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Knowledge and Innovation Support for ADB's Water Financing Program

Sri Lanka: Water Productivity Measurement-Mahaweli Water Security Investment Program

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For Asian Development Bank

Asian Development Bank

Water Productivity Assessment for Improved Irrigation Performance and Water Security in the Asia-Pacific Region: Sri Lanka

Technical report

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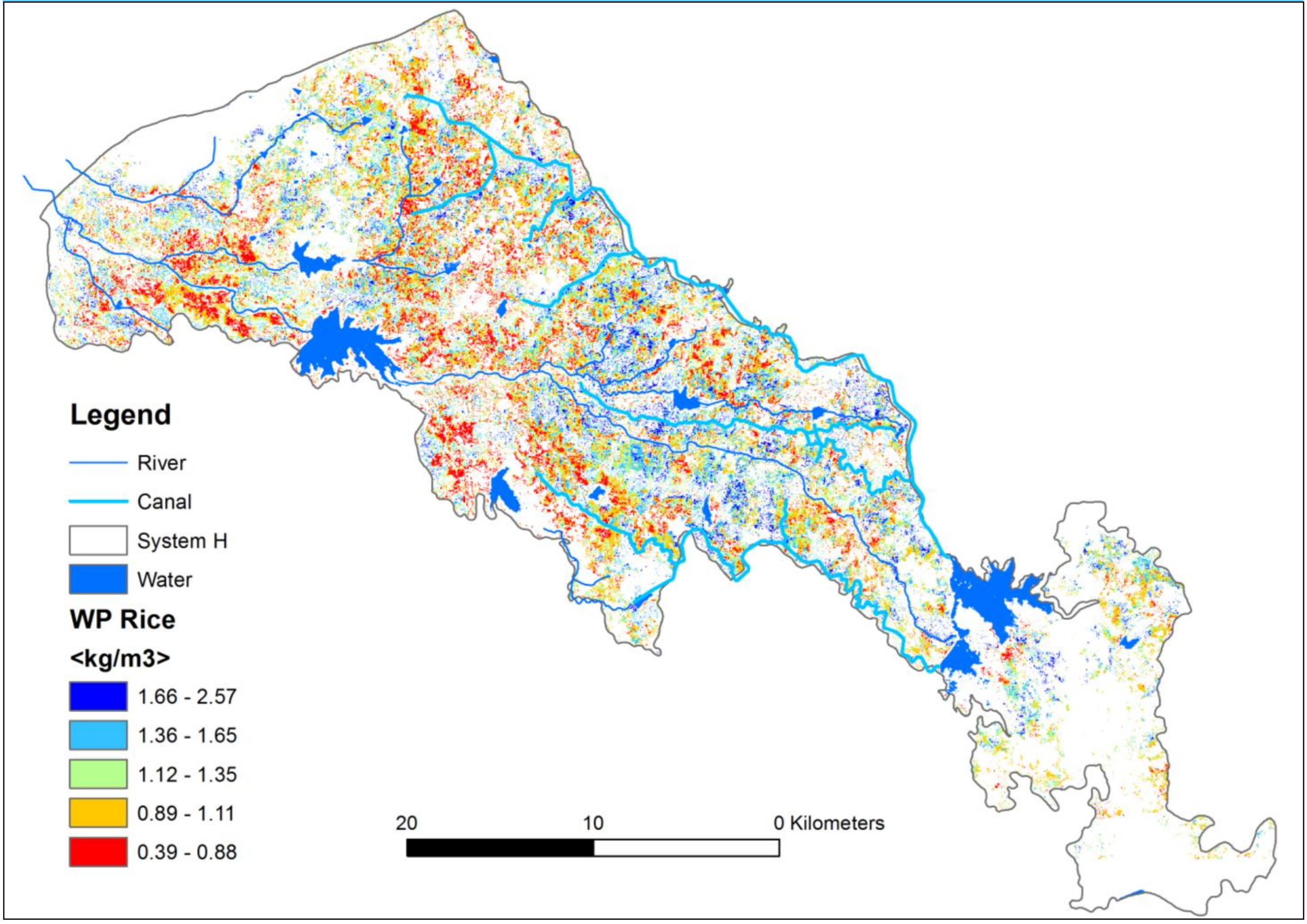

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Executive summary

IHE-Delft in cooperation with the Asian Development Bank (ADB) conducts a pilot project on assessing Crop Water Productivity in Asia, aiming to contribute to sustainable development in Asia's irrigation sector, and create more value from scarce water resources. Sri Lanka is one of the 5 pilot countries where advanced technologies to measure Water Productivity (WP) from satellite data were introduced. Given the challenges such as growing population, expanding agricultural activities, degrading land and increasing water scarcity in upcoming decades, the Sri Lanka government aims to rehabilitate its irrigation systems, third largest in the world. More insights in the spatial distribution of irrigation water and water productivity of rice paddies could contribute to decision-making in current and future rehabilitation investments.

This report describes the assessment of WP of paddy rice in Sri Lanka using the pySEBAL methodology. PySEBAL is a tool that translates raw satellite measurements into maps of actual evapotranspiration and crop production, among others. Crop types of specific growing seasons can also be mapped using satellite images. The actual crop water consumption (i.e. actual evapotranspiration) and crop yield can now be estimated for every 30 m x 30 m, even if data on irrigation water application is not available. With this information, rice production per unit of land (kg/ha) as well as per unit of water consumed (kg/m^3) can be computed. Focus of this study are sites in System H in the Mahaweli Basin. Fieldworks were conducted to support the mapping with 'ground truth' data. The ground truth data is collected with field observations and questionnaire of famers and extension officers. This data, together with secondary data from local governmental institutes are used to verify the remote sensing outputs.

The pilot study demonstrates a successful application of satellite images to assess crop water use, yield and water productivity as baseline condition of 2016 Yala season in System H. The assessment was supported with ground during the growing season. Satellite images from Sentinel 2, Landsat 8, ProbaV and VIIRS were combined to remove the effects of clouds and to develop time series 30 meter resolution maps. The results were analysed to assess the performance of the current system and the potential for improvement. Field data is highly limited, the study also used satelliate information to digitize canals, river streams, and tanks and examined their relation with CWP, ETa, and yield to investigate the reasons for variability in system performance.

The WP maps show poor and good irrigation management practices coincide in the system. The average WP of paddy rice was 1.15 kg/m^3 for the 2016 Yala season, similar to that of the world-wide average value for WP at 1.1 kg/m^3. The average rice yield was 5.1 t/ha and the average ETa was 452 mm. The spatially explicit maps also show variability and the scope for improvement. The coefficient of variations (CV) of WP, ETa, and yields are 27%, 31%, and 17% respectively. The variability is higher than recent studies in Indonesia, Vietnam, and India, indicating greater potential for improvement.

High level of water shortage is found for the study area in 2016 Yala season. Average ET deficit is 156 mm for the entire growing season, which translate to a 26% shortage should the demand be fully met. Several water scarcity is therefore the main constraint for improved food production of the system.

Canals, rivers, and tanks are found to be closely linked with the performance of the system. Positive correlation was found for CWP and yield of rice with distance to canals. The closer a farm is to a canal, the more likelihood this farm will have higher CWP and yields, accompanied with higher water consumption. Similar trend is observed with the distance to rivers. The farms within 250 meter distance to rivers seem to have much higher yield and CWP. The Ta to ETa ratio is also higher in these areas,

indicating better on farm water management in these areas. There are large number of tanks in the system which contribute to high yield but lower performance. Rice yield is positively related to the distance with tanks. The areas closer to tanks have increasing yield, but decreasing CWP. The proximity to tanks give nearby farms better access to water. But unfortunately, such easy access also leads to reduced level of CWP, as explained by rapid increase of ETa.

Significant potential for WP improvement exists, through yield improvement, but also through water savings. The WP maps are created and can be used to indicate potential investment areas. These are often areas of low WP where opportunities for improving are likely present and the biggest. There areas are typically found in downstream areas, but also mid-stream where high performing areas concentrate.

Bright spots of high WP areas, or hero farmers, exist from upstream to downstream. While not always directly comparable, they provide a level of indication of the potential for farmers from the same areas. Furthermore, great water saving potential is observed through separation of Ta, the amount of water consumed through crop transpiration, from Ea, which is evaporation from open waterbodies and soil. On farm water management has the greatest potential in improving CWP. The Ta is 57% of total consumed water. While this is already high, pockets of areas with very low ratio also exists, especially in mid-stream areas. Improving CWP will require close collaboration with these farmers to improve their on farm water management practices.

This research shows promising results linking pySEBAL outputs with the ground truth even though the amount of fieldwork was limited. Clouds hinder the use of satellite images. The inclusion of the new HANTS algorithm proves to be technically feasible, creating the technical opportunity to make daily WP reports for all rice fields in Sri Lanka, also under cloudy conditions. This could be a big information boost to support irrigation managers with their daily services of bringing water to farmers. The HANTS outputs and Landsat outs do not match exactly, due to the inherent sensor difference. A further cross sensor calibration is recommended for future application of the method. Whereas some key explanatory reasons were detected (i.e. distance to canal, river, and tanks), it is recommended to further explore relations between WP and influencing factors in the local context together with local irrigation officers. Even though the research revealed some limitations causing uncertainties, this new remote sensing technologies can support an efficient and effective investment purposes on modernization of irrigation. It is recommended that the Ministry of Irrigation & Water Resources Management and Ministry of Mahaweli Development and Environment recognize WP as a new policy instrument and implement it both at central level and irrigation district level.

The demonstration is coupled with a training on pySEBAL to selected participants. A total of 21 participants learned the concept of WP and followed exercise using state-of-art remote sensing technology to assess CWP in agricultural areas. This training is meant to create awareness and interests. It does not seem to be of sufficient duration to transfer the full modelling capacity. The latter needs to be achieved through more in depth training on the methods, and broader training on remote sensing as well as PYTHON programming, together with sufficient exercises. The HANTS cloud removal algorithm is also particularly relevant for applications in Sri Lanka. Further training, and expose to apply the methodology by a smaller group of persons with reasonable remote sensing background will be essential to take the momentum forward. They can then also act as trainers to distribute the methods to more users.

1. Introduction

1.1 Water productivity for water and food security

Asia is the world's most dynamic region with fastest economic growth. Due to economic and demographic development pressures, water is becoming an increasingly scarce resource. If left unmanaged, this poses a real threat to continued growth and prosperity of the Asia region. The latest analysis by the International Institute for Applied Systems Analysis indicates that 80% of the population in Asia will be water insecure by the year 2050 (IIASA, 2016). Global water demand is projected to increase by about 55% (from 4,500 billion cubic meters in 2010 to 6,350 by 2030) with growing demand from manufacturing, thermal electricity generation and domestic use (Addams et al., 2009). Agricultural demand for water will be most intense in India whereas the People's Republic of China will have the greatest growth in industrial water use.

According to an unpublished and recent research from the WaterAccounting.org group, the irrigation water withdrawals in Asia are about 73% of the global total. Table 1.1 summarize the modelled irrigation water withdrawals by 4 different groups. The irrigation water withdrawals in Asia is estimated to be from 1174 to 3861 with an average value of 2,350 km^3 in year 2010. Over the past few years many Asian countries have seen renewed investment interest into irrigation, leading the region's irrigation development to outpace world average. Hence the role of Asian irrigation systems in the world is dominant, and their management is of great significance to global food and water security.

Table 1.1: Assessment of irrigation water withdrawals in Asia based on 2010 conditions

Data source	**Asia % of world**	**Total irrigation withdrawal world**	**Total irrigation withdrawal Asia**
		Km^3/yr	Km^3/yr
LPJmL model	63.4	1851	1174
Globwat	77.5	2640	2047
PCR-Globwb	86.6	4457	3861
WaterGap	64.5	3591	2317
Average	**73**	**3219**	**2350**

The gap between food production and food demand is increasing in many countries. While this is mainly related to the population growth and changing diets, there is also an emerging issues of insufficient water resources being available to produce the large amounts of food required. Food production consumes significant amounts of water, ranging from 4,000 to 12,000 m^3/ha/season, and for certain tropical fruit crops this can even reach 22,000 m^3/ha. One of the solutions is to produce the same amount of food from less water, or when feasible, produce more food from less water resources (or popular "*more from less*"). The key performance indicator to express this is the crop water productivity (or popular "*more crop per drop*").

Increasing crop water productivity (CWP) involves dual objectives of increasing crop yields and/or reducing crop water use. CWP is a relative indicator and higher WP does not necessarily mean better performance. For example, CWP of rainfed agriculture could be higher than that of irrigated agriculture. Local conditions vary and the potential in crop yields are different. Depending on water resources availability, water saving in agriculture is not always desirable across space and crop growing duration. An assessment by the Challenge Program on Water for Food of CGIAR fund vast differences in the performance of agricultural water management in ten international river basins across Asia, Africa and Latin America (Cai et al., 2011). The CWP changes in spatial and time domain with the changes in underlining yields and water consumption, and that local conditions determine the potential and means for improvement.

1.2 A shift from efficiency to water productivity

The water productivity (WP) concept is developed in recognition of the constraints with traditional irrigation efficiency indicators. The traditional indicators focus heavily on engineering aspects of irrigation, which has a bias towards infrastructure investments like canal lining. It does not capture water reuse in a system and the ability of irrigation systems to turn water supply into food production. It does not reflect the competitive demand from outside the agriculture sector at a larger scale. Figure 1.1 shows that irrigation efficiency in effect represents only a small portion of hydrological processes in a farming system. Irrigation efficiency is not addressing the concepts of consumptive use from a viewpoint of total water resources available. It merely looks at water from sources to the field from a "supplier" point of view. Farmers are more interested in the results of irrigation (e.g. nutrition, income, jobs) rather than on how efficient that production is acquired. Food production is more essential for them, and if water is the major input constraint to food production, it make sense to express it per unit of water consumed. This philosophy is now widely accepted and adopted in the international community, including donor agencies.

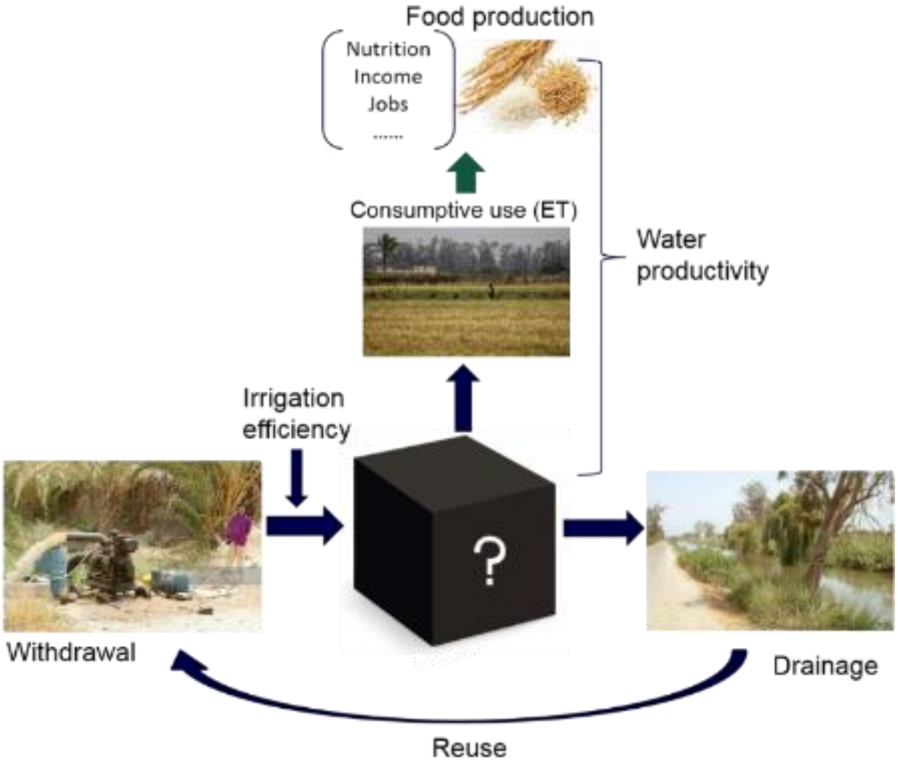

Figure 1.1 The irrigation efficiency and water productivity indicators for irrigation systems. The two indicators are complementary while WP covers more advanced and broader components of irrigation performance.

WP indicators are broader than irrigation efficiency indicators. As shown above WP does not replace irrigation efficiency. Rather it brings two major outcomes of irrigation water management into one single expression: Crop production, the purpose of farming and irrigation, and the water consumed, the means to achieve the production. In achieving higher WP, it is still important to look at field level application efficiency, and cross sector, upstream/downstream allocative efficiency at catchment/basin level.

WP focuses on consumed water. Irrigation systems are highly modified, leading to complex water cycling processes, which is further exacerbated by management practices including irrigation and drainage. Remote sensing (RS) based WP assessment focus on actual evapotranspiration (ETa) – the water actually consumed. Further, the ETa is divided into crop transpiration, a beneficial consumption, and evaporation from soil/water and canopy interception, a non-beneficial consumption from production point of view (Figure 1.2).

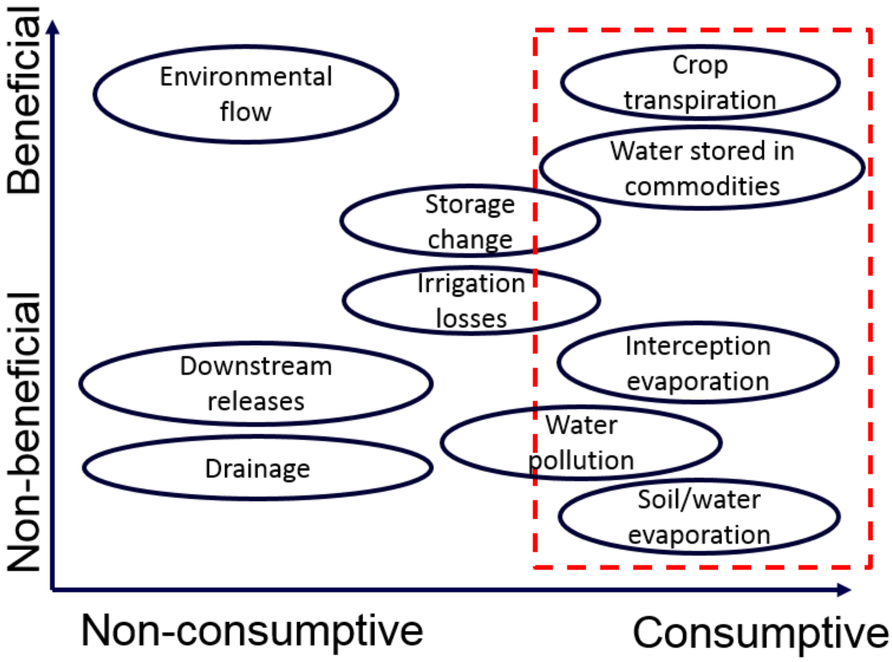

Figure 1.2 Remote sensing based WP approach focuses on the beneficial and non-beneficial consumptive use of water.

WP also promotes more integrated approach to water management. Water productivity was originally an agronomy term to measure plant water use efficiency. It was revised and given a new definition to represent the ability of a system to covert water consumed into goods and services (Molden, 1997). WP is a significant step forward in linking water management with broader policy goals such as water security, food security, and economic development. Kilograms of fresh food can be converted into gross returns ($), employment (jobs), nutrition (calories). Reducing the consumptive use enables more water to remain in the physical system for allocation to other sources. WP benchmark link water managers with development target settings and investment strategies.

Although improving crop water productivity can indeed contribute to the solution to combat the water and food crisis, in reality it is more difficult to achieve crop water productivity improvements at farm level, partially because target values are absent and farmers/irrigators are not guided by any means. They often associate water savings with a lower amounts of applied water, fewer irrigation turns, or a higher on-farm irrigation efficiency, and are not considering the consumptive use of irrigation water and the production that is associated with that.

Various strategic programs ranging from United Nations to National Departments assume that crop water productivity can be improved. This is recently confirmed by scientists from FAO and IHE that showed a skewed behaviour of crop water productivity towards the lower side (see Figure 1.4). This simply means that for many cereal fields, it is feasible to improve water productivity from a below-average value to a mean value. Yield of rice also has great potential for improvement (Papademetriou et al., 2000).

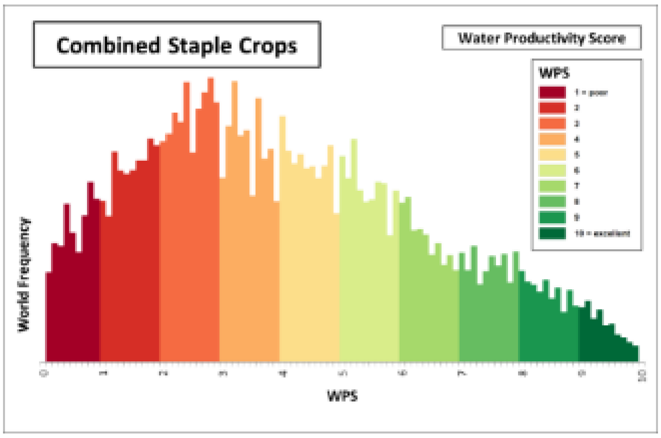

Figure 1.3 Frequency distribution of the Global Water Productivity Score (GWPS) reflecting wheat, rice and maize crops at the global scale. This graph could be created due to climate and crop normalization. A GWPS of 1 is poor and of 10 is excellent (Bastiaanssen and Steduto, 2016)

1.3 The collaboration between IHE Delft, ADB and Sri Lanka on building up capacity in water productivity for better investment

The Sustainable Development Goals (SDG) include goal 6.4 to describe efficient use of water in agriculture. The implication of this, is that countries now have to report on their WP. It marks a significant shift in WP from a research tool (Kijne et al., eds 2003) to a monitoring indicator for policy making and operational management. The term and concept already received attention from international development agencies such as FAO (2003), World Water Assessment Programme (2009), USAID (2009), World Bank (2010), and regional development cooperation such as CAADP (2009). The wide uptake of WP marks a shift from technically focused investment in irrigation and agricultural water management to outcome oriented decision making.

The Asian Development Bank (ADB) results based lending on agricultural water management should lead to increased production and more sustainable water use. While most projects are currently targeting on improving land productivity (kg/ha), this will be complemented with CWP (kg/m^3) improvement requirements, in new projects and lending during 2016 and beyond. It is rather unclear - however - what the current status of water productivity is, both at the start and at the end of ADB-related projects. There is a large gap in the understanding of the concept of CWP at various levels, and how to measure and implement it. A capacity building program for stakeholders is necessary. Policy makers, irrigation engineers, agronomists and practitioners should be reached. This cannot be accomplished with a short term project, but a start needs to be made with introducing the concepts and make some local diagnosis of good and poor performing farms.

To make the start, IHE is working with ADB to raise awareness, build capacity, and test frontiers of CWP with irrigation and water managers in five Asia countries (Vietnam, Indonesia, Sri Lanka, India, and Pakistan). The project will establish a performance baseline for irrigation systems which can be used to measure the benefits of ADB investments. The implementation of the project will be carried out closely with national partners to raise the awareness of using CWP to benchmark agricultural water management, hence improving the planning, design, and management of irrigation systems.

The overall objective of this pilot and capacity building project is to help improve planning processes of the ADB investments in water security and irrigation systems, and enhance capacity to countries on the concepts of CWP. The recipient organizations were explained on the difference between water productivity and irrigation efficiency. They were offered a training course for technical staff to gain hands-on experiences in using satellite images to assess irrigation water consumption, crop yields, and CWP. They also learnt how to diagnose good and poor performing fields, as well as determining improvement potential through scenario analysis. A CWP diagnosis of selected irrigation projects in these countries is provided in this report to the local organizations to demonstrate the technology, and provide inputs to ADB on-going irrigation investment projects. Information on fields familiar to local partners will increase their understanding on how to operationalise concepts of CWP under practical conditions in Asian developing countries.

The project is expected to contribute to ADB agenda on water security which is heavily underlined with irrigation water use in many Asian countries. “More crop per drop” will help ADB and its clients look at more efficient way of developing and managing the biggest water user – irrigation, and potentially, exploring possibility of building WP as diagnostic tool and monitoring indicator into ADB and country investment and management plans (figure 1.7).

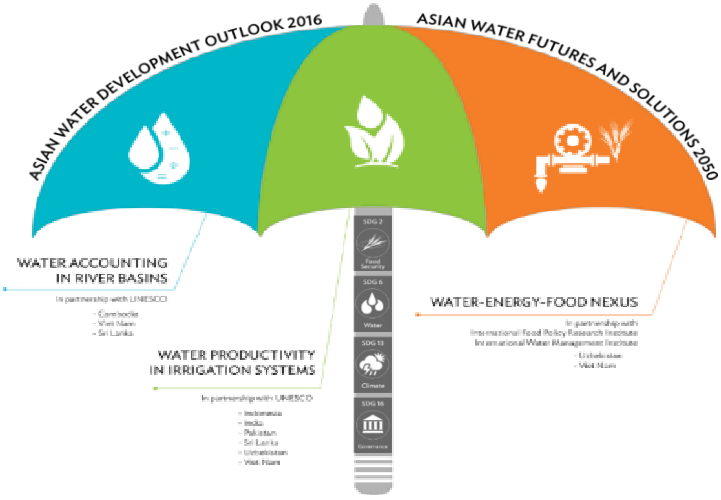

Figure 1.4 The role of Water productivity in irrigation systems, the single biggest water user, to support ADB initiatives for Asian water security. (Source: ADB, 2016)

The project was implemented with close collaboration with the Ministry of Irrigation & Water Resources Management and Ministry of Mahaweli Development and Environment (MMD&E). The scope and sites of the project in Sri Lanka was agreed through a consultation meeting with the ministries in May 2016. Rice, a dominant crop in Sri Lanka, was set as the main crops for pilot study.

1.4 pySEBAL training workshop

A pySEBAL training workshop was organized as part of the capacity building of the project. The objective of the training workshop is to introduce the concept and frontiers of crop WP (CWP) for applications in irrigation investment and management, and to build up in-house capacity using RS and model tool (pySEBAL) for assessing CWP. Specifically:

- What is CWP?
- How to use SEBAL and satellite data to assess CWP?
- How to use the results to improve irrigation planning, design, and management.

A separate training on QGIS, organized by ADB Sri Lanka Resident Mission, was conducted prior to the pySEBAL training workshop in order to prepare the participants. This was helpful as the pySEBAL CWP assessment involves heavy GIS processing. In addition, the QGIS trainer was also present again at the pySEBAL training workshop to help with hands on exercises.

The pySEBAL workshop was organized with the two concerned ministries at the Kothmale International Training Institute, from 26 – 30 September 2016. The 5-day workshop was divided into two parts: the introduction and field trip in Tambuttegama, and the second part on pySEBAL and hands on exercises. A total of 21 participants completed the training. About half of them are from MMD&E and half from the Irrigation Department. The workshop schedule and list of participants can be found in annex 5.

The tailor-made-training course includes introductions to general introduction to RS, RS data and the applications for agriculture and water management. The training then focused on hands-on exercises with pySEBAL model. Data for an area in Northern Sri Lanka was provided for exercises, based on which, the participants were able to reproduce water productivity and associated maps at the end of the training workshop. They were also taken through the results to learn how to interpret the maps, and conduct analysis to extract information useful for planning and management.

2. Overview of the methods

IHE Delft has developed a method for CWP assessment in irrigation systems. The methodology, centered on the tool pySEBAL, uses satellite images and weather data to map agricultural water consumption (actual evapotranspiration), crop yields, and crop water productivity. pySEBAL is the latest development of the well-known SEBAL model, an ETa algorithm (SEBAL stands for Surface Energy Balance Algorithm for Land). It is based on Python, an open source language, and built in crop growth simulation model and CWP algorithm. The remote sensing based approach revolutionize how we could assess field conditions. It does not require field water measurements, which is a main obstacle in many countries. It is however very important to validate the results, especially crop yields, and to help understand the results from image analysis. Field survey is therefore needed to collect crop type and crop yields. Information on infrastructure, soil, management practices, seeds and fertilizers etc. will also help understand the variability of performance, and develop appropriate recommendations. An overview of the methodological flow chart is given in figure 2.1. More detailed description of the pySEBAL model is attached in annex 2 (manual) and annex 3 (list of publications).

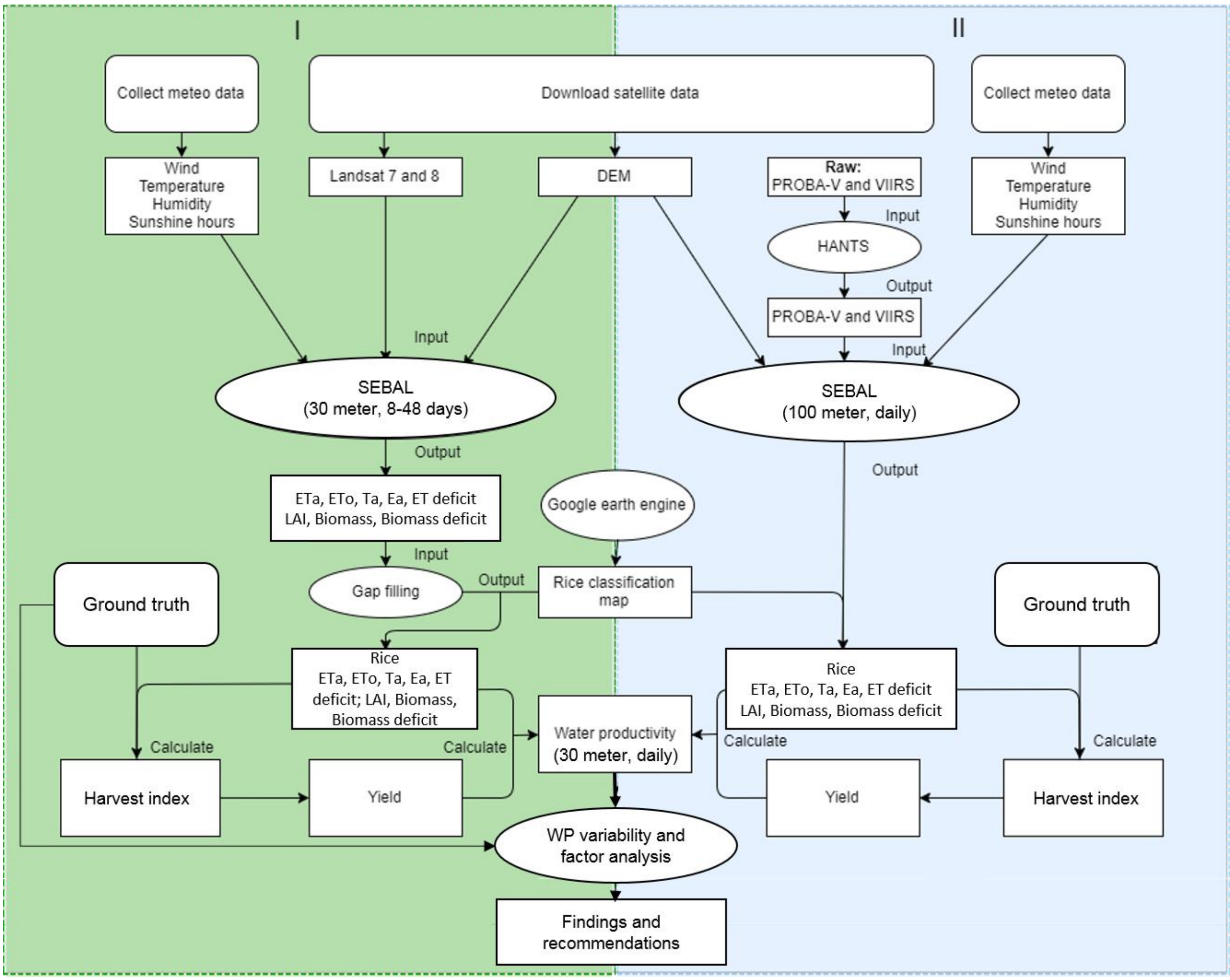

Figure 2.1 The methodological framework of CWP assessment. In this case two parallel processes, one using Landsat images, another using Proba-V/VIIRS images were used to calculate CWP separately. The results are then integrated to capture daily dynamics

The current version of pySEBAL automates most of the image processing processes. The pySEBAL version 3.3.7 incorporates several new developments towards improving accessibility by users. These include open source, open data, and automated processing of various options of input data, which represents several breakthroughs for public uses. PySEBAL, however, does require a crop type map to estimate crop specific yields and water productivity.

2.1 Open source automated approach

Python is an open source programing language widely used by research community and industries. Python based models are transparent and users can exam or modify each and every command or module to their needs and specific contexts. For simplicity the pySEBAL is designed in a way that all the inputs are organized in a separate Excel file where users fill in image information and weather data, and have the opportunity to change few parameters such as soil properties and crop height.

Automated processing represents one of the major technological advance of the new model. PySEBAL can now automatically process images from raw data to a range of outputs, avoiding previous manual hot and cold pixel selection processes, therefore reduces experience related uncertainties. The automated version involves no manual image preparation or processing, which can greatly reduce processing time for multi-year seasonal analysis which often involves large amount of images. The model is accessible through a GitHub: https://github.com/wateraccounting/SEBAL.

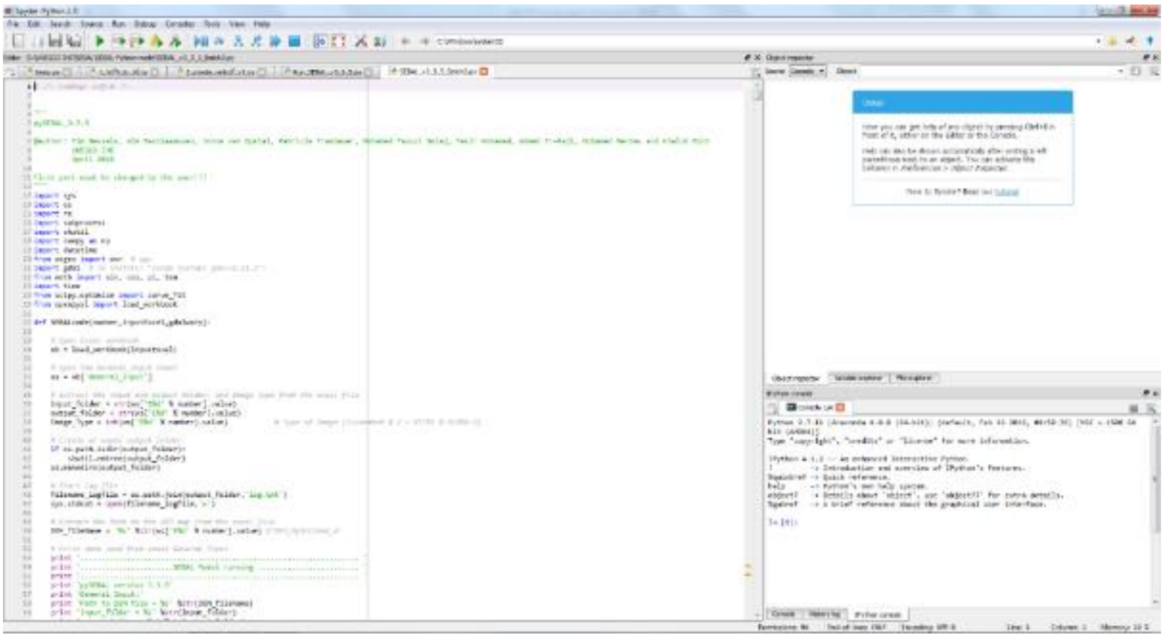

Figure 2. 2 Screenshot of the Spyder2 (a version of Python) software as platform for implementation of pySEBAL

2.2 Open access data

Open data approach is another underlying principle of the new pySEBAL model. Currently, data supported include Landsat 5, 7 and 8 images (from 1984 to date), ProbaV and VIIRS (from 2013 to date) and MODIS (from 2002 to date). In addition, the model can also take separate image inputs such as NDVI, Albedo, SAVI and land surface temperature, meaning users can process from other any possible image sources. The spectral definitions and additional information provided varies from Landsat 5 to 8. The Landsat number therefore needs to be specified among the input requirements. While Landsat 5 and 7 have a single thermal band, Landsat 8 has a dual thermal system. Users can use either of the bands or both. The default is to use both thermal bands.

There are also images from several other public domain satellite sensors not included in current version of SEBAL. Examples include Sentinel from European Space Agency (ESA), and many other sensors with multiple spectral bands. Although many lack thermal bands required for land surface energy balance, images of these satellite sensors are useful for water productivity assessment at irrigation scheme, river basin and country level. PySEBAL development will continue to expand support to more data sources.

2.3 Crop type mapping for crop specific assessment

PySEBAL processes the surface energy balance and plant growth at landscape level with a grid of 30 m independent of crop type information. All c3 crops namely show the same response to solar radiation and environmental conditions. The ETa and biomass production of individual crops can be made without any a priori information on the type of crop and type of soil. A crop map is however required for making crop specific production analysis such as for (i) crop yield and (ii) water productivity. The storage organs that will be harvested are a fraction of the total biomass production, and this fraction (i.e. harvest index) is thus crop dependent.

A two-step classification process was used to map main crop types of the study area. The first step is to map cropland from Sentinel 2 images, and the second step is to map crop types from within cropland areas using time series outputs from pySEBAL. Acceptable clear sky image for land cover classification was only available outside of the Yala season. So these images (from 22nd March 2016) were used to map cropland areas. This step employs standard supervised classification method using groundtruth and Google Earth zoom-in views as training samples. The second step therefore looks at ETa changes over the cropland areas, and separate rice paddies from other crops and fallow cropland for the Yala season. This is based on the assumption that paddy rice has the highest ETa rate compared with other crops for the rice growing period, as well as the period preceding transplanting dates (early vegetative period).

2.4 HANTS algorithm for cloud removal and reconstruction of daily time series

Time series data helps continuously monitor crop and water conditions, detect periodical stresses, and better estimate seasonal total water consumption and production. Satellites like Landsat series have a revisit period of 16 days, which provide reasonable temporal coverages to cover key crop growth stages. However, clouds could significantly reduce the availability of clear sky images and affect the data continuity. The influence is stronger in tropical areas and in rainy seasons, which typically are the main crop growing seasons. An algorithm, called HANTS - Harmonic ANlysis of Time Series (Menenti et al., 1993, Verhoef et al. 1996), was therefore adopted and developed to fill up the pixels with cloud contamination and further, to reconstruct time series at daily intervals.

The HANTS algorithm is based on Fourier transformation of input variables. A Fourier transformation decomposes a time series into several sub-components (called harmonics) which can then be used to recreate the original curves. Outliners, as identified by a set of input parameters, are removed during the transformation process (figure 2.3).

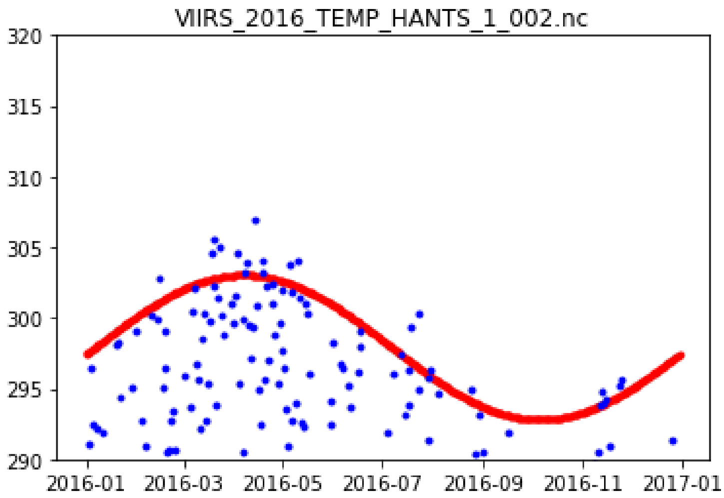

Figure 2.3 HANTS reconstruction of daily time series VIIRS surface temperature data

HANTS algorithm was coded in python and applied to PROBA-V and VIIRS images for the Vietnam sites. Both PROBA-V and VIIRS images have daily repeat. The PROBA-V 100 meter top of canopy reflectance was used to calculate NDVI, SAVI and ALBEDO. The VIIRS single thermal band SVI05 (375 meter) was used to estimate the land surface temperature. Figure 2.4 illustrates a test using VIIRS 2015-16 data. The left image shows the original input with presence of clouds. The right image shows the HANTS reconstructed images of the same date after the clouds are removed. Overall the algorithm is capable of removing clouds with good spatial variability, and extrapolate to daily time steps. The quality however tends to reduce if the no-data gap prolongs.

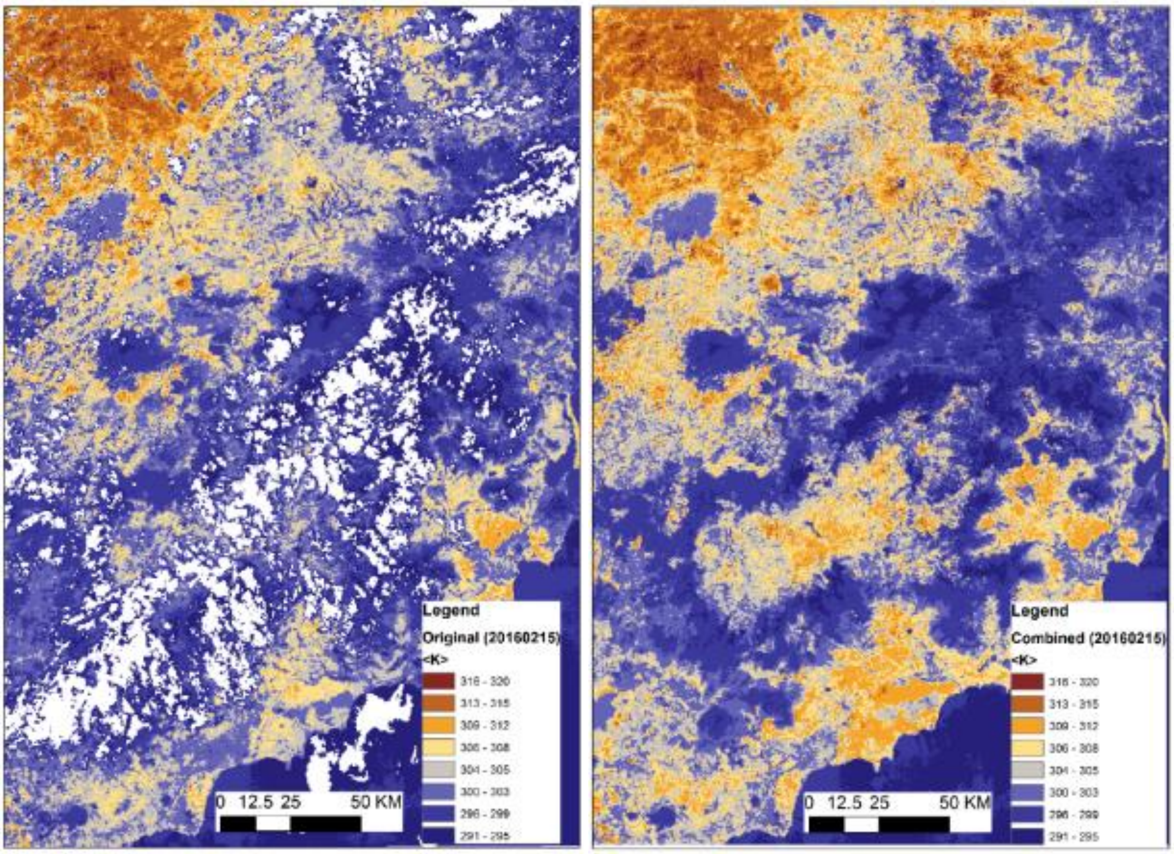

Figure 2.4 VIIRS land surface temperature (before and after) using HANTS algorithm

The outputs from Landsat images and ProbaV/VIIRS images are integrated to produce one set of daily outputs. The Landsat 7/8 has a higher resolution of 30 meter but a combined revisit period of 8 days, which could be further worsen with presence of clouds. The ProbaV/VIIRS are daily images and have gone through cloud removal algorithm with HANTS. It therefore has a spatial resolution of 100 meter at daily time step. These two sources of maps can be combined to produce outputs at 30 meter resolution on daily repeat.

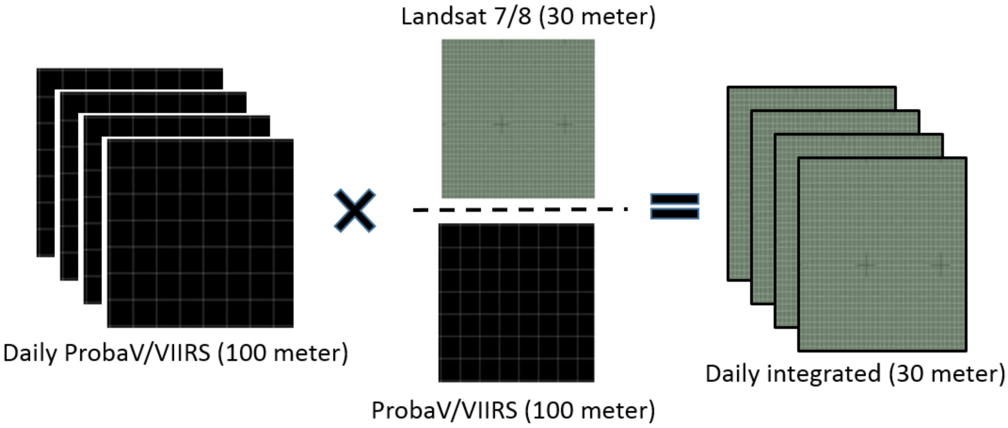

Figure 2.5 Integration of ProbaV/VIIRS and Landsat outputs to achieve results at 30 meter resolution daily step

2.5 Smart phone based field survey

Ground truth survey was conducted using smartphone application. A GT survey form was developed digital forms and built into an Android smart phone application ODK Collect. ODK Collect takes advantages of the GPS, camera, and internet connection capability of smart phones. It can record the coordinates, text description, multi-choice selection, and multimedia such as pictures, voice recording and videos. Two types of data collection forms were designed: the normal mode which has questions on crop yield, growing season, water management and canal information etc to be answered by a farmer in the field; and a quick mode which allows for non-stop quick tagging of crop type on the map. A detailed description of the GT survey methods and the ODK Collect is attached in Annex 3.

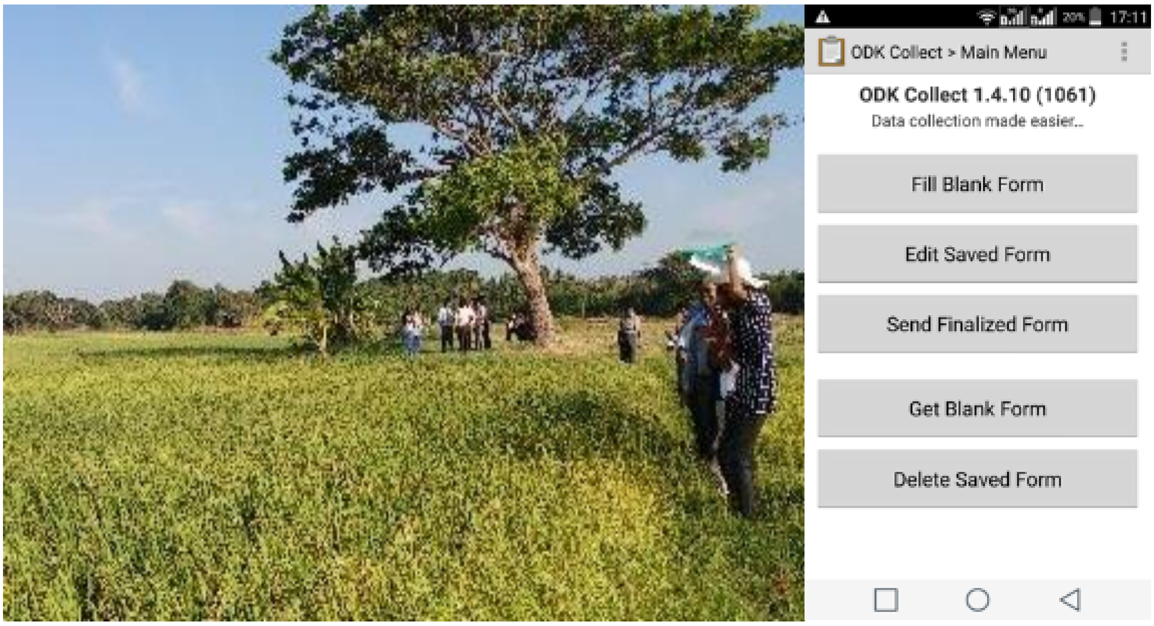

Figure 2.6 Ground truth with smart phones. On the right is the interface of the application

3. Project areas and data collection

3.1 Study area

System-H is an irrigation system in Mahaweli River Basin with diversion from Mahaweli Ganga. Currently System-H is a combination of the ancient Kala Wewa irrigation system and a few tank irrigation systems shared by Kurunegala and Anuradhapura Districts. The system is located in the dry zone of Sri Lanka. It is characterized with two monsoon seasons, the drier Yala season from April to August and the wetter Maha season from September to March. Periodical droughts severely impact the area (Burchfield and Gilligan, 2016). The current irrigation area is estimated to be 29500 ha with average size of 1 ha per family. There are also considerable areas designated for ecological conservation with forest, wetlands and water bodies. The main soils are Tropaqualfs for lowlands and Rhodustalfs for uplands respectively.

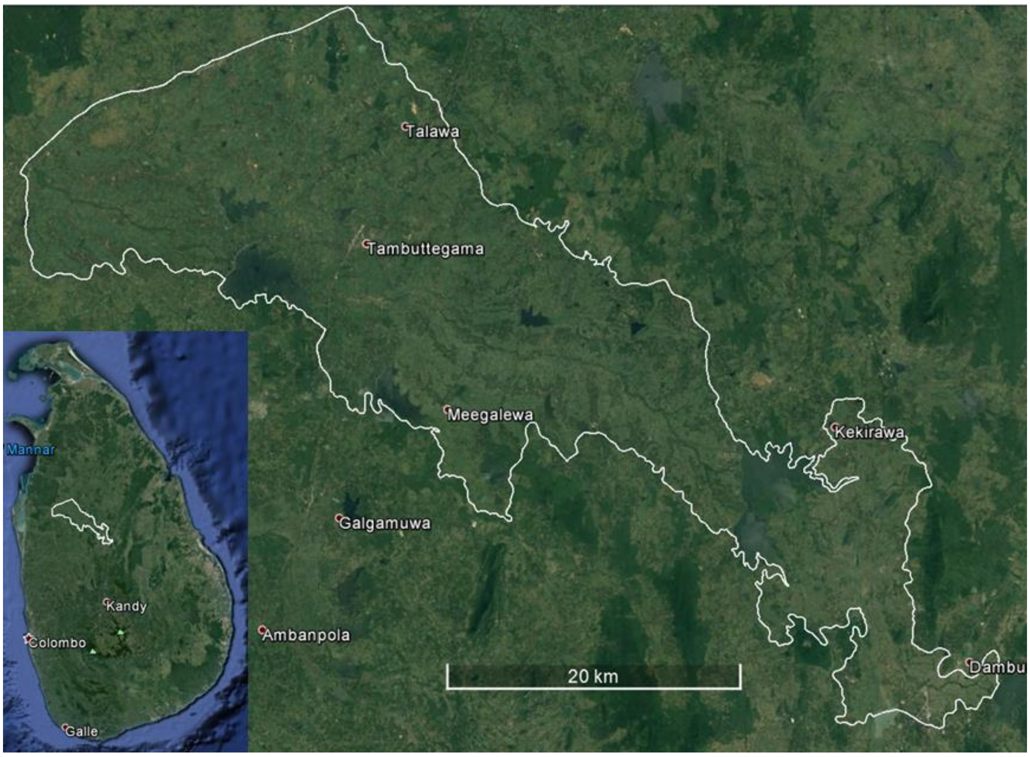

Figure 3.1 System H study area

Rice is the dominant crop in the system. Cultivation of rice in the system is largely dependent on water availability and therefore, has a significant variations in Yala season crop areas year to year (figure 3.2). The year of 2016 is reported to be very dry year and as a result, the Yala rice growing area is low. Apart from rice, the other single crop with notable areas are soybean. The area ranges from about 2000 ha to over 5000 ha in recent years.

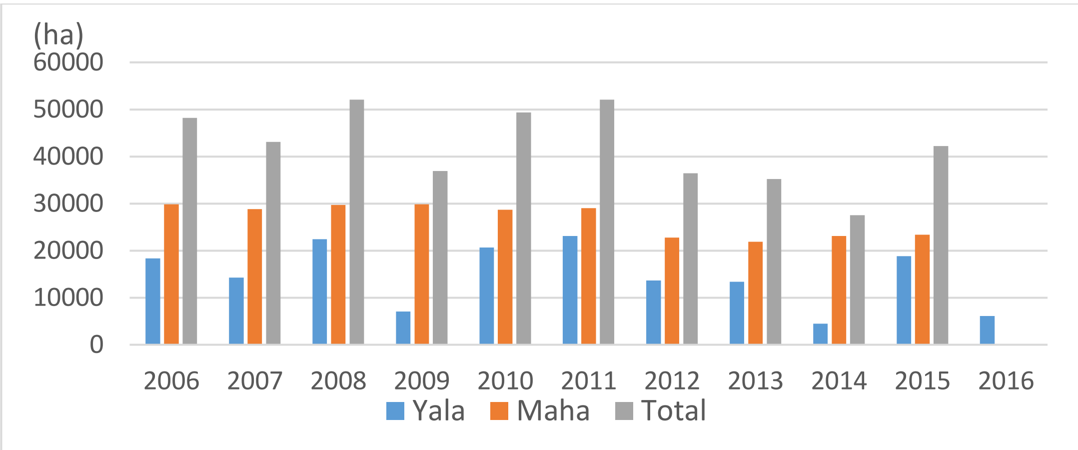

Figure 3.2 Rice cultivation areas in System-H from 2006 to 2016 (only Yala season is available for 2016). Data source: Ministry of Irrigation

Irrigation water is supplied in two seasons. During Maha season there is generally enough water thanks in part to a cross-basin transfer. But water shortages are observed during Yala seasons. In order to cope with water scarcity, less water intensive crops, such as chili, opinion, soybean, corn and vegetables were promoted.

3.2 Crop

Rice is the crop of focus of current assessment. It is a water intense crop generally involving land preparation and vegetative growth stages. Field preparation is necessary for both transplanted and direct seeded rice. The duration of field preparation and amount of water used depends on field conditions. In general, field preparation takes 3 – 4 weeks. A rice cycle has different growing stages: the Vegetative Phase, Reproductive Phase and the Ripening Phase (Figure 3.3). Rice is transplanted (in few cases directly seeded) in puddle soil. After transplanting the field is flooded either continuously or in intermitted stages throughout the three phases to maintain anaerobic conditions (IRRI, 2017). The water depth is increased with biomass growth, ranging from 3 to 10 cm. To maintain a shallow flooded field, irrigated rice fields are levelled and embanked. Up until 7 days till 3 weeks before harvesting the field is drained.

Rice growing season depends on individual famers but are broadly in line with irrigation release dates. The first date of irrigation water issue for planting was 15 May 2016 and the last water issue before harvesting was 13 September. The estimate peak of planting season was the first week of June while field survey shows some variability between the end of May to second week of June, and the harvest dates from early to end September. The study period is therefore determined to be from 15 May to 25 September, 2016. This is a total of 134 days including land preparation and possibly a short post-harvesting period for most fields.

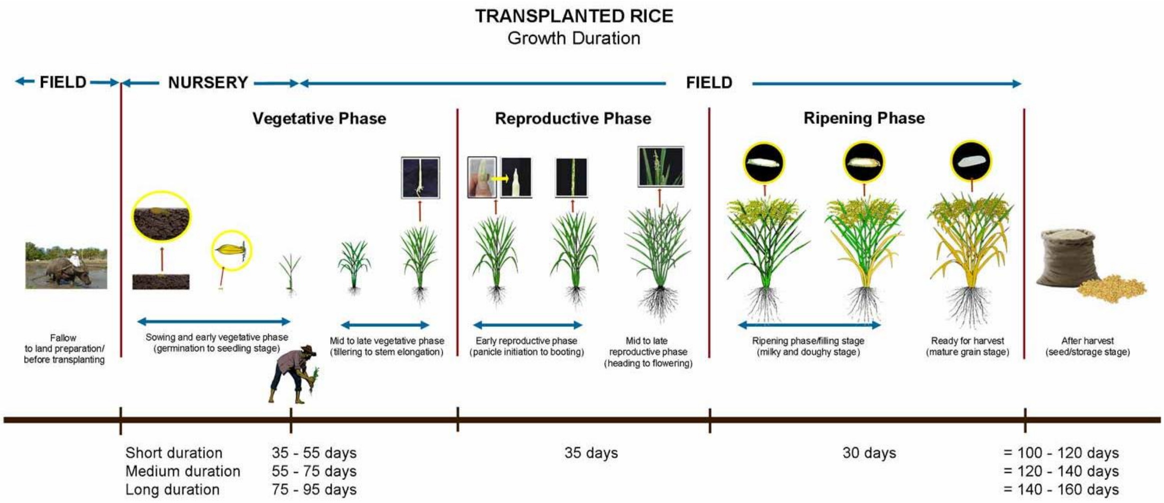

Figure 3.3 Growing stages of a rice cycle (Source: IRRI, 2017)

3.3 Data

Landsat 8 and Sentinel 2

Landsat 8 imagery is one of the most widely used images in the field of natural resources and agriculture. The have 30 meter resolution in multispectral bands while the thermal band is 100 meter. They have a 16 day repeat cycle. Clouds however could affect images, especially in tropical countries like Sri Lanka. In pySEBAL the areas affected by small patches of clouds are filled up using a linear interpolation algorithm. Sentinel 2 images are of 10 meter resolution. It does not provide thermal band as Landsat 8 does, therefore not useable for pySEBAL processing at the moment. But the 10 meter resolution image is a good source for land cover classification and crop identification.

System-H project site was covered with Landsat 8 path/row of 141/054. Images from the period of 2 May to 30 23 September 2016 were downloaded from the USGS EarthExplorer data centre (https://earthexplorer.usgs.gov/). A total of 5 images were downloaded but only 3 found to be of usable quality after removing the heavily cloud contaminated images. Two Sentinel 2 images of 22nd March were downloaded for landcover classification.

PROBA-V and VIIRS

The PROBA-V is a satellite from the European Space Agency focusing on vegetation. Its images are freely available at a spatial resolution of 100 meters and daily repeat. The PROBA-V satellite has 4 bands; Blue, red, NIR and SWIR. The high temporal revisit frequency of PROBA-V makes it less affected by clouds when using the 5-day composite product. These together with VIIRS daily temperature data will further go through HANTS cloud removal process.

VIIRS stands for Visible Infrared Imaging Radiometer Suite. This satellite uses a whiskbroom scanning radiometer (NOAA guide). The whiskbroom scans sideways (cross-track) in aspect to the satellites direction, provides 22 imaging and radiometric bands including applications like sea surface temperature, aerosol and vegetation (NOAA VIIRS). The I05 band from VIIS, which measure brightness temperature at 375 meter resolution, is downloaded for application with pySEBAL model. The images are sharpened to 100 meter resolution using NDVI layer to math with the resolution of PROBA-V.

Weather data

The pySEBAL requires daily and instantaneous weather data at image capture time to estimate land surface energy balance. Daily and hourly weather data from April to October 2016 was obtained from the Maha Illuppallama meteorological station of the Field Crops Research and Development Institute. The data items includes temperature, relative humidity, wind speed, solar radiation and sunshine hours.

Ground truth

Field campaign is needed to collect crop type and crop yield information, as well as other secondary data. The work was carried out through an external consultant with technical guidance from IHE. The activities were carried out from July to September in 2016. The field trips identified crop types, water use information, and crop yield and crop management practices. Among the total of 58 GT points collected, 31 was for rice, 5 for soybean, 5 for fallow cropland, and 4 for corn. Secondary information on water users associations, water quality, seeds, etc, is also collected. Annex 3 provides more details into the ground truth methods.

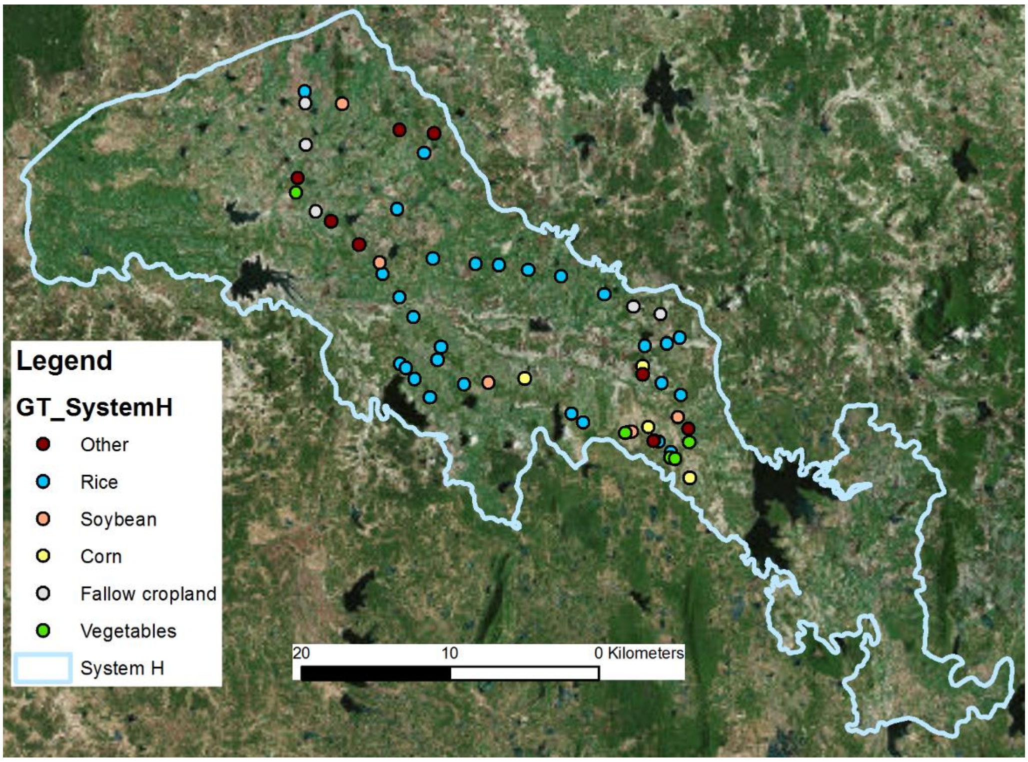

Figure 3.4 Groundtruth points in System H

4. pySEBAL results for system H

During the analysis of pySEBAL outputs it became clear that paddy rice could have different start of growing seasons and harvest time even in the same irrigation system. This is determined based on the development of vegetation measured using biomass production. For overall system assessment it is therefore necessary to select a slightly larger window of time to accommodate the cropping calendar difference. This may introduce extra "water consumption" for fields that are harvested earlier. However it is an acceptable compromise as we expect post harvesting ETa will be very low from the fallow land. With consideration on vegetation changes from satellite iamges, the assessment period was determined to be from the period in between 16th May to 30th September, 2016. It therefore includes the land preparation phase which includes large amount of irrigation water supply.

4.1 Crop area

Sri Lanka is a tropical country with clouds severely affecting the use of optical remote sensing images. Mapping of cropland and crop types are therefore not always possible due to presence of clouds. A broad search into normal optical satellite images reveals no "clear" images are available for the Yala season of 2016. Instead, good quality SENTINEL 2 images were found for the 22nd March of 2016.

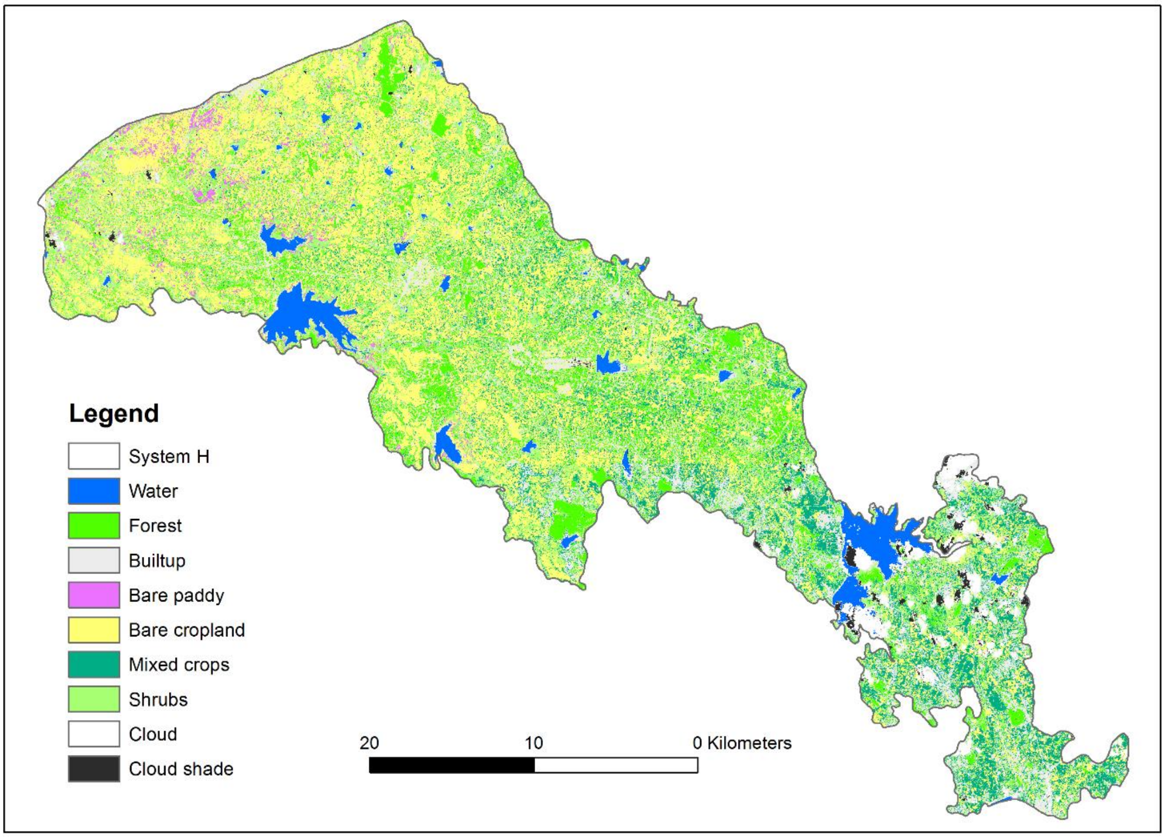

Figure 4.1 Land cover map of System H. The cropland area is mapped but crop types are not separated.

The area is dominated with agricultural land but also abundant shrub lands, forests, and water bodies. Of the total area of 95 955 ha area covered in system H boundary, about 47 136 ha is cropland, 27 588 ha for forest and shrubs, 3 520 ha of waterbodies, and 14 109 ha for builtup area. There was about 3 600 ha of area covered with clouds and cannot be identified. In total, 35 588 ha of paddy rice was mapped.

4.2 Water consumption (ETa)

The actual evapotranspiration (ETa) map of System H is generated combining daily Proba-V/VIIRS outputs and Landsat 8 outputs. Figure 4.2 shows the ETa ranges from 300 to over 800 mm and the average is 452 mm with a standard deviation of 75 mm. The ETa map shows that areas upstream to the Kala Wewa reservoir generally low, with other low areas observed downstream of the reservoir, and the furthest downstream of the system to the North West. High ETa areas are found to be in the mid-stream where extensive distribution of irrigation canals, rivers, and tanks exist.

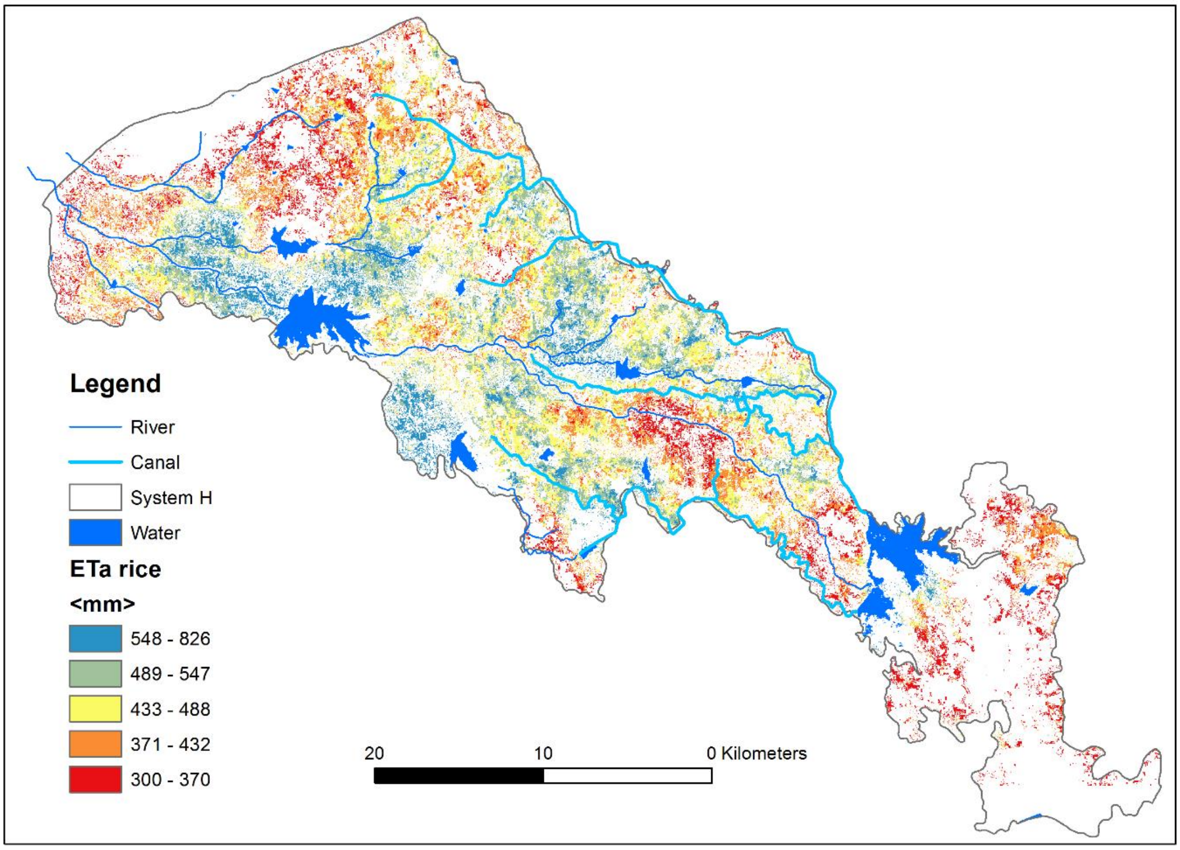

Figure 4.2 Map of actual Evapotranspiration for rice in System H for the period of 16 May – 30 Sept 2016.

The ET deficit is the difference between ETa and potential ET. It measures the less of stress the crop in achieving potential ET. ET deficit map is shown in figure 4.3. The ET deficit averages at 156 mm with a standard deviation of 64 mm. The deficit is high, indicating high water stress in the area during the study period. High deficit areas are generally found in low ETa areas, which pin-point areas for attention for planning and management of the system.

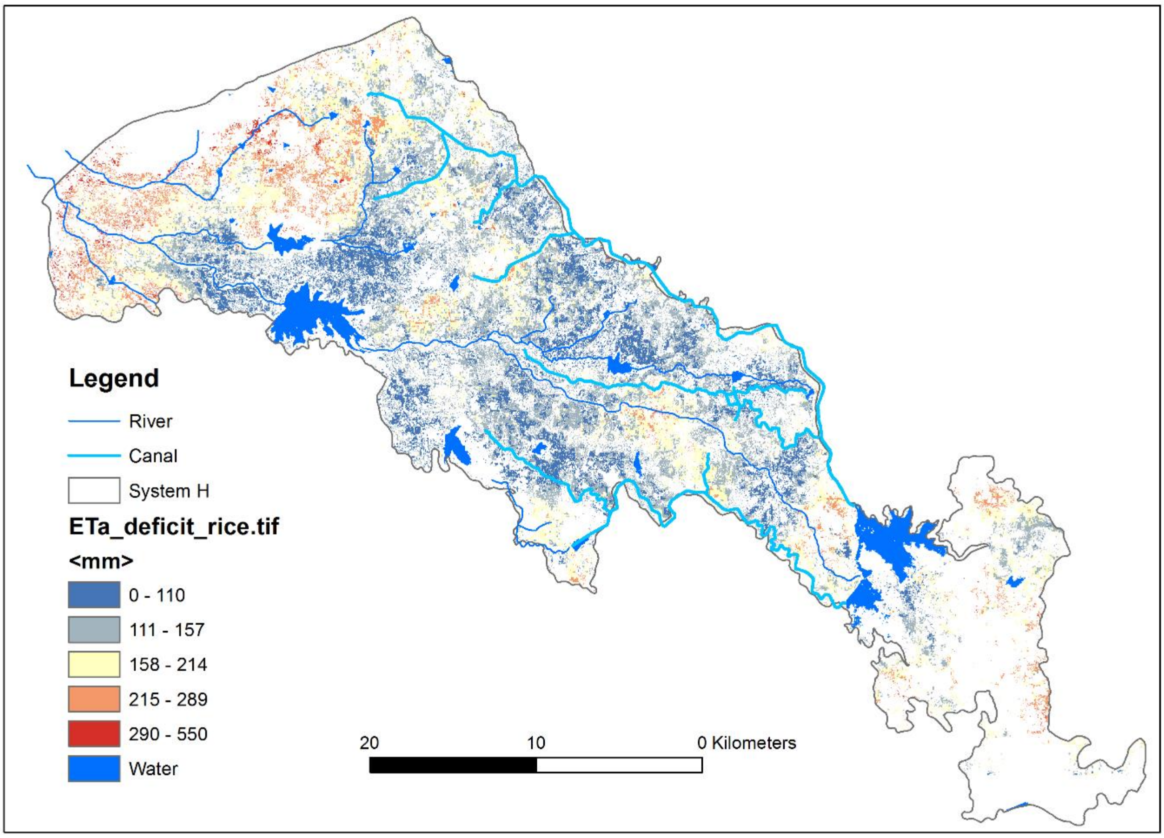

Figure 4.3 Map of the ET deficit (mm) of paddy rice in System H for the period 16 May – 30 Sep 2016.

The transpiration of the rice plants is the beneficial evaporation which is used for the plant to grow. The map of the transpiration can be found in figure 4.4. Transpiration is the water consumed by crops through canopy photosynthesis process. It is therefore also considered a beneficiary consumption in production point of view. The average value of transpiration is 219 mm with a standard deviation of 91 mm. high variability is again observed not only in terms of standard deviation, but clearly present on map showing different trends with maps previously shown. Although most high Ta areas are still observed in mid-reach areas, the variability is considerably higher. Which indicates that the famers' ability to turn field water consumption to useful crop water consumption is different. There are significant potential for improvement through on farm water management practices.

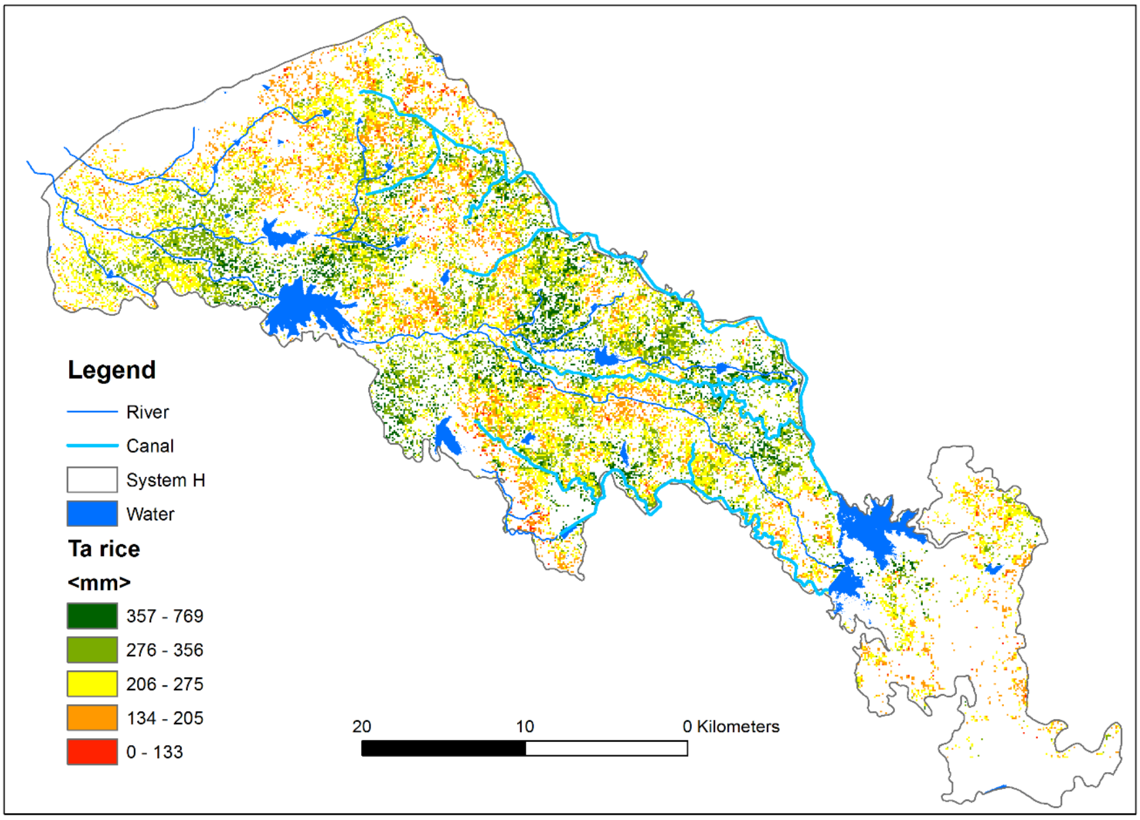

Figure 4.4 Map of the Transpiration, or beneficiary water consumption (mm) of rice, 16 May – 30 Sep, 2016.

4.3 Crop yield

The crop yield is mapped through biomass first and then converted to yield map using harvest index established with field data. The average biomass mapped for paddy rice area is 10.4 ton/ha. A field survey of 24 farmers recorded their estimated crop yield and location. The average yield of these points are 5.1 ton/ha, corresponding to an average biomass production of the same locations at 10.0 ton/ha. Using the yield divided by biomass production we can calculate the average apparent harvest index to be 0.521, in line with those reported in literature. The GT data and harvest index calculation can be found in annex 4.

Figure 4.5 shows paddy rice yield map. The average yield is 5.2 ton/ha with a standard deviation of 1.6 ton/ha.

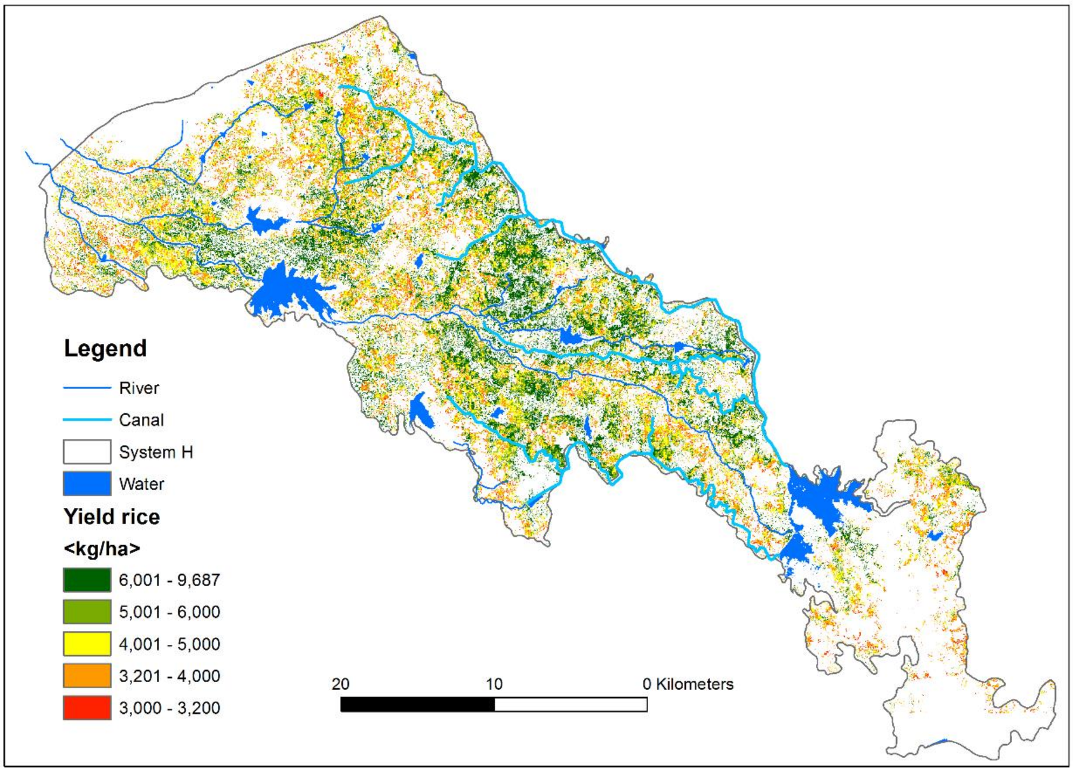

Figure 4.5 Map of rice yield (kg/ha) for System H for the 2016 Yala season

4.4 Water productivity

Water productivity maps of rice were produced using the yield maps divided by ETa maps, after the units were converted. Figure 4.6 shows the WP map of rice produced for System H. The WP ranges from 0.39 to 2.57 kg/m^3. The average is 1.15 kg/m^3 with a standard deviation of 0.31 kg/m^3. The average WP is relatively low compared with values frequently reported in literature. The variability seems also to be higher than those reported in other countries through the same project.

The CWP map shows combined effects of yield and water consumption. High yield areas do not always have high WP values, due to the results of high water consumption. In areas where ETa is low, however, some have low CWP due to very low yield, and some other areas have high CWP values. The high variability is clearly visible on the histogram (figure 4.7). There is a wide spread of WP in different areas (represented by number of pixels on the vertical axis). In general, the narrower the histogram, the more uniform the WP, hence performance, is. Management needs to explore reasons to narrow the differences.

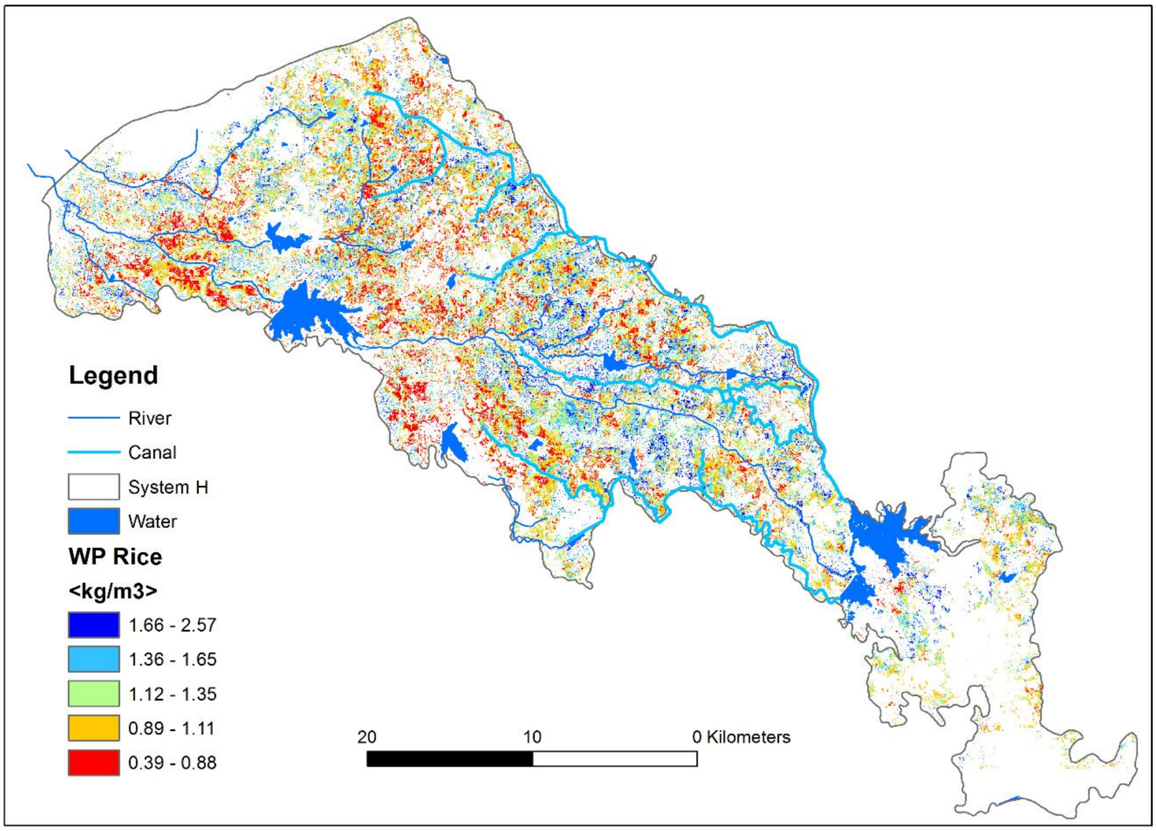

Figure 4.6 Map of rice crop water productivity (kg/m^3) for System H for the 2016 Yala season

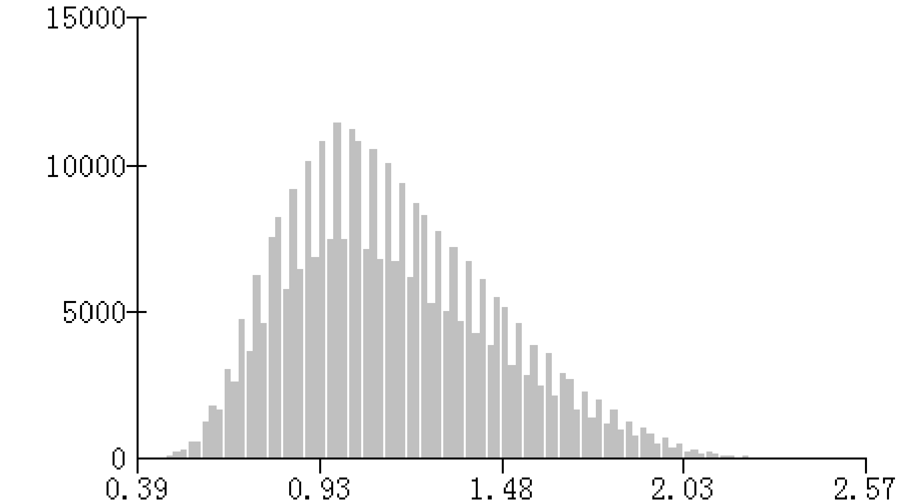

Figure 4.7 Histogram distribution of rice water productivity map

4.5 Factors affecting water consumption, yield and water productivity

The remote sensing based approach provides a detailed but also quick snapshot of what is happening on the ground. To understand the spatial distribution of the results, information from the ground is compared to the pySEBAL outputs. This study collected secondary information to understand how WP, yield, ETa and Ta changes in relation to each other. The results of CWP assessment are compared with the following factors: canal and river networks as well as distribution of waterbodies (figure 4.8). The findings of the comparisons is explained in the following section. More factors should be considered if the data is available, and can be done in a similar way.

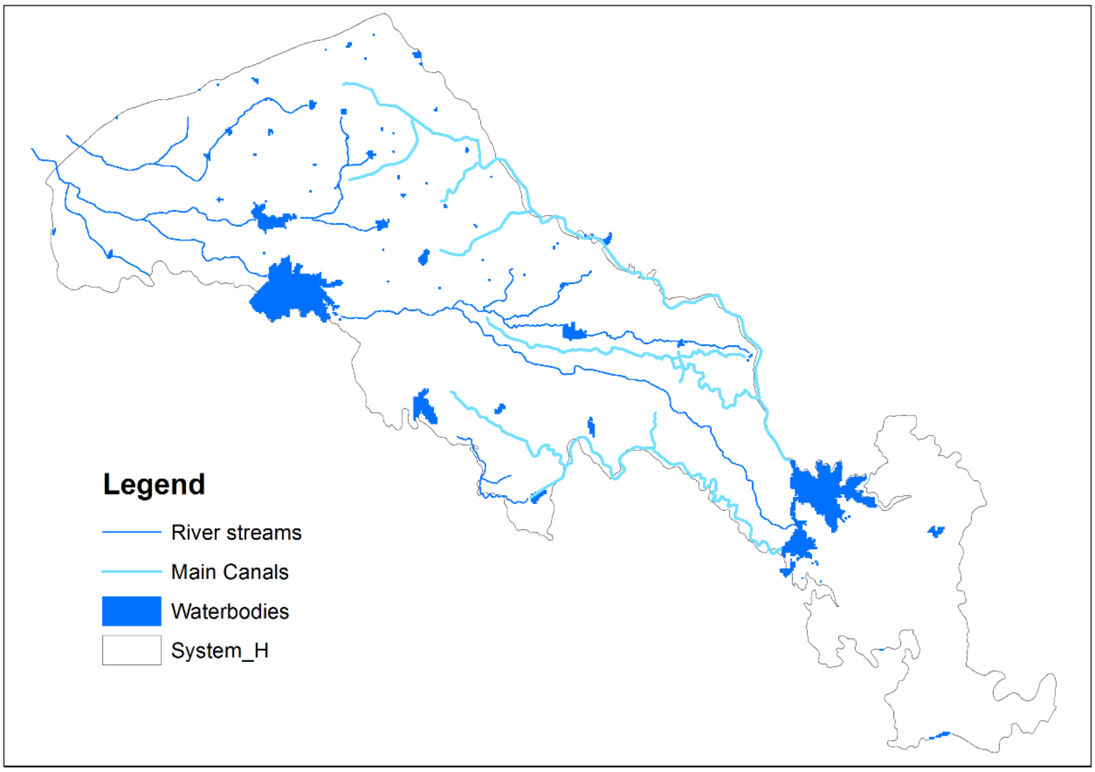

Figure 4.8 The main irrigation canals, river streams, and tanks in System H used for factor analysis

4.5.1 Distance to canals

The CWP of rice is found to correlate with the distance to canals. The relationship between the distance to the canals and the WP, ETa, Ta, and yield is shown on Figure 4.9. This analysis is performed using buffers of 250 meter, 500 meter, 1000 meter, 2500 meter and 5000 meter, around the primary canals. Then, zonal statistics is used on each buffer to obtain the statistics for the WP, ET and yield. The WP, yield, and Ta seem to be strongly correlated to the distances to the canals. Higher values exist in areas closer to the canals with no exception. The ETa however varied when it is between 2000 to 5000 meter distances to canals. It increases at this stage, which is mainly caused by proximity to rivers and tanks. The beneficiary consumption, however, did not increase with increase of ETa.

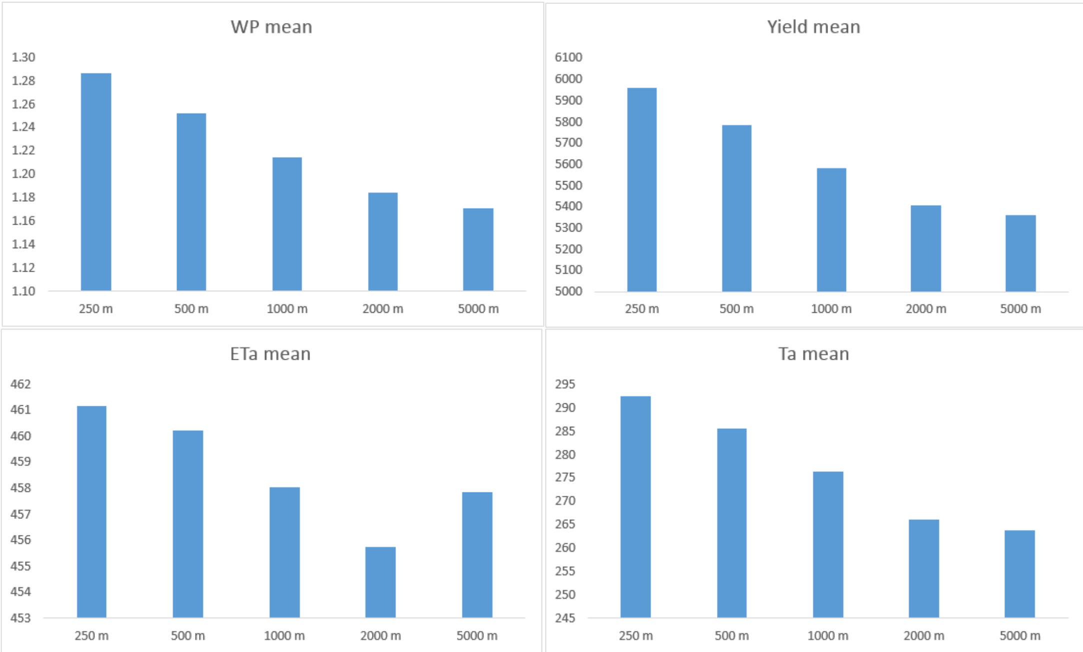

Figure 4.9 The relationship between CWP, ETa, Ta, and yield of rice and distance to canals

4.5.2 Distance to rivers

The relation between WP variables and the distances to rivers are less apparent compared with distances to canals. Figure 4.10 shows that the WP values was much higher for areas within 250 meter to rivers, but no clear trend is observed beyond that. This is also confirmed with much higher yield in the 250 meter zone, and moderately higher ETa in the same zone. The on farm efficiency is much higher as indicated by higher Ta rate.

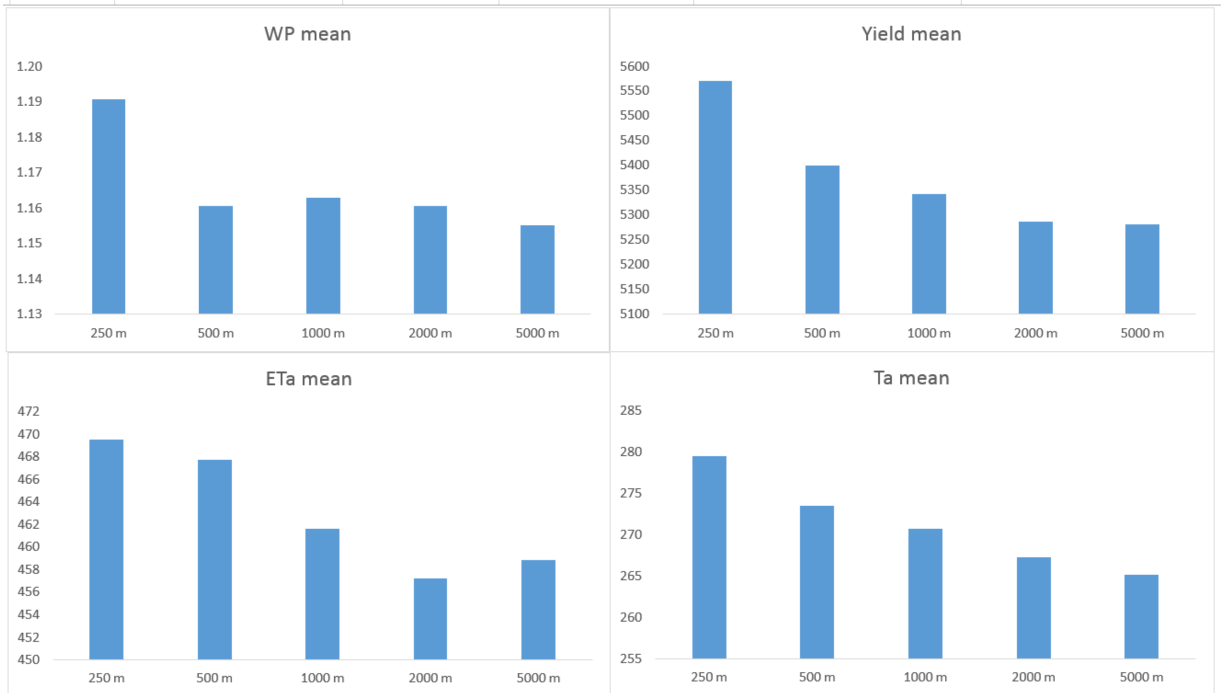

Figure 4.10 The relationship between CWP, ETa, Ta, and yield of rice and distance to river streams

4.5.1 Distance to tanks

The relation between WP and distances to tanks show reversed trend. Figure 4.11 shows that WP increases further away from the tanks. Although crop yield is much higher closer to tanks, especially within 500 meter distance, the ETa is also much higher. Causing WP values to go down. Farmers closer to tanks enjoy better access to water, hence higher productivity. However, they are not water efficient and there is much room for improvement needed. It may also be necessary to look at ways of improving the beneficiary range around the many tanks in the systems.

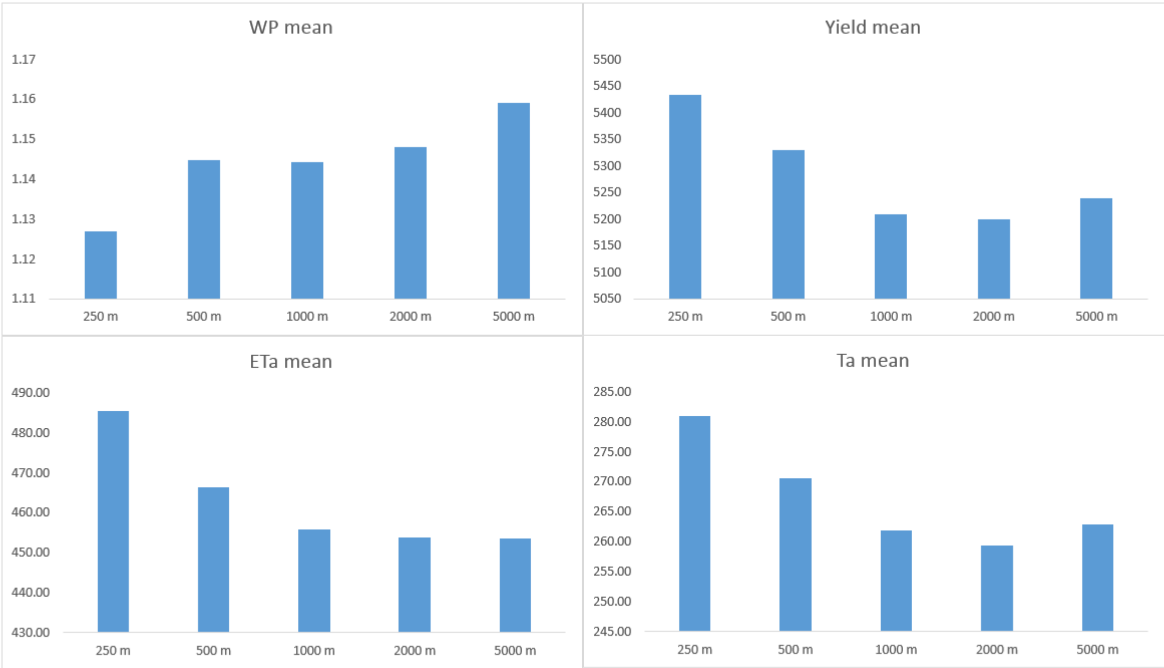

Figure 4.11 The relationship between CWP, ETa, Ta, and yield of rice and distance to tanks

4.6 Potential for improvement and areas of priority interventions

A combined analysis of ET, yield and WP provides a comprehensive picture of the results and outputs of irrigation management. It is a vehicle for diagnosing management gaps and identifies directly the local potential for gaining more benefits (food, income, nutrition) from water resources. The practical interpretation of image analysis requires extensive field knowledge, and understanding of local water practices that cannot be seen on an image. The specific intervention analysis for solving problems in irrigation management can be achieved by combining the images produced with field visits to discuss the observations with local stakeholders. Such type of activity is beyond the scope of current assessment. However, an analysis into the irrigation System H is illustrated to demonstrate how planning and management agencies best can embrace these technologies.

Yield – often referred to as land productivity – and water productivity should both score high in an ideal situation. Figure 4.1 shows yield and WP of rice for every 30 m x 30 m field. The two dimensional plot shows most of the pixels fall in a shape that is defined by a straight line at the bottom, ad a curve-linear line on top. The bottom line is defined by the potential ET that is controlled by atmospheric conditions. The upper line is defined by local water management practices, including on-farm management. This graph demonstrates vertical with farmers who produces the same yield but with low and high WP. This shows that a lower ET is not necessarily bad. In the verticals, farmers should move up from the bottom to the top. The horizontal show that a large group of famers are scoring high in WP, but their yield is low, and hence their income and perhaps even own staples.

Not all farms have the same potential due to soil, water, and other limitations. It is therefore often not possible to push all the farms towards the top-right corner of figure 4.12.

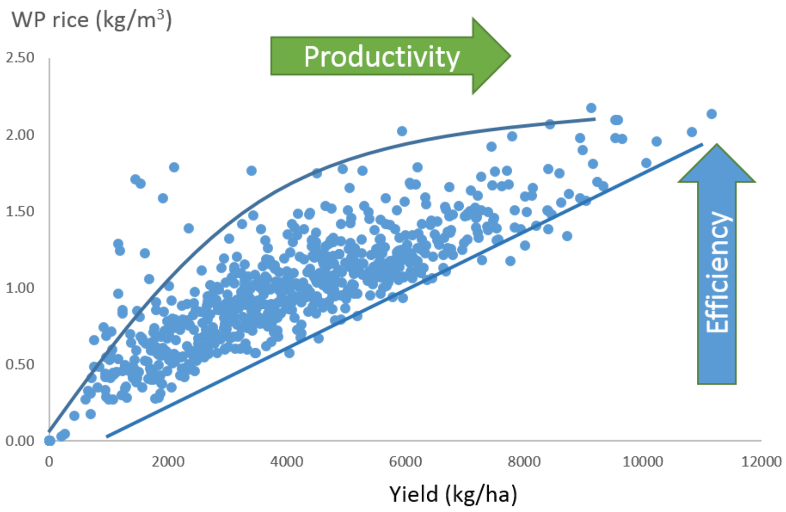

Figure 4.12 the Relationship between CWP and yield of rice in System H.

Transpiration (Ta) is the beneficial consumption of water for crop biomass production directly. The ratio of Ta to actual evapotranspiration (ETa) is therefore a measure of on farm water management efficiency as how the depleted water is partitioned between Ta and Ea, the non-beneficiary water consumption through open water, soil, or canopy interception. Figure 4.13 shows the map of Ta to ETa in System H for 2016 Yala season. The ratio varies between 0.23 and close to 1. The average is 0.57 with a standard deviation of 0.12, which means of all the water consumed, only 57% is directly consumed by crops for biomass production. The ratio is rather high considering paddy fields have long period of inundation. Open water evaporation, especially at earlier growing stages, is high. Improving the performance will need to look at low Ta/ETa ratio areas, and work with farmers to increase the same to better performing areas.

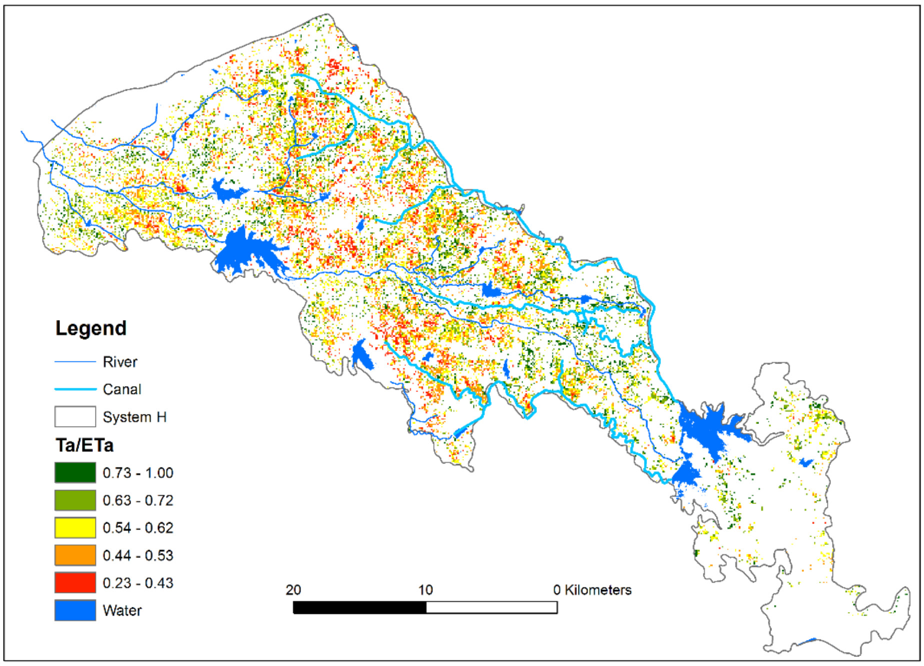

Figure 4.13 On farm water management efficiency as represented by the ratio of actual transpiration (Ta) to actual evapotranspiration (ETa) in System H for paddy fields during 2016 Yala season.

Priority for interventions can be identified first even though the absolute potential is not known. Figure 4.14 shows two different approaches to identifying priority areas for interventions. Due to resources and/or capacity constraint, it is often difficult to spread resources to large area at one. However, one can choose from the areas shown on the figures below to decide either to focus on the below average areas, or even less areas (those below 1 standard deviation of the average).

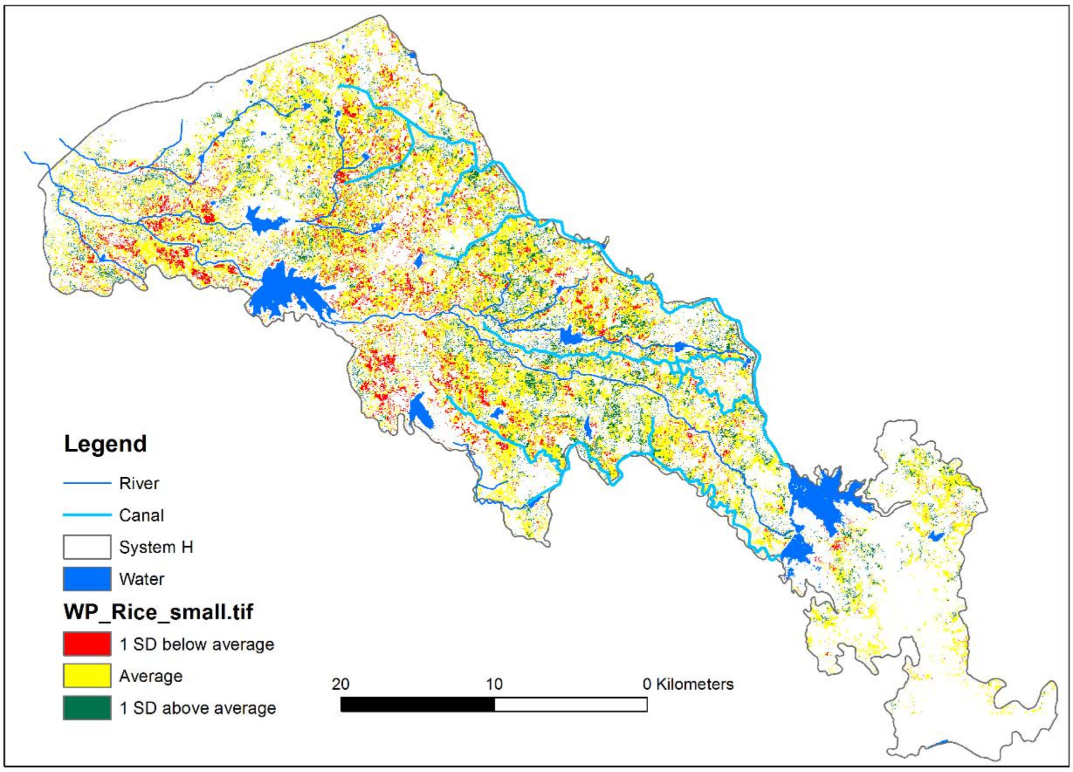

Figure 4.14 Trade-offs in determining priority intervention areas. The areas with CWP 1 standard deviation below average, on average, and 1 SD above average.

5. Summary and the way forward

The pilot study demonstrates a successful application of using satellite images to assess crop water use, yield and water productivity as baseline condition of 2016 Yala season in System H. The assessment was supported with ground during the growing season. Satellite images from Sentinel 2, Landsat 8, ProbaV and VIIRS were combined to remove the effects of clouds and to develop time series 30 meter resolution maps. The results were analysed to assess the performance of the current system and the potential for improvement. Field data is highly limited, the study also used satelliate information to digitize canals, river streams, and tanks and examined their relation with CWP, ETa, and yield to investigate the reasons for variability in system performance.

The WP maps show poor and good irrigation management practices coincide in the system. The average WP of paddy rice was 1.15 kg/m^3 for the 2016 Yala season, similar to that of the world-wide average value for WP at 1.1 kg/m^3. The average rice yield was 5.1 t/ha and the average ETa was 452 mm. The spatially explicit maps also show variability and the scope for improvement. The coefficient of variations (CV) of WP, ETa, and yields are 27%, 31%, and 17% respectively. The variability is higher than recent studies in Indonesia, Vietnam, and India, indicating greater potential for improvement.

High level of water shortage is found for the study area in 2016 Yala season. Average ET deficit is 156 mm for the entire growing season, which translate to a 26% shortage should the demand be fully met. Several water scarcity is therefore the main constraint for improved food production of the system.

Canals, rivers, and tanks are found to be closely linked with the performance of the system. Positive correlation was found for CWP and yield of rice with distance to canals. The closer a farm is to a canal, the more likelihood this farm will have higher CWP and yields, accompanied with higher water consumption. Similar trend is observed with the distance to rivers. The farms within 250 meter distance to rivers seem to have much higher yield and CWP. The Ta to ETa ratio is also higher in these areas, indicating better on farm water management in these areas.

There are large number of tanks in the system which contribute to high yield but lower performance. Rice yield is positively related to the distance with tanks. The areas closer to tanks have increasing yield, but decreasing CWP. The proximity to tanks give nearby farms better access to water. But unfortunately, such easy access also leads to reduced level of CWP, as explained by rapid increase of ETa.

Significant potential for WP improvement exists, through yield improvement, but also through water savings. The WP maps are created and can be used to indicate potential investment areas. These are often areas of low WP where opportunities for improving are likely present and the biggest. There areas are typically found in downstream areas, but also mid-stream where high performing areas concentrate.

Bright spots of high WP areas, or hero farmers, exist from upstream to downstream. While not always directly comparable, they provide a level of indication of the potential for farmers from the same areas. Furthermore, great water saving potential is observed through separation of Ta, the amount of water consumed through crop transpiration, from Ea, which is evaporation from open waterbodies and soil. On farm water management has the greatest potential in improving CWP. The Ta is 57% of total consumed water. While this is already high, pockets of areas with very low ratio also exists, especially in mid-stream areas. Improving CWP will require close collaboration with these farmers to improve their on farm water management practices.

This research shows promising results linking pySEBAL outputs with the ground truth even though the amount of fieldwork was limited. Clouds hinder the use of satellite images. The inclusion of the new HANTS algorithm proves to be technically feasible, creating the technical opportunity to make daily WP reports for all rice fields in Sri Lanka, also under cloudy conditions. This could be a big information boost to support irrigation managers with their daily services of bringing water to farmers. The HANTS outputs and Landsat outs do not match exactly, due to the inherent sensor difference. A further cross sensor calibration is recommended for future application of the method. Whereas some key explanatory reasons were detected (i.e. distance to canal, river, and tanks), it is recommended to further explore relations between WP and influencing factors in the local context together with local irrigation officers. Even though the research revealed some limitations causing uncertainties, this new remote sensing technologies can support an efficient and effective investment purposes on modernization of irrigation. It is recommended that the Ministry of Irrigation & Water Resources Management and Ministry of Mahaweli Development and Environment recognize WP as a new policy instrument and implement it both at central level and irrigation district level.

The demonstration is coupled with a training on pySEBAL to selected participants. A total of 21 participants learned the concept of WP and followed exercise using state-of-art remote sensing technology to assess CWP in agricultural areas. This training is meant to create awareness and interests. It does not seem to be of sufficient duration to transfer the full modelling capacity. The latter needs to be achieved through more in depth training on the methods, and broader training on remote sensing as well as PYTHON programming, together with sufficient exercises. The HANTS cloud removal algorithm is also particularly relevant for applications in Sri Lanka. Further training, and expose to apply the methodology by a smaller group of persons with reasonable remote sensing background will be essential to take the momentum forward. They can then also act as trainers to distribute the methods to more users.

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7. List of annexes

Annex 1. pySEBAL model description
Annex 2. SEBAL publication from 2005 onwards
Annex 3. Groundtruth
Annex 4. Crop yield estimate
Annex 5. Program and participant list of the training workshop