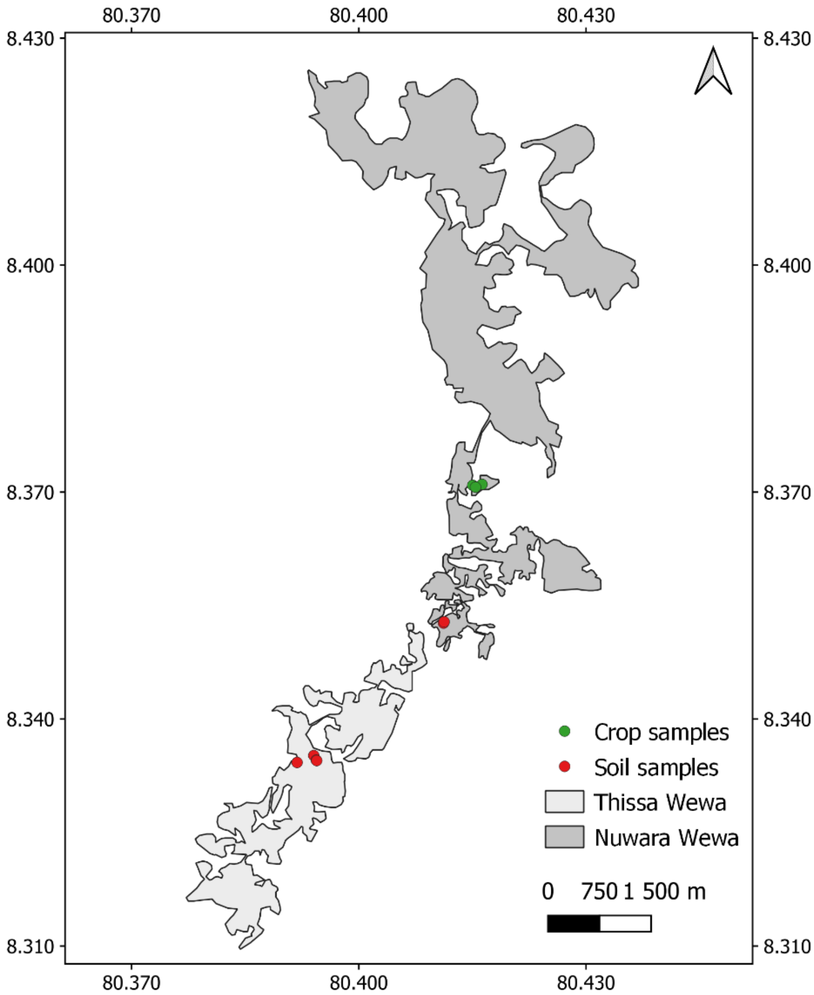

Figure A.1 *Soil (red) and crop (green) sampling locations in Thissa and Nuwara Wewa irrigation scheme. Soil samples included samples for textural analysis and crop samples include HI and LAI samples. Hydraulic conductivity (K_{sat}) was measured by where the crop samples were taken. All samples were taken at the end of the Maha cultivation season, in March 2022.*

Soil Properties

Measurements of the soil textural analysis were conducted at 6 sample sites in the Thissa and Nuwara Wewa irrigation schemes (Figure A.1), using a simplified hydrometer method (based on Stoke's law, relating the settling velocity of a spherical particle with its diameter). The 6 samples were taken using a soil auger collecting the soil sample for a 30 cm depth. With the help from a knife, the soil samples were scraped from the auger and placed in plastic bags to be taken to the lab. In the lab, each soil sample was spread out on a plastic sheet-covered tray to air dry for about 24 hours. In the meantime, 5 % Calgon reagent was prepared by the Rajarata University lab assistants (50 g Calgon in 1 l of water). The dry soil was then sieved through a 2 mm sieve to separate the gravel in the soil from the rest of the fine soil. The analysis proceeded by grounding the remaining fine soil to free separate particles. In a container a suspension of 40 g of soil, 100 ml of the Calgon solution and 300 ml of distilled water was prepared to soak overnight.

The next day, the suspensions were poured to sedimentation cylinders and distilled water was added to give the total volume of 1000 ml. A blank sample was also prepared, with 100 ml Calgon and the rest filled with distilled water up to a total volume of 1000 ml. The upper parts of the cylinders were covered with plastic and rubber stopper. The measurements then started by turning the cylinder end-over-end 10 times to mix the contents. A drop of amyl alcohol was added when the surface of the suspension was covered with foam. With the help of a hydrometer (standard hydrometer, ASTM No. 152 H, with Bouyoucos scale in g/l), measurements were taken at 40 seconds and then at 2 hours after mixing. A correction value was also added to the measurements (see Equation A.1).

$$Correction\ value = 0{,}36 \times (C - 19{,}4) \tag{A.1}$$

Where C is the temperature of the suspension [°C].

For the same 6 samples the moisture content was calculated. This was done by weighing 6 crucibles, and then weighing them again with 10 g of wet soil. These samples were then placed in an oven to dry overnight (about 10 hours) for 105 °C. They were then placed in a desiccator with silicones to cool down the samples, and thereafter the weight of the crucible with the dry soil was measured.

The moisture content was calculated using Equation A.2.

$$MC_{soil} = \frac{m_{wet\ soil+crucible} - m_{dry\ soil+crucible}}{m_{wet\ soil+crucible} - m_{crucible}} \tag{A.2}$$

Where MC_{soil} is the moisture content of the soil [%], $m_{wet\ soil+crucible}$ is the weight of the wet soil and the crucible [g], $m_{dry\ soil+crucible}$ is the weight of the dry soil and crucible [g], $m_{crucible}$ is the weight of the crucible [g].

The dry weight of the soil was then calculated using Equation A.3.

$$W = m_{soil\ sample} \times (1 - MC_{soil}) \tag{A.3}$$

Where W is the dry weight of the soil sample [g], $m_{soil\ sample}$ is the weight of the soil sample (40 g).

The sand, clay, and silt content [%] could then finally be calculated using Equation A.4, A.5, A.6.

$$Sand\ content = 100 - (R_{40s} - R_L) \times \frac{100}{W} \qquad (A.4)$$

$$Clay\ content = 100 - (R_{2h} - R_L) \times \frac{100}{W} \qquad (A.5)$$

$$Silt\ content = 100 - (Sand\ content + clay\ content) \qquad (A.6)$$

Where R_{40s} is the hydrometer value 40 s after mixing [g/l], R_{2h} is the hydrometer value 2 hours after mixing [g/l], R_L is the hydrometer value for the blank [g/l] and W is the dry weight of the soil [g].

After calculating the different ratios of sand, clay and silt, identification of the textural class for each sample was determined with help from the “Soil Water Characteristics” program from USDA[1]. This program also helped determine the physical characteristics of the soil; permanent wilting point (PWP), field capacity (FC) and saturation (SAT).

The saturated hydraulic conductivity (K_{sat}) of the soil was determined by measuring the infiltration rate with a double-ringed infiltrometer. Where the infiltration rate at steady state is roughly equal to K_{sat} (Eijkelkamp 2018). This was done by using a double-ringed infiltrometer (about 30 and 55 cm in diameter). The infiltrometer was placed next to the paddy field where the crop measurements were conducted (Figure A.1), on a dry and undisturbed part of the soil. It was then inserted into the soil at a 5 cm depth with the use of a hammer. A plastic sheet was placed in the inner core. Water was then poured in the outer core (used as a buffer to avoid lateral movement of the water) and thereafter in the inner core to a depth maintained for the duration of the test. The plastic sheet was then removed so that the infiltration could start in the inner core as well. Every 5 mm of water surface decline in the inner core, the time was measured. Water was re-filled in the inner and outer core every 5 minutes to maintain the depth of the water. Measurements were finished when the infiltration rate [mm/h], calculated by Equation A.7, reached steady state. The saturated hydraulic conductivity (K_{sat}) was obtained from this steady state, i.e., the value of the constant infiltration rate.

[1] https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/drainage/?cid=stelprdb1045310

$$Infiltration\ rate = \frac{d}{t * 3600} \qquad (A.7)$$

Where d is the decline of the water surface [mm] and t is the time [s].

Crop Characteristics

Crop characteristics were measured by taking 3 samples in the field, (location can be seen in Figure A.1). These were taken at the end of the Maha growing season in March, just before harvest, (field site can be seen in Figure A.2). An area of 0.25 m^2 was measured out with the help from a quadrant (a quadratic frame), that was placed in the paddy field. All the plants, with the roots included, were collected from the area within the quadrant and placed in a plastic bag.

Figure A.2 *A photograph of the field site where the crop characteristics measurements as well as the hydraulic conductivity (K_{sat}) measurement were conducted. The picture shows a rice paddy field by the Rajarata University, located in the Nuwara Wewa, at the end of the Maha cultivation season in March. The exact location of where the crop measurements were conducted can be seen in Figure A.1.*

To measure the leaf area index (LAI), the leaves from the crop were separated from the mother plant, placed on a white sheet, and then covered with a transparent sheet along with a ruler. A picture from each sheet was captured and thereafter transferred to a laptop to measure the area of the leaf blade using the software imageJ[2]. This was done for all the leaves for the first sample, and the mean area of the leaf blades ($A_{mean\ leaf}$) was calculated, using Equation A.8. For sample 2 and 3 the leaf area was calculated by counting the number of leaves from each sample and then multiplying this number by the mean leaf area calculated from sample 1 to get the total leaf area for the samples (see Equation A.9). The LAI was then calculated by taking the ratio of the total one-sided leaf area $A_{total\ leaf}$ [m^2], over the area of the quadrant $A_{quadrant}$ [m^2], (see Equation A.10).

$$A_{mean\ leaf} = \frac{\sum_1^{n_x} A_{leaf}}{n_x} \qquad (A.8)$$

Where $A_{mean\ leaf}$ is the mean one-sided area of a leaf [m^2], n_x is the number of plants in sample x, and A_{leaf} is the one-sided leaf area specific for each leaf in the sample.

$$A_{total\ leaf} = A_{mean\ leaf} \times n_x \qquad (A.9)$$

$$LAI = \frac{A_{total\ leaf}}{A_{quadrant}} \qquad (A.10)$$

The LAI values were then converted into canopy cover (CC) values to fit the model input requirements. This was done using Equation A.11 (Hsiao et al. 2009).

$$CC = 1{,}005 \times (1 - e^{(-0{,}6LAI)})^{1{,}2} \qquad (A.11)$$

To calculate the harvest index (HI), the same 3 samples collected for the LAI were used. From each sample the grains were separated from the plant and placed in a container. The moisture content of the grains was measured using a moisture meter, calibrating the content of moisture in percent. The remaining plants, including the roots, were cut up and placed in a paper bag and dried in an oven at 60 °C for about 48 hours. The grains were also dried for 48 hours, but at room temperature. After air drying, the grains from each sample were weighed and the moisture content was measured again. The weight of the yield grains as per 14 % moisture content, was calculated, using Equation A.12 and A.13.

[2] https://imagej.nih.gov/ij/index.html

$$m_0 = m_x - \left(m_x \times \frac{x}{100}\right) \tag{A.12}$$

$$m_{14} = m_0 \times \frac{114}{100} \tag{A.13}$$

Where m_0 is the weight of the grains with 0 % moisture content, m_{14} is the weight of the grains with 14 % moisture content and m_x is the weight of the air-dry grains with x % moisture content.

The remaining plant samples were also weighed and then oven-dried again for two hours. The drying process (with a measurement interval of one hour) was continued until a constant weight of the sample was obtained (the dry weight at 0 % moisture content).

The HI was then calculated by the ratio of the grain yield at 14 % moisture content over the total biomass weight, using Equation A.14.

$$HI = \frac{m_{14}}{m_{14} + m_{plant}} \tag{A.14}$$

Where m_{plant} is the weight of the remaining plant sample with 0 % moisture content.

To measure the maximum rooting depth of the rice crop, the length of the longest root for 20 plants divided between the 3 locations were measured using a ruler, and thereafter the mean value was calculated.

Management Practices

A survey including field management practices was conducted (see Appendix B). At each of the three irrigation schemes, 5 farmers from different parts of the scheme participated (15 farmers in total). The farmers were selected and contacted with the help from the Irrigation Department of Sri Lanka and consisted of questions regarding the crop growth, plant phenology, field control, fertilizer usage and irrigation. Translation during the field survey was done with help of a translator from the Rajarata University of Sri Lanka. The survey was conducted at the end of the Maha cultivation season, in March 2022. The answers from the survey were compiled for each irrigation scheme and the mean values were used in the AquaCrop model. The survey focused on rice paddy crop; the main crop cultivated. Other crops were considered negligible.

Appendix B. Field Survey

Field Study Questionnaire

* This form will record your name, please fill your name.

Form of Consent

This survey is part of a research project conducted by Veronika Widengren, a Master student at Uppsala University and Swedish University of Agricultural Sciences (SLU) in Sweden, as a part of an internship at International Water Management Institute (IWMI) in Colombo.

The objective of this project is to evaluate the irrigation scheme performance for three different irrigation schemes in the Malwathu Oya River Basin by assessing remotely sensed data and primary collected field data. The questions will focus on farm management practices.

This survey is anonymous and no personal information will be collected. The survey is voluntary and will take approximately 25 minutes to complete. The respondent is entitled to stop the survey in the middle if needed. The survey will be used purely for research purposes

1. By clicking "I agree" you are indicating that you have understood this consent form and agree to participate in this research study.

   ◯ I agree
   ◯ I disagree

Crop

2. What crop did you plant in Maha and Yala (previous)?

3. What is the area you planted in this Maha season (area of cropland) (ha)?

4. How much yield (kg) was obtained during the current and last Maha season?

5. How much yield (kg) was obtained during the last Yala season (2021)?

1

Phenology

6. Is the crop transplanted?
   If yes, what is the size of the seedling that is being transplanted (cm2)?

7. At what date is the crop sown/transplanted?

8. At what date does flowering occur? What is the duration of flowering?

9. At what date is full canopy cover reached (all plants are covering the ground surface)?

10. At what date is the crop harvested in the current Maha season?

Irrigation

11. What form of irrigation is being used?

- ◯ Basin irrigation
- ◯ Furrow irrigation
- ◯ Drip irrigation
- ◯ Sprinkler irrigation

12. How frequently was paddy field irrigated?

13. How much irrigation water was applied in each event (mm)?
    (For how long time do you irrigate, and at what capacity is the pump?)

Field Control

14. Are mulches being used?
    If yes, what type?

    - ◯ Organic plant mulches
    - ◯ Plastic mulches

15. How much of the ground surface is being covered by mulches (%)?

16. Are soil bunds used?
    If yes, what is the height (m)?

17. How is weed controlled, and how frequently?

18. Are there any frequent diseases causing yield reduction (what time during the season)?

19. Do you practice crop rotation? If so, please mention

Fertilizer usage

20. What type of fertilizers were used?

21. What was the date of application?

22. How much is being applied (compared to general recommendations)?

- ◯ Non limiting
- ◯ Near optimal
- ◯ Moderate
- ◯ About half
- ◯ Poor
- ◯ Very Poor

23. (How much is applied in kg/ha?)

24. Are there any problems with the soil?

25. Is tillage performed?
If yes, please describe the method.