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India: Water Productivity Measurement-Karnataka Integrated Sustainable Water Resources Management Investment Program Tranche 1

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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: Karnataka, India

Technical report

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Executive summary

India invests heavily on building new irrigation systems and upgrading existing ones. The Karnataka state government is working to improve the performance of irrigation in the Tungabhadra left bank system with a loan from the Asian Development Bank (ADB). In order to better assess the current conditions, and develop more appropriate indicators to measure the performance of irrigation water management, IHE works with ADB and ACIWRM to introduce the concept of crop water productivity (CWP) and use of remote sensing technology for assessing the same. The CWP indicator, together with yield, and ETa (actual crop water consumption), are a simple and attractive set of indicators to assess how well the limited irrigation water are used for its intended purpose: to produce more food. This report describes the application of, pySEBAL, a remote sensing approach to assess rice CWP in the Tungabhadra irrigation system. Baseline conditions were established by means of mapping the crop type, water consumption, crop water deficit, crop yield, and the crop water productivity in the reference period of the 2016 rice Kharif season at resolution of 30 m by 30 m using publically available imagery. Factors affecting CWP parameters were analysed and scope for improvement is discussed. A training workshop was conducted to introduce pySEBAL model to local researchers and practitioners. The training provided the participants with an overview of the latest concept, exposure to the technology, and opportunities for hands-on exercises with state-of-the-art remote sensing capabilities.

A novel yet practical remote sensing approach was applied to the Tungabhadra irrigation system. The computations of crop production and crop evapotranspiration requires an energy balance model that converts available radiation from sun and earth into water and carbon fluxes. The updated Surface Energy Balance Algorithm for Land (SEBAL) model with automated calibration process was used for this purpose. This so called pySEBAL model is programmed in python language. pySEBAL bases on freely available data from the Landsat, ProbaV/VIIRS and Sentinel satellites. Hence, there are no costs involved to repeat and expand these type of analysis. Smart phone based groundtruth improves efficiency and reduces the costs of field works.

The CWP of rice in the Tungabhadra irrigation system is not low but with high spatial variability for the 2016 Kharif season. The average CWP of the TLBC is 1.44 kg/m^3 with a CV of 13%. The average yield and ETa are 6.4 ton/ha and 448 mm respectively. The command areas of RBHL and RBLL has slightly higher CWP at 1.5 kg/m3 by using less water (437 mm) and producing higher yield (6.5 ton/ha). There was a shortage of 25 MCM, or 3% of current consumption, for TLBC to satisfy full crop water requirement. However, this does have to come from additional supply. In fact, only 268 mm, or 60%, of total ETa is consumed through transpiration (Ta), meaning significant potential for improvement

High spatial variability represents non-uniform performance across the system. The up to mid- streams of TLBC, areas along the main river, and the RBLL command have high water consumption of 475 mm or more. However, the crop yields are not high, leading to moderate CWP. Large area of low ETa is found in the command of RBHL which also has high yields, and therefore high CWP. The tail end of TLBC has low water consumption and very low yields, which leads to low CWP. The areas along the main river, which are fed with direct diversions from the river, also have very relatively high water consumption but very low yields.

The factors potentially linked to water consumption, yield and CWP are investigated for location, slope, soil, crop pattern, fertilizer application, and seeds. The analysis did not find significant correlation between the CWP indicators and the distance to canals. But the distance to the main dam, as a measure of head – tail effect, is affecting CWP, yield and ETa. The 20-50 km zones in the middle reach have the lowest CWP with high total water consumption (but low beneficial consumption) and low yield. No significant correlation is found between the CWP parameters with slope. The sandy soils have the lowest CWP due to low yields from similar water consumption. Cropping patterns also have an effect on CWP of the assessed Kharif season, the higher the intensity, the lower the CWP is found. For single cropping intensity, areas performing Rabi season farming has higher CWP than that of areas with Kharif season farming. When farmers apply both N and P at recommended level, they have the highest CWP compared with those applying less or more. And the research seed variety produces higher CWP than other varieties.

Significant potential exists for on farm water savings. The average ratio of beneficiary consumption (Ta) to total consumption (ETa) is 60% for TLBC and 64% for RBHL/RBLL. While these values are already high and they don't equate to water saving potential, they still indicate areas where higher potential exists. Figure 6.2 shows such potential in a spatially explicit manner. The highest water saving potential is along the main river where the beneficiary consumption ratio is only 40-50%, a 10-20% potential for improvement if we just take system average of 60% as a modest target. Large areas in the upper to middle stream of TLBC also show lower ratio with a potential of about 5-10% improvement. Managing field water consumptions are ultimately linked with system performance through measurement of CWP. Increases in CWP is linearly related to the increases in Ta/ETa value through on-farm water management improvements.

There are always a need to determine priority interventions areas due to constraints in resources. This for example can be easily done using the CWP map classified in 3 categories: hotspots or poor performing areas with CWP 1 standard deviation (SD) below average, areas with average CWP, and bright spots/hero farmers for those well performing areas with CWP 1 SD above average. The hotspots are not expected to achieve the same results as the bright spots, but could learn from the hero farmers. Unsurprisingly, the tail end of TLBC (upper right) are mostly green. Higher CWP here does not imply better performance, but rather, farmers used the little water available to them more efficiently.

More in-depth understanding of the remote sensing outputs, and therefore any appropriate interventions, need to be linked with field situations. This study involved intense but also efficient field survey using smart phones. It is recommended that any further interpretation of the outputs and development of interventions will have to be location specific considering current water use, yield and CWP conditions, and that this requires further interactions with farmers, extension services and local water, agronomic, and policy experts.

Follow-up actions are needed for continued learning and applications of the CWP theory and remote sensing technology. The training workshop has successfully stimulated interests from participants in rethink their approach, and the need to work together across water-agriculture sectors. ACIWRM already started working on plans for continuity and upscaling. Continued learning in both theory and hands-on exercises, preferably with individual investment projects, are essential to keep the momentum. In particular, emphasis should be given to diagnoses of the causing problems and monitoring of the irrigation system to detect improvements.

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	**73.0**	**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 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.

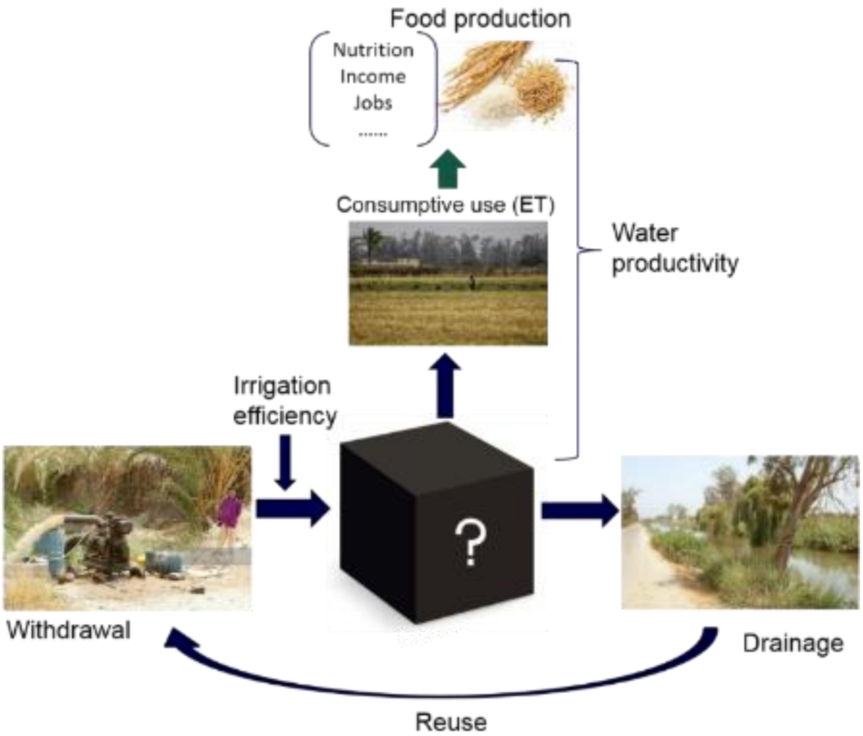

Figure 1.1 The irrigation efficiency and water productivity indicators for irrigation systems. The two indicators are complementary while WP covers more advanced and broader components of irrigation performance.

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 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).

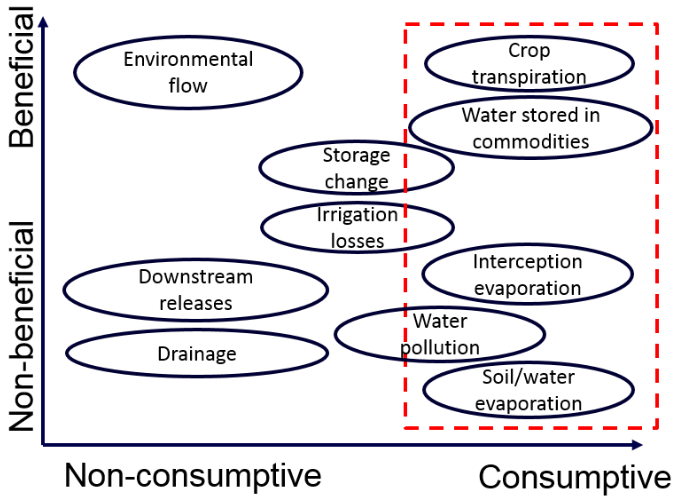

Figure 1.2 Remote sensing approach focuses on the beneficial and non-beneficial consumptive use of water.

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 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 UNESCO-IHE that showed a skewed behaviour of crop water productivity towards the lower side (see Figure 1.3). 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).

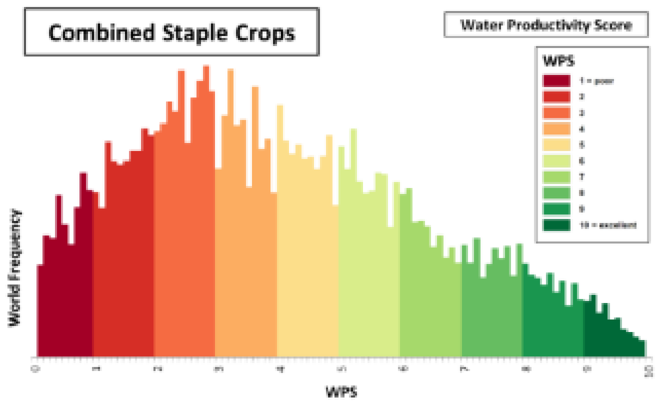

Figure 1.3 Frequency distribution of the Global Water Productivity Score (GWPS) reflecting wheat, rice and maize crops at the global scale. This graph could be created due to climate and crop normalization. A GWPS of 1 is poor and of 10 is excellent (Bastiaanssen and Steduto, 2016)

1.3 The collaboration between IHE Delft, ADB and ACIWRM 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).

In India two separate states, Karnataka and Madhya Pradesh, were included in the project. In Karnataka the Advanced Centre for Integrated Water Management (ACIWRM) is the main collaborating partner. As the research arm of the Water Resources Department (WRD), ACIWRM has rich experiences in water (including irrigation water) management and respective technical capacity.

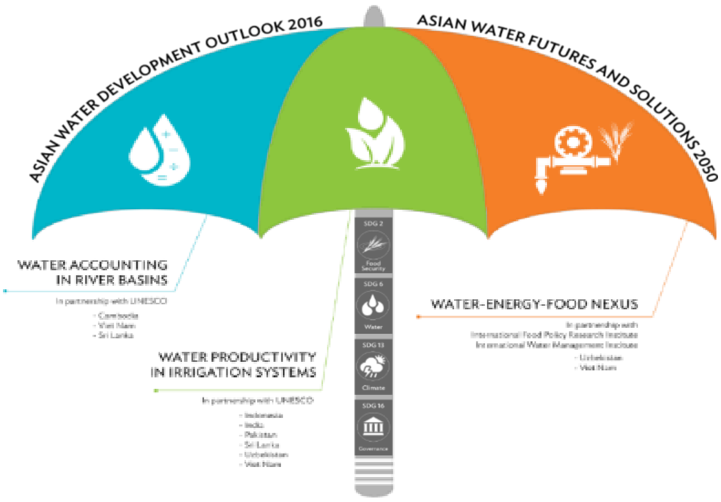

Figure 1.7. The role of Water productivity in irrigation systems, the single biggest water user, to support ADB initiatives for Asian water security. (Source: ADB, 2016)

1.4 pySEBAL training workshop

A 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 remote sensing and model tool (pySEBAL) for assessing CWP. Specifically: What is CWP? How to use pySEBAL and remote sensing data to assess CWP? How to use remote sensing based CWP assessments to improve irrigation planning, design, and management.

The workshop was organized with ACIWRM and conducted in Hospet from 9-13 Oct 2017. A total of 31 participants joined the training, including those from ACIWRM, University of Agricultural Sciences, Raichur, Bengaluru, University of Horticultural Sciences, Bagalakote, Karnataka State Remote Sensing centre, Karnataka Neeravari Nigam Limited, Department of Agriculture and Department of Horticulture. Detailed training program and participant list is attached 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).

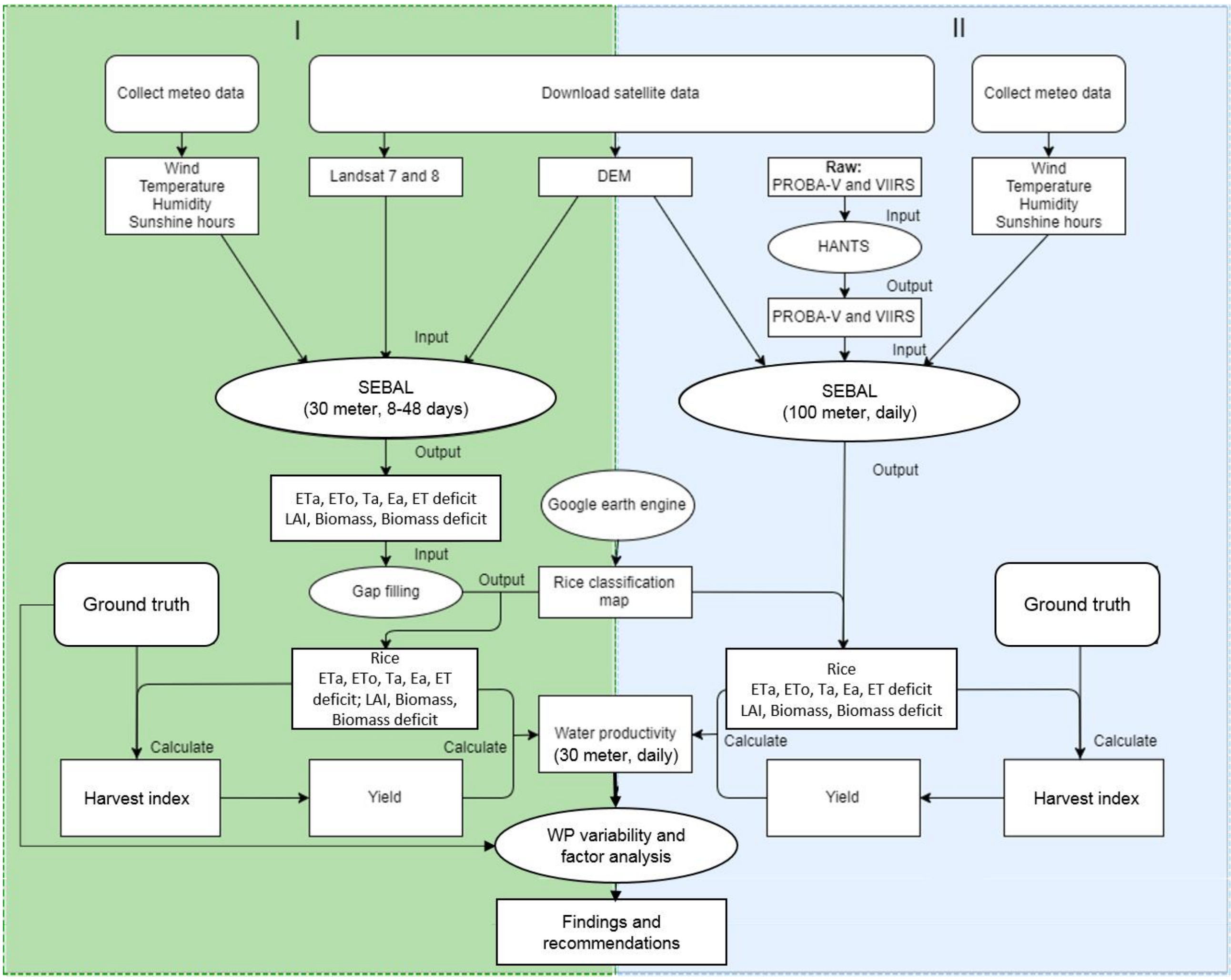

Figure 2.1 The methodological framework of CWP assessment. In this case two parallel processes, one using Landsat images, another using Proba-V/VIIRS images were used to calculate CWP separately. The results are then integrated to capture daily dynamics

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.

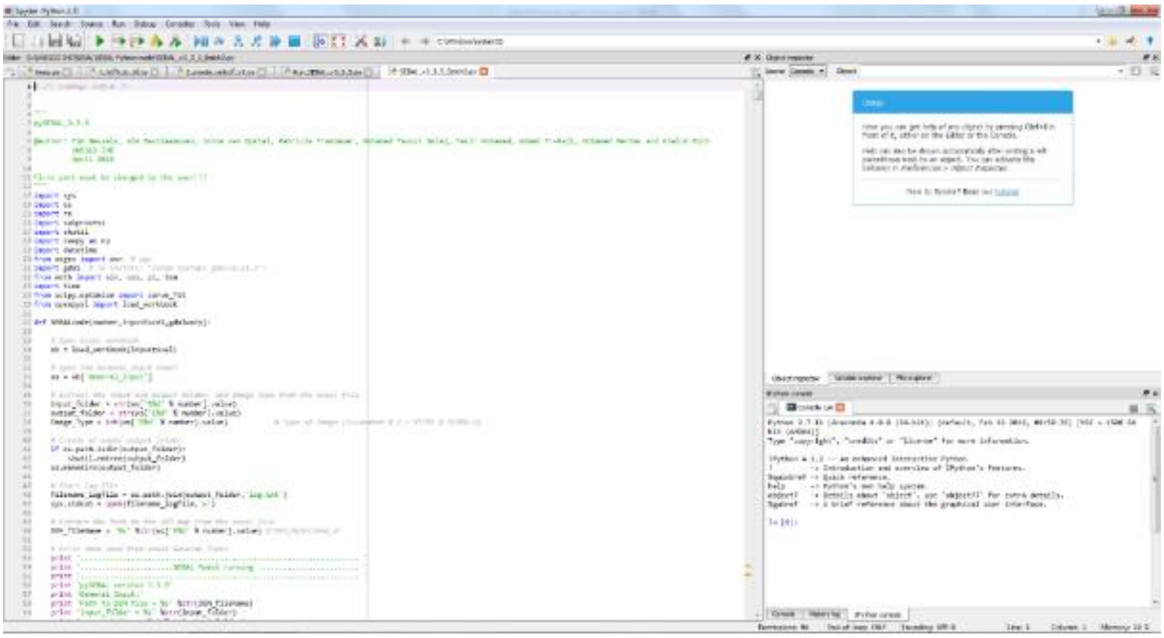

Figure 2. 2 Screenshot of the Spyder2 (a version of Python) software as platform for implementation of pySEBAL

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. In the Tungabhadra irrigation system the dominant irrigated crop in the Kharif season is rice, which has been chosen as the focus crop of this assessment.

The crop types were mapped using a supervised classification approach with the Maximum likelihood algorithm. The 2016 Kharif rice season started late in September and was harvested in December. This is a dry period with natural vegetation showing much less rigours than irrigated crops. It is therefore much easier to identify crops using Landsat 8 images during peak rice growing season. The classification focuses on agricultural areas and water bodies, and is supported with extensive field surveys and Google Earth high resolution zoom-ins.

2.4 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.

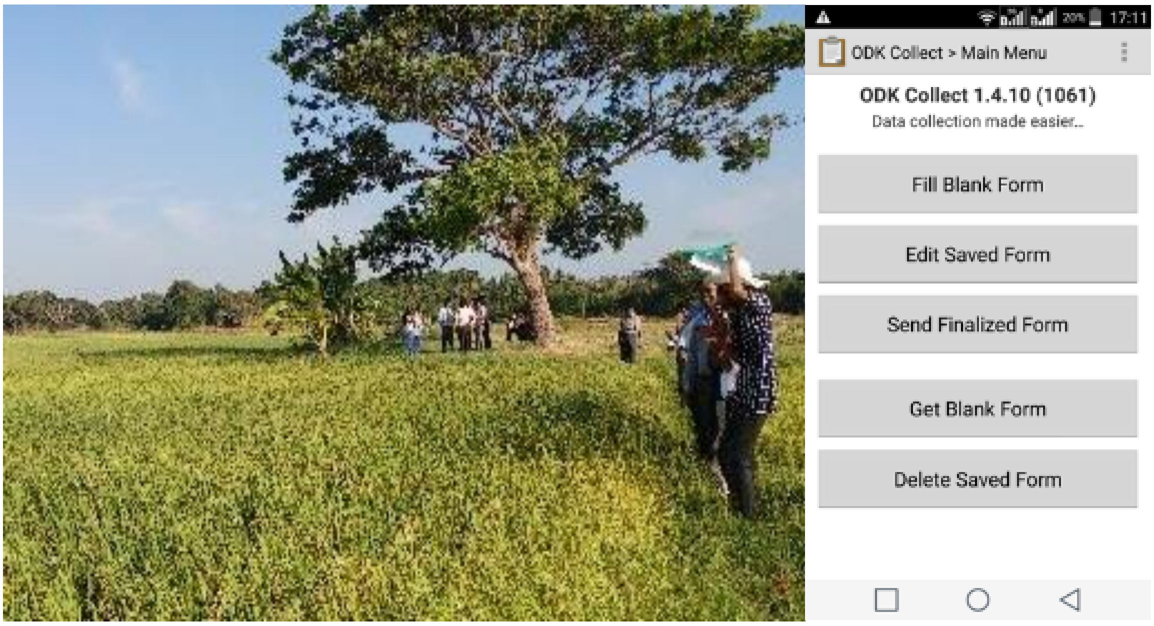

Figure 2.3 Ground truth with smart phones. On the right is the interface of the application

3. Project areas and data collection

3.1 Study area

The Tungabhadra irrigation system is a large irrigation system with water supplied from the Tungabhadra dam. It is located in the Karnataka part of the Krishna Basin, which is the fifth largest in India in terms of surface area. The system comprises the Left Bank High Level and Low Level Canal

(TLBC), the Right Bank High Level Canals (RBHL) and Right Bank Low Level Canals (RBLL). Figure 1 shows the location of the system, the available weather stations nearby, and the footprint of the Landsat 8 images used for assessment.

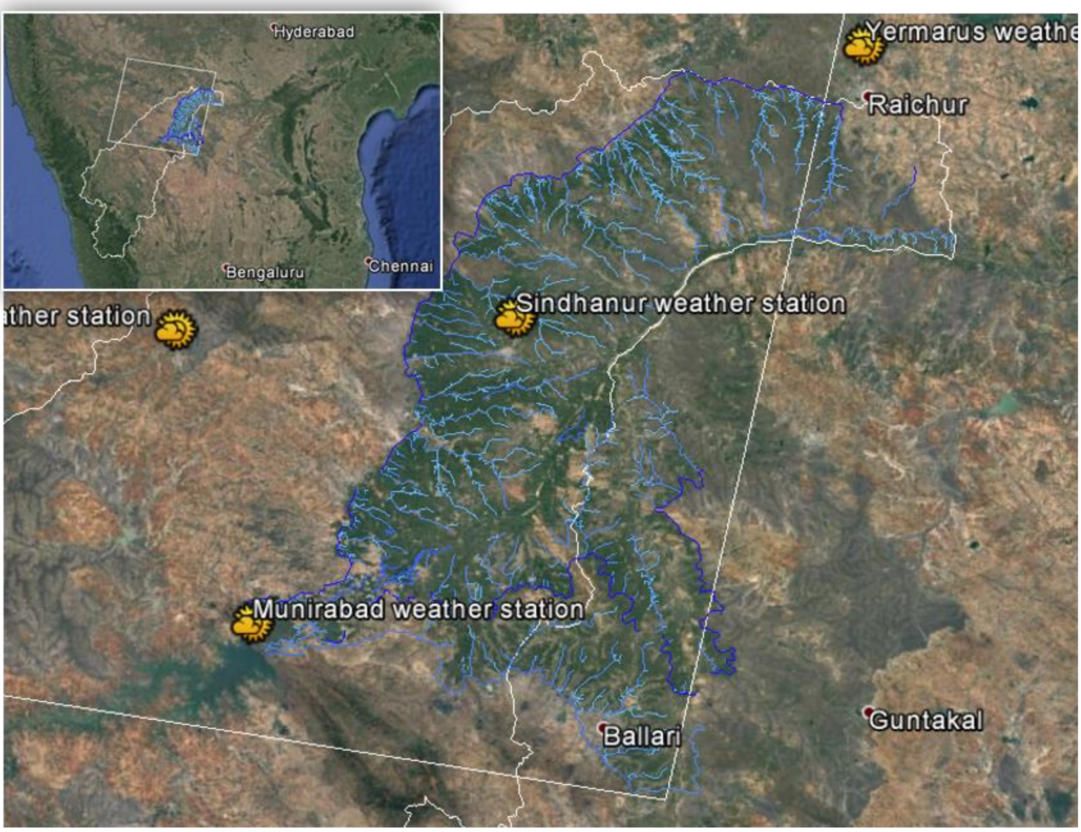

Figure 3.1 The Tungabhadra irrigation system canal networks, available weather stations, Tungabhadra basin boundary, and the Landsat 8 image footprint (P145/R049)

The actual irrigated areas may differentiate from official boundary. As seen from figure 3.1 above, there are large areas with strong indication of irrigation further away from the demarcated system boundary. Table 1 summarizes the main canal length and command areas according to official statistics.

Table 3.1 The canals and command areas of the Tungabhadra irrigation system, source: ACIWRM

Canals	Length (km)	Command area (ha)
TLBC Left Bank Low level	227	244,103
LBHC Left Bank High level	15	469
RBLL Right Bank Low Level	251	106,250
RBHL Right Bank High Level	105	150,000

3.2 Crop

Due primarily to water constraint, single crop cultivation is typical farming practices. Areas where farmers grow two crops a year are confined to those upstream and others closer to main canals. The pilot study focuses on the paddy rice crop, the dominant crop and the most water intensive in the system. 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 3.2). 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.

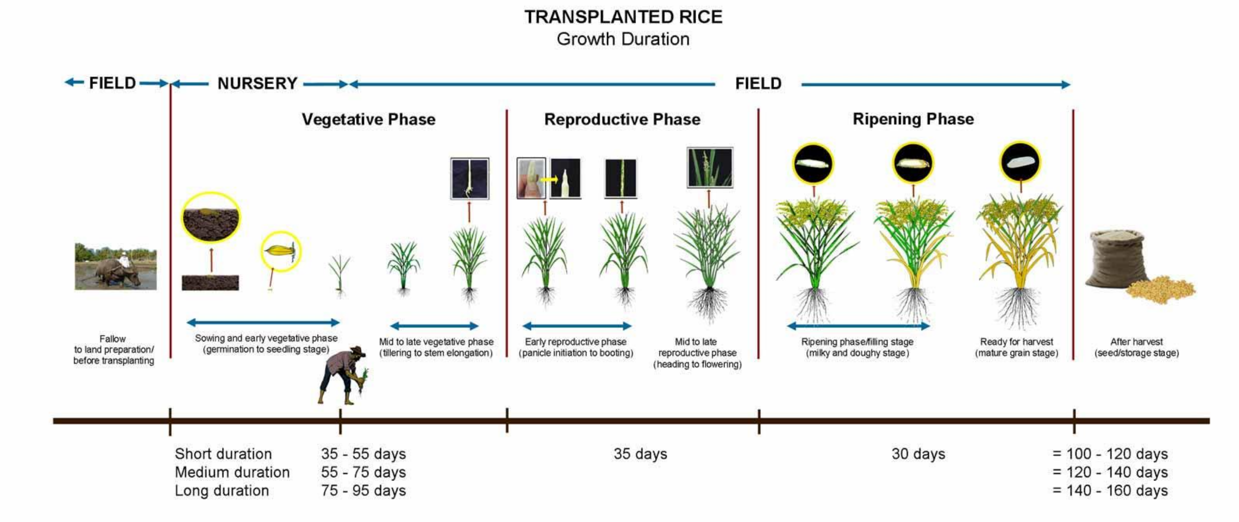

Figure 3.2 Growing stages of a rice cycle (Source: IRRI, 2017)

Rice growing season in TLBC varies between individual famers but is highly dependent on irrigation release dates. Time series images show a clear vegetation cycle from the mid-September to late December. The study period is therefore determined to be from 1st September to 31st December, 2016. This is a total of 122 days including land preparation and possibly a short post-harvesting period for most fields. As no accurate information on field irrigation supply dates were available, this estimate aims to includes possibly slightly more days than for many fields in order to accommodate varitiblity in differences in the start season by different farmers.

3.3 Data

Landsat 8

The Landsat 8 imagery is one of the most widely used images for remote sensing applications in natural resources and agriculture. It has a 30 meter resolution in multispectral bands while the thermal band is 100 meter. Landsat 8 has a 16 day repeat cycle. A total of 8 Landsat 8 images with path/row number 145/049 were downloaded from USGS EarthExploerer (https://earthexplorer.usgs.gov/) for the 2016 Kharif rice growing season from 1st Sept to 31st Dec. Clouds in the season are overall negligible, although it was more obvious in the month of September. In pySEBAL areas affected by small patches of clouds are filled up using a linear interpolation algorithm.

Weather data

Hourly and daily weather data from four meteorological stations were collected for the study period. The four weather stations, as shown in figure 3.1, are Sindhnur, Munirabad, Kushtagi, and Yermarus. The data includes temperature (Min, Max, and Average), relatively humidity, wind speed and sunshine hours. Other data such as precipitation and pan evaporation was provided but not used.

Ground truth

The GT data was collected using ODK Collect for the TLBC. The field trip collected a total of 1094 observations in quick mode and 195 in normal mode during the period of 13 days from 23rd September to 5th October, 2017 (figure 3.3). No GT was conducted for the right bank main canal command.

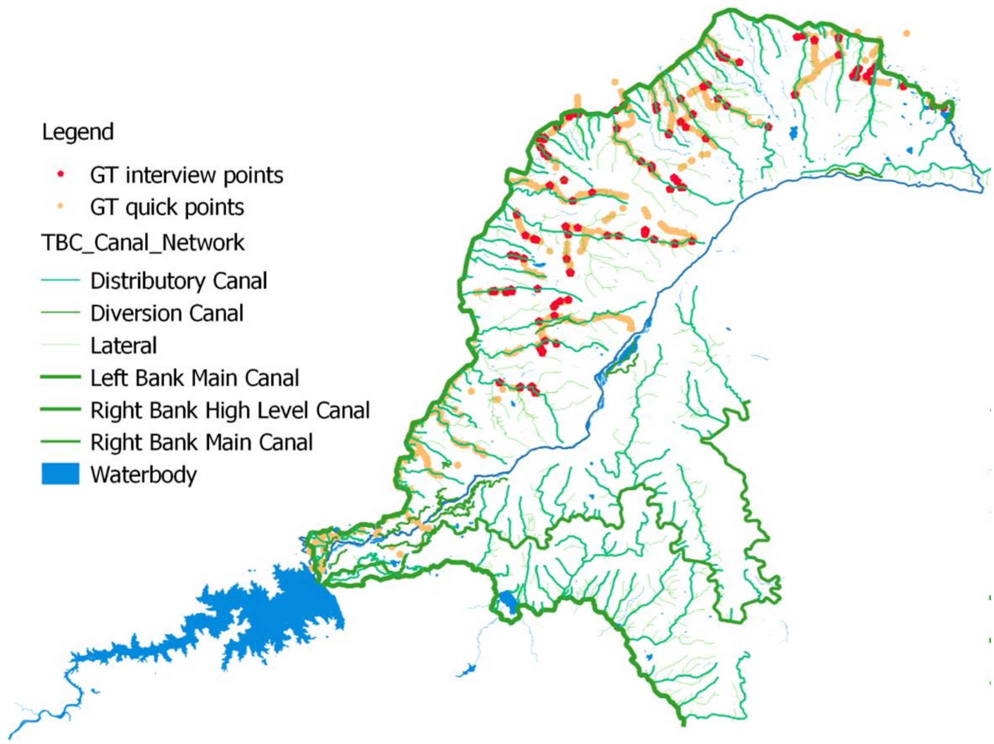

Figure 3.3 The ground truth points in the TLBC area collected from 23 Sept – 5 Oct 2017. The normal mode points are those with farmers interviewed, the quick points are those only with crop type and no farmers'' interviews.

4. Water consumption, yield, and crop water productivity of paddy rice

This section presents the results from image analysis on the paddy rice growing area of the 2016 Kharif rice season. Seasonal total evapotranspiration and biomass production were mapped for Landsat image 145/049. They will then extracted using a rice crop mask layer to focus on the paddy areas within the TLBC command. In addition, because the right bank canal command also falls in the Landsat image coverage, rice CWP of these areas are also assessed.

4.1 Rice map

The dry season makes the irrigated crops significantly different with natural vegetation in their phenology. The rainfall is so little only irrigation crops show robust vigour and high NDVI throughout the months from September to December. A Landsat 8 image of 6th November 2016, during the peak rice growing period, is used to map paddy rice, together with the large number of ground truth points. The Landsat 8 image 145/049 does not cover the entire command area of TLBC. A small area towards the tail end was left out. To cover this area will need processing of Landsat 8 image 146/049 not only for crop identification, but also time series pySEBAL analysis, which doubles the amount of efforts required. An agreement was therefore made with ACIWRM that title 145/049 is enough for demonstration purpose. The mapped paddy area is shown on figure 4.1.

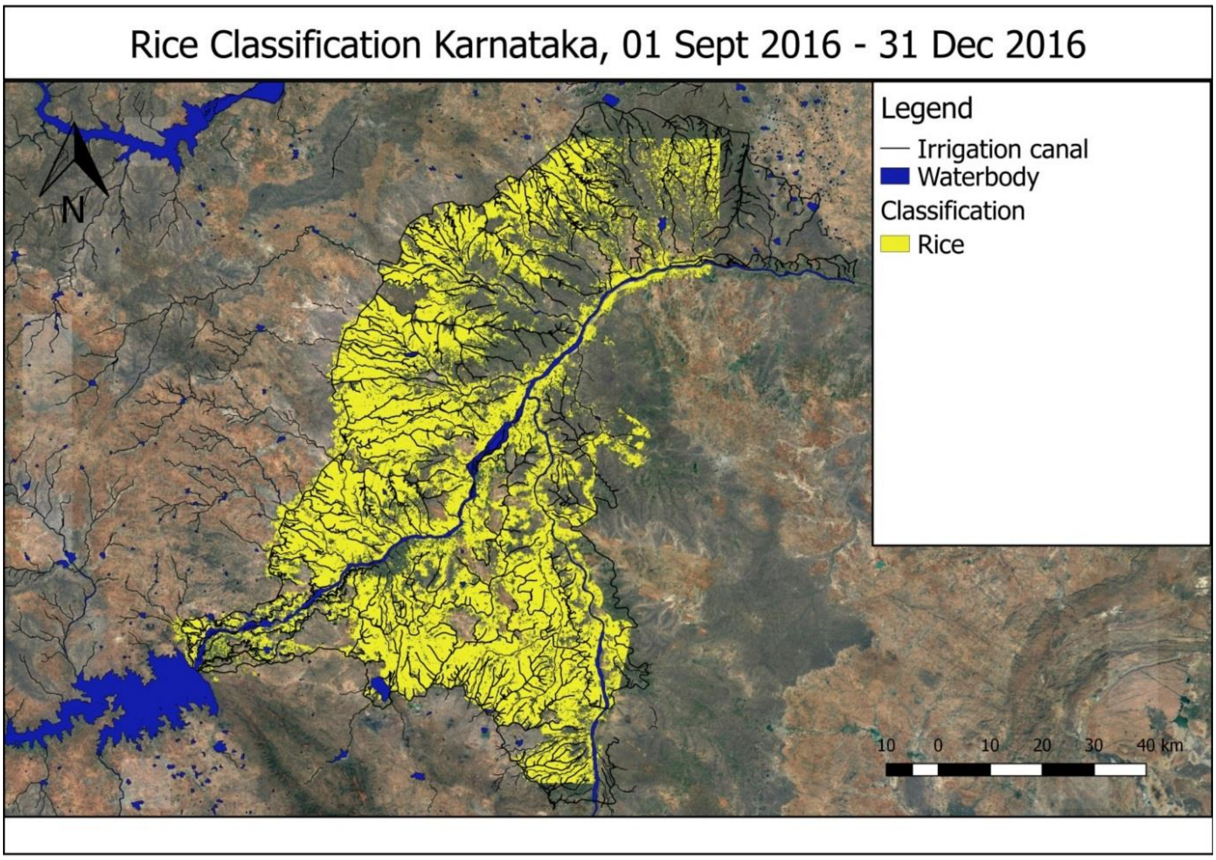

Figure 4.1 Paddy rice cultivation area in Tungabhadra irrigation system mapped from Landsat 8 image of 6th Nov 2016

The paddy rice areas in all the command areas can be calculated using the command boundary. Some paddy areas close to the main canals but outside of official boundaries can be seen along both the left and right main canals. When these areas are included, the total paddy rice area is 195,202 ha in the lower/upper left canal command, and 164,499 ha in the lower/upper right canal command for the study period.

The paddy rice areas are located closely along the main and distributary canals and the main Tungabhadra River. As the areas shrink towards downstream of TLBC, they cluster tightly along the distributary canals, implying strong dependence on the canals, and the reduction in rice areas towards tail ends due to lack of sufficient and/or reliable water supply. Areas further to the east, which is downstream and outside of canal command boundary, also show strong evidence of intense cropping. These areas are not included in current CWP assessment but they probably also benefit from the return flows from the canal supplies.

4.2 Crop water consumption and deficit

The rice consumptive water use through ETa

Crop water consumption in this study is referred to as consumptive use of water by crops through evapotranspiration processes. This is the amount that leaves the irrigation system and can no longer be reused by downstream users. The actual evapotranspiration (ETa) is generated from integrating time series Landsat 8 images for the period of 1st September to 31st December 2016, extracted for rice paddies using the rice map presented in section 4.1.

The 30 meter resolution ETa map reveals the level of water consumption as well as their spatial variability across canal command area. Figure 4.2 shows the ETa map of rice paddies. The ETa ranges from 273 mm to 569 mm with an average value of 443 mm and a coefficient of variation (CV) at 8.6%. This is on the lower side for rice compared with those frequently reported in literature internationally

(400 – 800 mm). Together, the paddy rice irrigation areas consumed 1,594 Million cubic Meters (MCM) of water through ETa, of which 875 MCM for TLBC and 718 MCM for RBHL and RBLL combined.

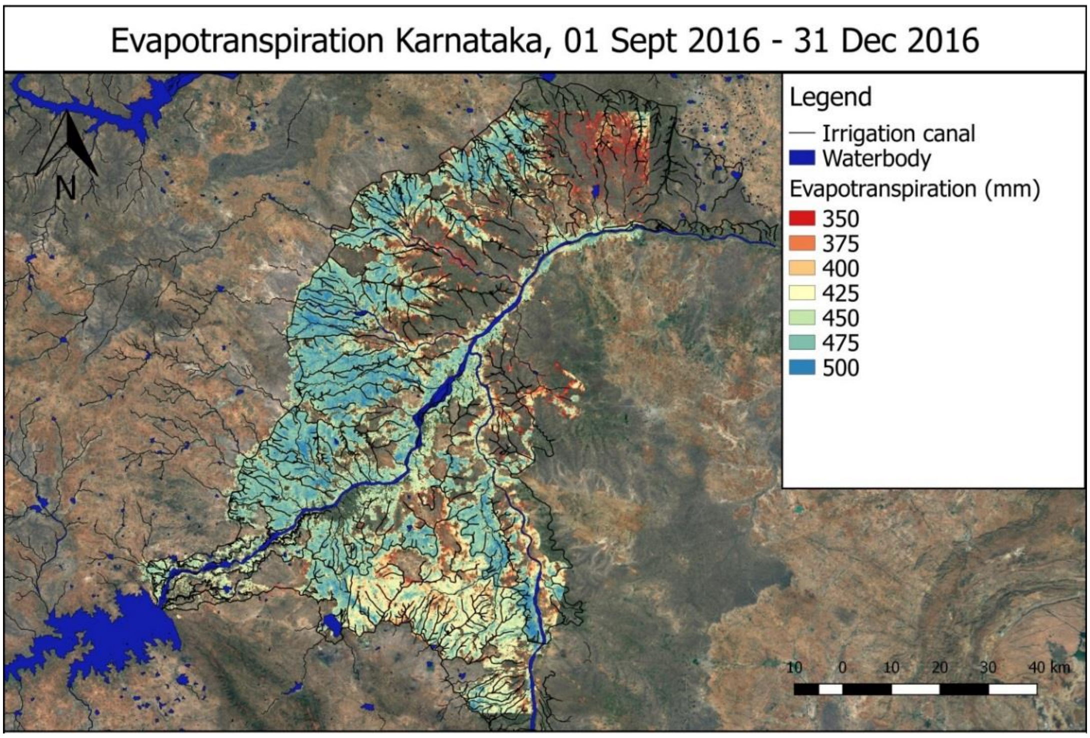

Figure 4.2 Map of actual rice Evapotranspiration (mm) for Karnataka, 01 Sept - 31 Dec, 2016

High and systematic variations of ETa is observed for the rice growing areas. The ETa map shows that large areas of relative high ETa (above 450 mm) can be found in areas along the TLBC, the main river, and the RBLL. However, large area of low ETa is found in the command of RBHL in the south. Very low ETa (less than 375 mm) is found frequently along the tail ends of most distributaries and the tail end areas of TLBC after distributary No. 92 (top right on the map). The histogram distribution of the map shows a skewed shape towards higher ETa. Large number of pixels are found to have ETa around 475 mm with a steep decline towards higher ETa (figure 4.3). In contrast, a much gentler slope is observed towards lower ETa. This shows that large areas with high ETa is near "saturated", that they have much water, probably more than enough, to consume. Some other areas, on the contrast, experience various level of water stress.

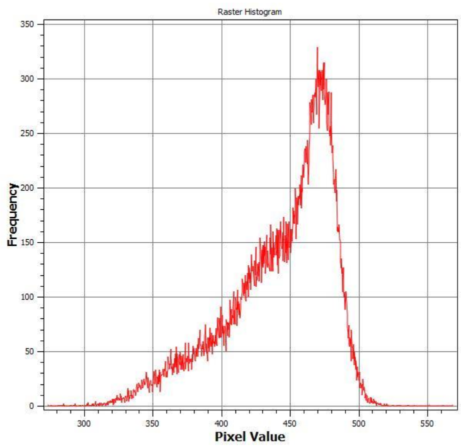

Figure 4.3 Histogram distribution of rice ETa (values ~ number of pixels)

The rice water consumption (ETa) can be further separated into Transpiration and Evaporation by pySEBAL model. 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.

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The beneficial consumption of water (Ta)

Transpiration (Ta) is the water consumed by crops through canopy photosynthesis process. It is therefore also considered a beneficiary consumption from production point of view. The map of the transpiration can be found in figure 4.4. The average value of transpiration is 273 mm with a CV of 15.4%. The value is slightly lower from the TLBC (268 mm) compared with that of RBHL/RBLL (279 mm). Together, the total beneficial consumption is 981 MCM, with 523 MCM for TLBC and 458 MCM for RBHL/RBLL combined, respectively.

High variability is again observed not only in terms of CV, but clearly present on map showing different trends with maps previously shown. High Ta areas are observed in RBHL, where ETa was found to be low, and most TLBC areas have moderate Ta values despite higher ETa values. 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. The farmers in RBHL is performing much better in this regard.

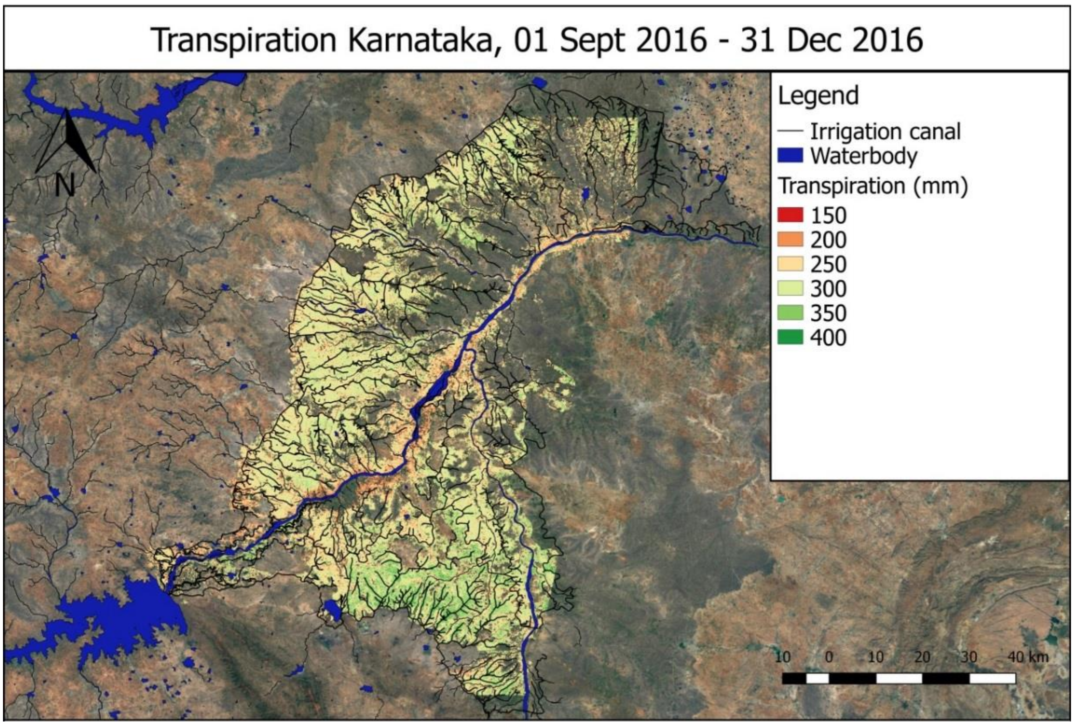

Figure 4.4 Actual rice transpiration (Ta) for the study period

Field water deficit

The ET deficit is another essential performance parameter that is produced by pySEBAL. ET deficit is calculated as the difference between potential ET (i.e. water unlimited ET at the actual crop development), and actual ET (ETa). ET deficit is a direct expression for water shortage the crop is experiencing on a pixel by pixel basis (figure 4.5). It helps assess, without any further information on canal flows, whether crops from certain fields have sufficient moisture in the root.

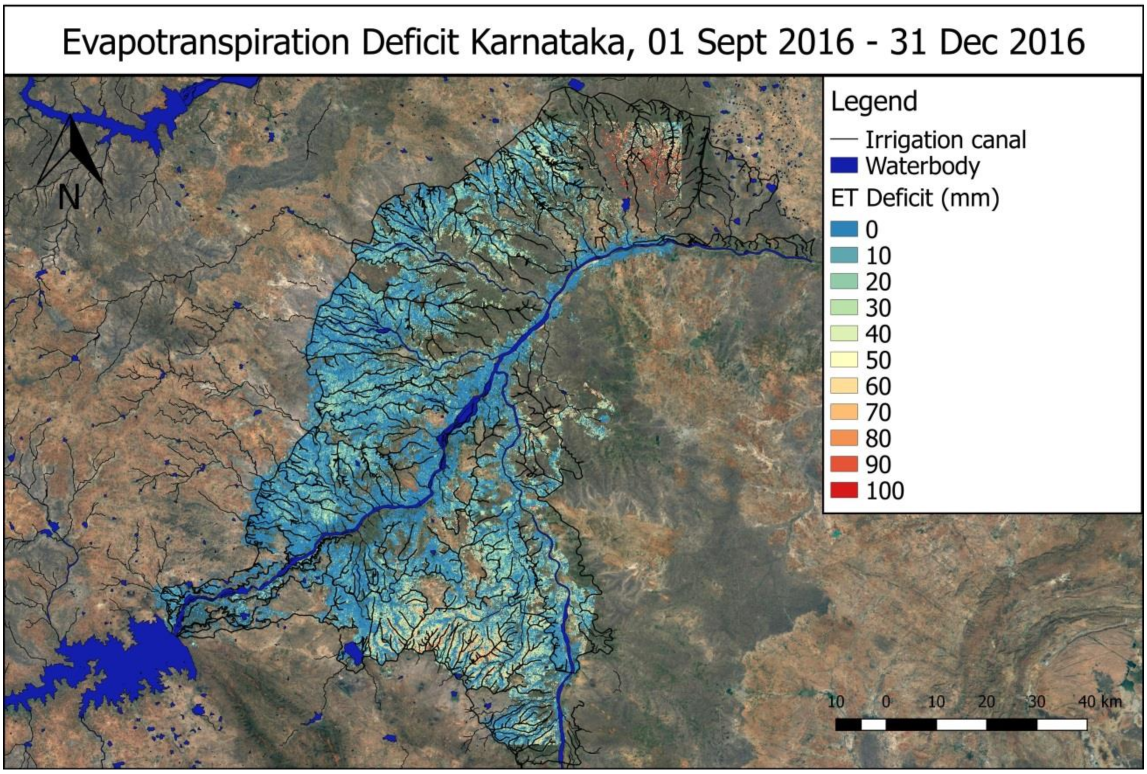

Figure 4.5 Pixel based water shortage as measured in ET deficit for rice growing season

Overall water shortage is low in the system for the studied period. The average ET deficit is 14.5 mm with a CV of 140%. This is 52 MCM shortage of crop water requirement, 25 MCM for TLBC and 27 MCM for RBHL/RBLL respectively. The average ET deficit is 3% of seasonal total ETa. Moderate to high water shortage areas are found to be in the RBHL area and the tail end of TLBC.

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 dry biomass is dry matter production accumulated through photosynthesis process which can be estimated using satellite image. The conversion from biomass to grain yield for rice however depends on many other elements such as seeds, crop temperature, nutrient, and water stress. Therefore a harvest index (HI) is commonly used to represent the ratio of crop yield over dry biomass production. This study establish such an apparent HI using crop yields (with moisture content accepted for marketing, typically at 12-15%) estimated by farmers divided by dry biomass production of the same location.

The average biomass mapped for paddy rice area is 11.6 ton/ha with a CV of 12.4%. A field survey of 40 farmers recorded their estimated crop yield and location. The average yield of these points is 5.25 ton/ha, corresponding to an average biomass production of the same locations at 9.82 ton/ha. Using the yield divided by biomass production we can calculate the average apparent HI to be 0.558. If an average moisture content of 12% is assumed. Then the HI for dry yield divided by dry biomass is 0.471, well in line with those reported in literature. The GT data and harvest index calculation can be found in annex 4.

The rice yield map is then produced using the biomass map multiplied with the apparent HI value. Figure 4.6 shows the yield map. The average yield is 6.5 ton/ha with a CV of 12.3%. The CV of yield is higher than that of ETa. High yield areas are found to be in RBHL, where ETa is low but Ta is high, and TLBC where both ETa and Ta are high. The areas along the main river has low yield in general in spite of low water deficit. The total rice production for the studied growing season is 2.32 million ton, with 1.25 produced from the TLBC areas and 1.07 million ton from RBHL/RBLL.

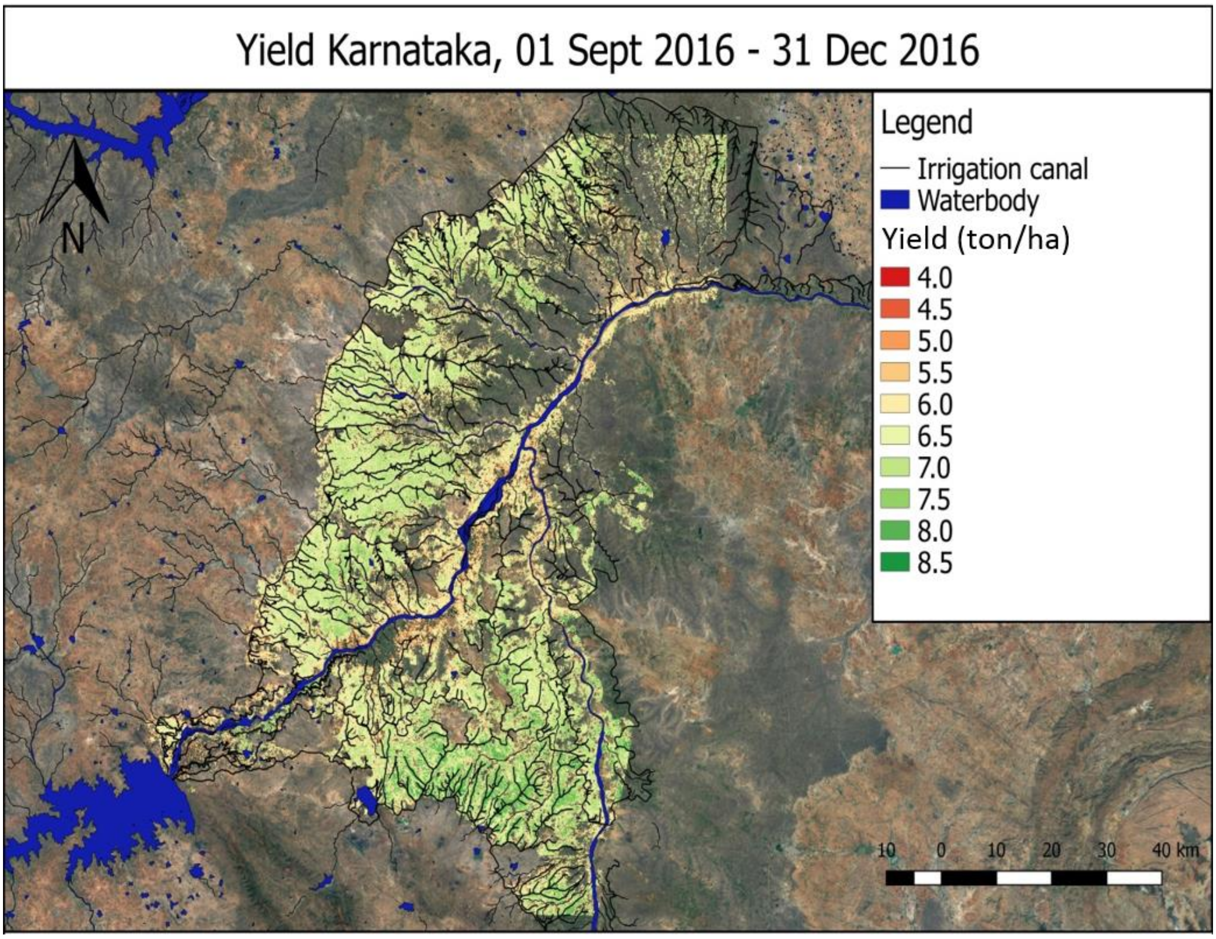

Figure 4.6 the yield map of rice

4.4 Crop water productivity

Water productivity maps of rice were produced using the yield map divided by ETa maps, after the units were converted. Figure 4.7 shows the WP map of rice produced for the study area. The WP ranges from 0.14 to 2.2 kg/m^3. The average CWP is 1.47 kg/m^3 with a CV of 13.6%. The average WP is relatively high compared with values frequently reported in literature.

The CWP map clearly demonstrates the spatial variability in the performance of different areas within the system. Low CWP is observed for areas upstream of TLBC and in the command of RBLL. The areas along the main river have the lowest CWP values due to low yields. Large part of the RBHL command, and the tail end of TLBC main canal, and the tail ends of the distributaries of TLBC, have high CWP values. While the areas in RBHL (down south) maybe considered well performing areas due to high yields and low water consumption, the other high CWP areas at canal tail end is mostly caused by a significant drop in water consumption with moderate to low yields. Higher CWP for these areas, in this case, does not represent better performance, but a combination of water shortage and improved management.

The areas along the river represent lowest outputs per water inputs. The reasons for this remain to be explored on the ground. But significant potential for improvement exists.

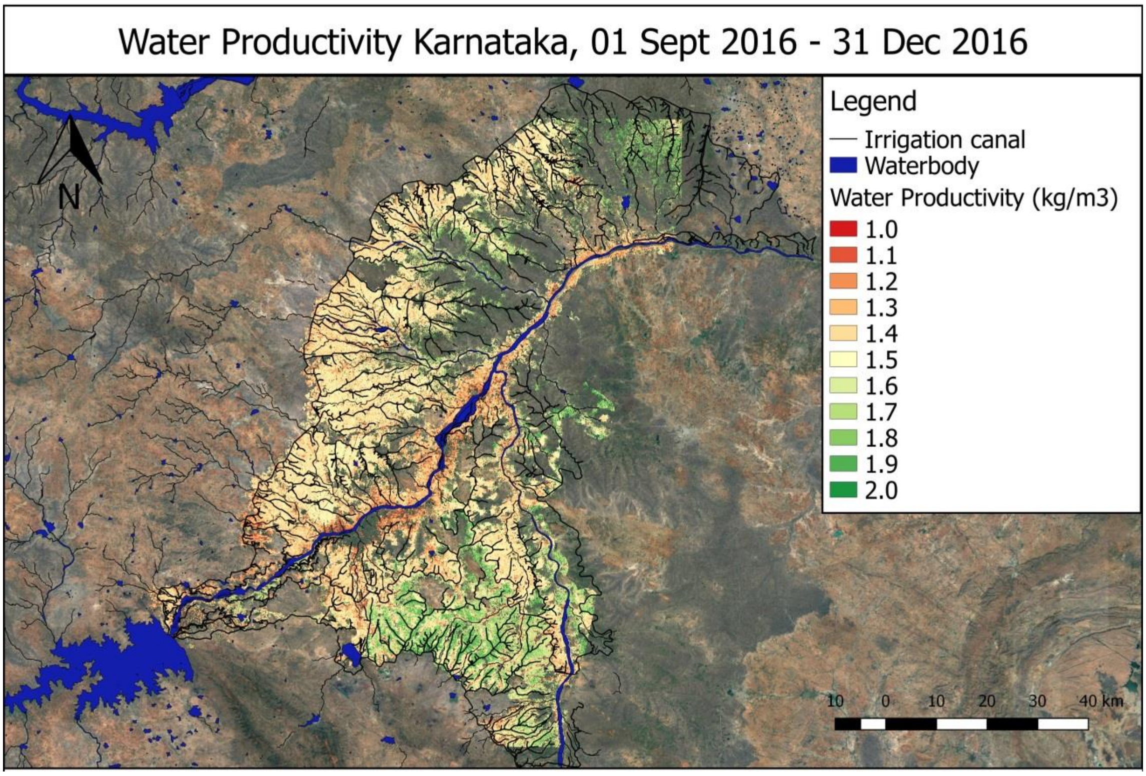

Figure 4.7 crop water productivity of rice for the September – December 2016 growing season.

5. Factors affecting crop 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 field 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: administrative boundaries for potential effects on extension services, distance to water bodies, distance to canals and rivers, slope, soil quality, season variations, soil, fertilizer, and seeds. 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.

5.1 Distance to the Tungabhadra Dam (water source)

The spatial distribution of CWP, ETa, yield and Ta in relation to the head-tail effects of canals are analysed. Buffer zones were created at 1 km, 5 km, 10 km 20 km, 50 km, 80 km, 110 km, and 150 km in distance from the Tungabhadra Dam (figure 5.1). The shape of the irrigation system means that the 1 km and 5 km zones have rather small areas.

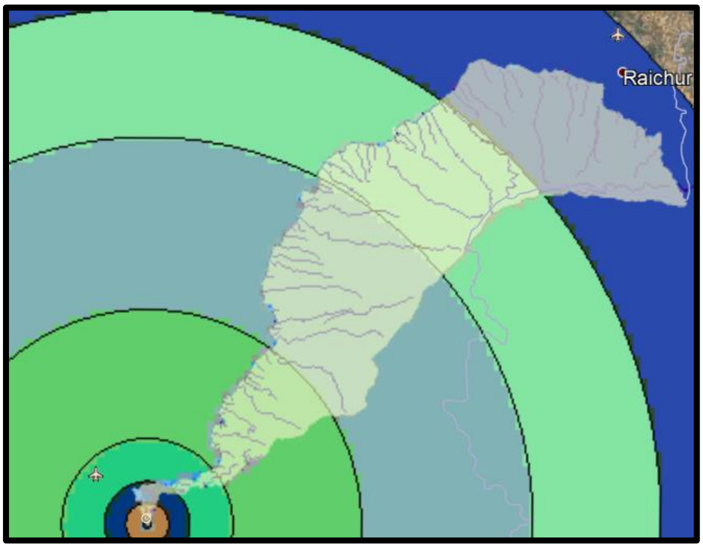

Figure 5.1 Buffer zones over the Tungabhadra irrigation system to segment the areas from upstream to downstream.

The average values of CWP, yield, ETa, and Ta is calculated for each zone. Figure 5.2 shows their distribution. Excluding areas within the 1 km and 5 km zones, the CWP and yield gradually increase moving away from upstream to downstream. The total water consumption ETa increases and peaks at 50 km buffer zone and before decreasing. The beneficiary consumption Ta however decreases to the lowest at 20 km buffer zone before increases again. It is evident that the 10 – 20 km buffer zone has the lowest rice yield, the lowest beneficiary water consumption, and the lowest CWP.

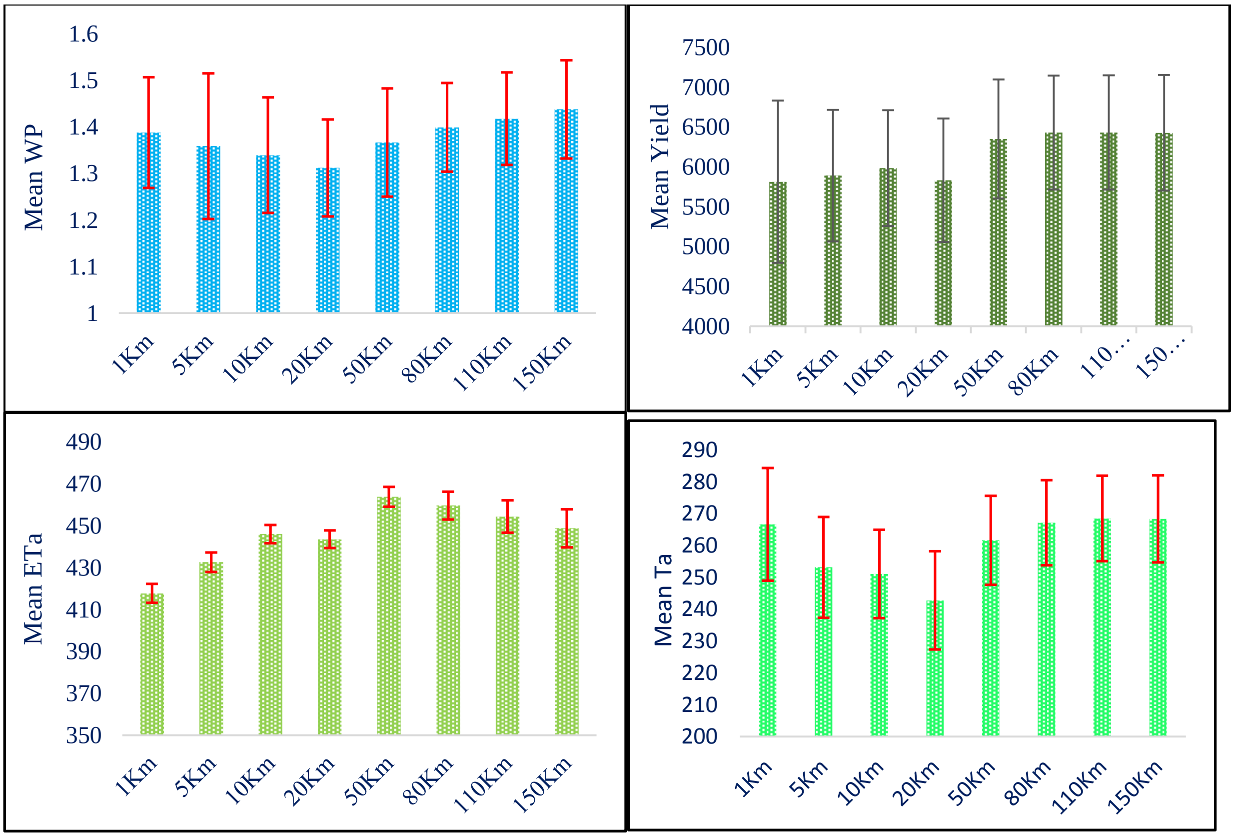

Figure 5.2 The variations of CWP, yield, ETa, and Ta of rice in relation to distance to the Tungabhadra Dam

5.2 Slope

The Tungabhadra irrigation system is located in hilly areas with gentle slopes along both sides of the main river. The slope may has an effect on paddy field water management. An analysis was therefore performed to assess whether slopes are correlated with performance indicators.

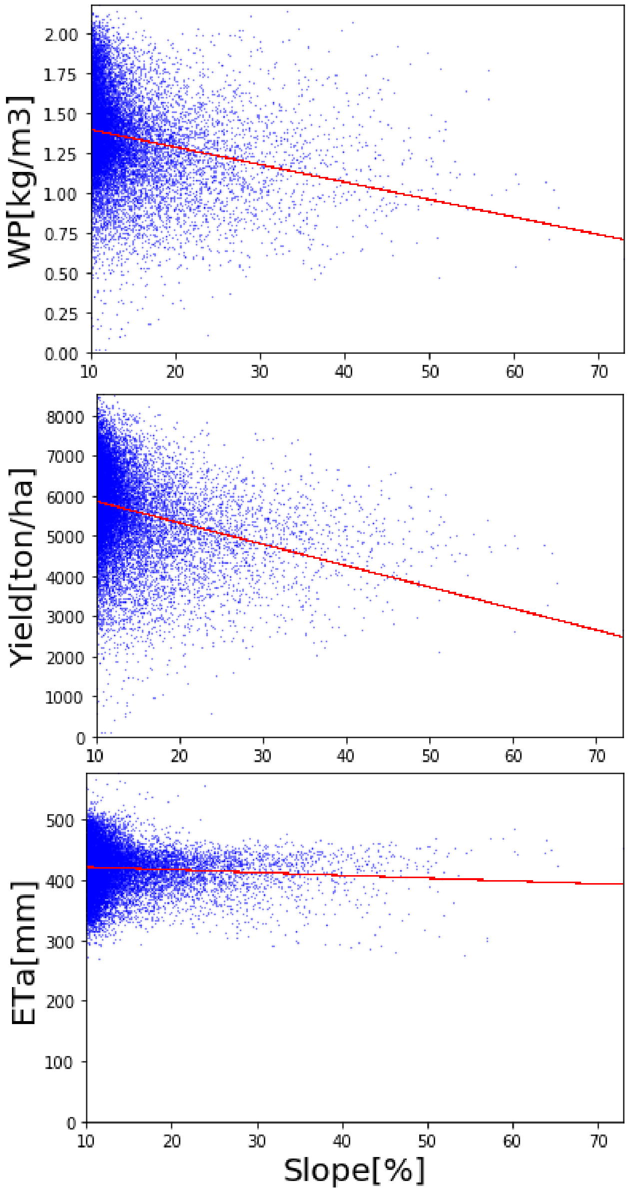

Figure 5.3 the relation between CWP, yield and ETa of rice with slopes.

No correlation could be found between CWP, yield and ETa of rice with slopes. Figure 5.3 shows that with varying slopes, the variables show no significant trend.

5.3 Soil

Soil types have been recorded in the GT survey which provides opportunity to examine the potential link with the performance indicators. Figure 5.4 shows the crop water consumption, yield and CWP for different soil groups based on the GT point data. No significant differences are observed for ETa from different soil types. Rice yield, however, is slightly lower for sand/sandy loam soils and slightly higher for loamy soils compared with that of clay/clay loam soils. The CWP of sand/sandy loam soil is significantly lower, most likely related to poor water holding capacity of sand/sandy loam soils.

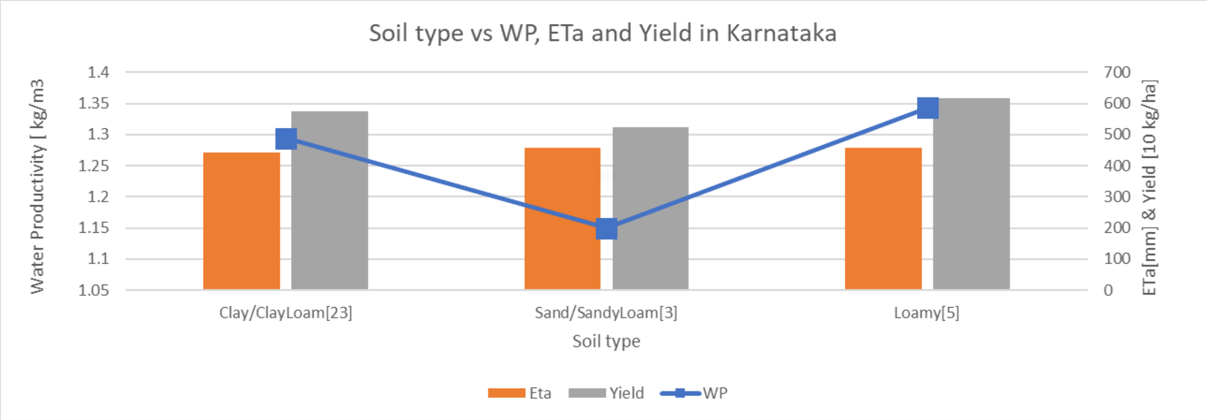

Figure 5.4 The relation between CWP, yield and ETa of rice with different soil types.

5.4 Cropping calendar and intensity

The irrigation system is mostly dominated with single cropping intensity. The crops may grow in Kharif or Rabi season, or in some cases, both or more seasons. The Natural Resources Census (NRC) National Land Use and Land Cover map 2008, produced by National Remote Sensing Agency, classifies cropland into Rabi season, mid-November up to including April (dry season), Kharif, July-Sept (rain season), and those in more than two seasons. The map is subject to an update for current conditions. Nevertheless, they could still provide insights as how CWP parameters may or may not change with different cropping calendars and intensity.

Figure 5.5 The relation between CWP, yield and ETa of rice with different cropping calendar and intensities

5.5 Fertilizer

The types and application rate of fertilizers were also collected during field trip and are used to analyse the effects on CWP indicators. Figure 5.6 and 5.7 show the relation between CWP, yield, and ETa of rice for the common types of fertilizers found in the system, and their application rates. The fertilizer application rate is recorded by asking farmers if it is below, equal to, or above application rate recommended by the Department of Agriculture. The application of both N and P produces the highest yields and CWP. Applications with recommended rate produces best results in terms of yield and CWP. Over application actually corresponds to 14% in yield reduction and 16% reduction in CWP.

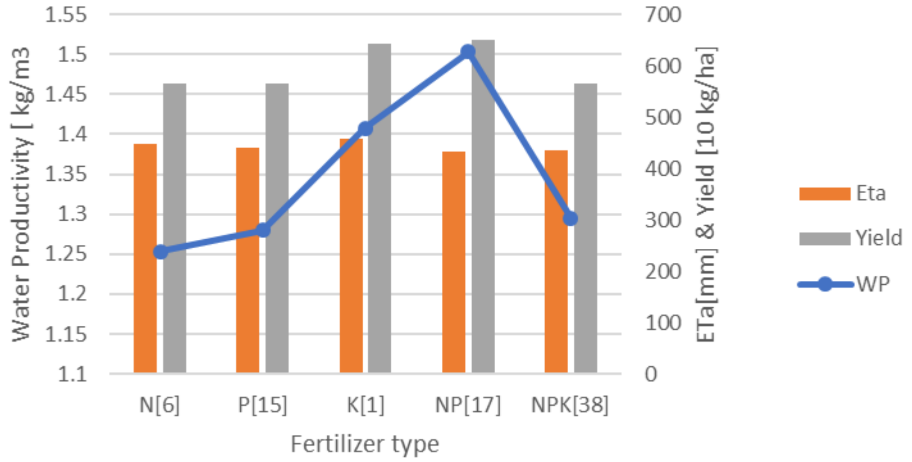

Figure 5.6 The relation between CWP, yield, ETa of rice with fertilizer types in the system

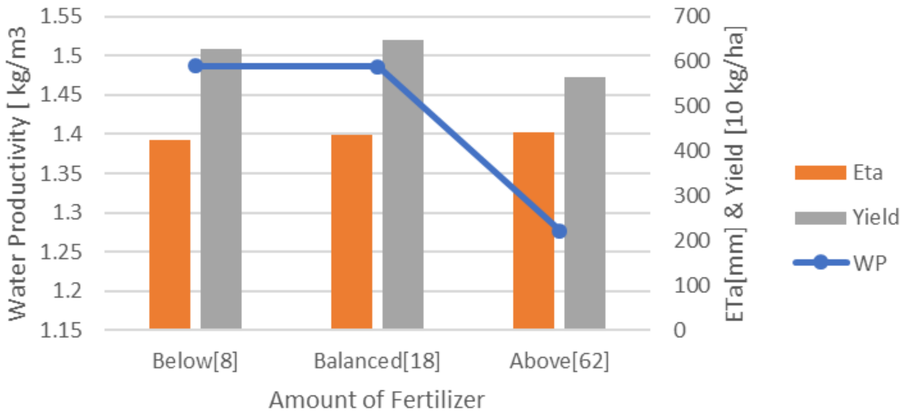

Figure 5.7 The relation between CWP, yield, ETa of rice with fertilizer application rate in the system (compared with recommended application rate from the agricultural department).

5.6 Seed

Information on seed types is also recorded during the field trip. There are several seed types available and they are categorized as certified variety, grain from past harvest, research variety and truthful label. Figure 5.8 shows that the ETa rate is similar across all seed varieties. The research varieties however produce the highest yield, about 7% higher than other varieties. As a result the CWP of research variety is also the highest at 1.46 kg/m^3, compared with 1.31, 1.32, and 1.38 kg/m3 for grain, certified, and truthful label respectively.

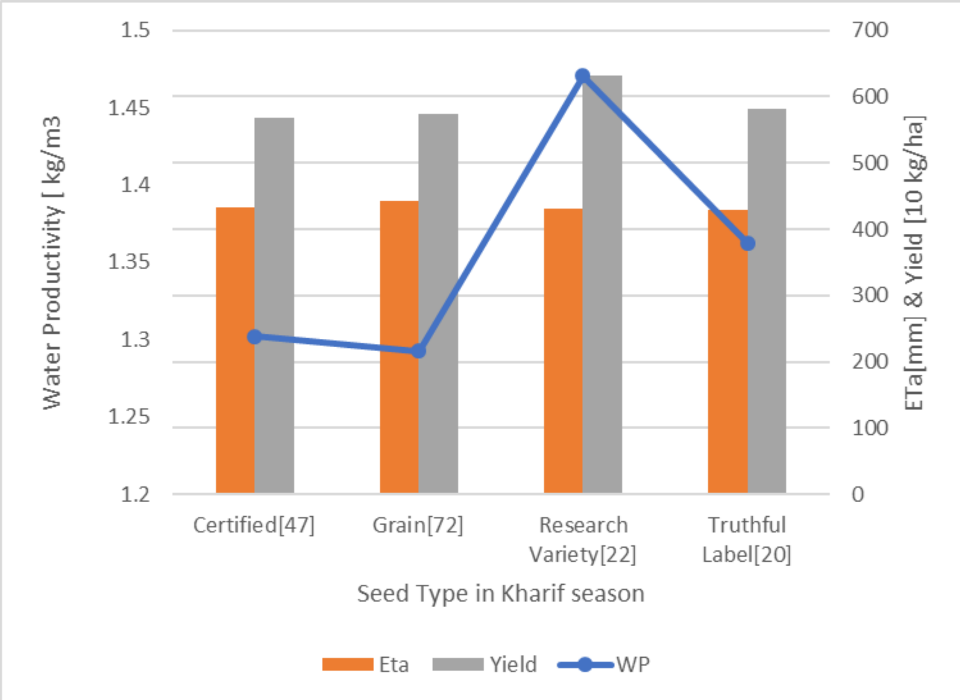

Figure 5.7 The relation between CWP, yield, ETa of rice with seed varieties in the system

6. Summary and the way forward

6.1 Summary of CWP results

The concept of WP helps irrigation mangers, agricultural extension workers, and policy makers to better understand whether water resources in agriculture are used efficiently. This pilot study introduce WP concept and demonstrates its applications in the Tungabhadra irrigation system. WP is a simple and attractive indicator to assess whether intended processes go well. More irrigation related performance indicators are needed to make a first diagnosis on how irrigation systems function. In this study, we introduced therefore also crop yield, ET deficit and beneficial consumption (Ta).

A novel yet practical remote sensing approach was applied to the Tungabhadra irrigation system. The computations of crop production and crop evapotranspiration requires an energy balance model that converts available radiation from sun and earth into water and carbon fluxes. The updated Surface Energy Balance Algorithm for Land (SEBAL) model with automated calibration process was used for this purpose. This so called pySEBAL model is programmed in python language. pySEBAL bases on freely available data from the Landsat, ProbaV/VIIRS and Sentinel satellites. Hence, there are no costs involved to repeat and expand these type of analysis. Smart phone based groundtruth improves efficiency and reduces the costs of field works.

The CWP of rice in the Tungabhadra irrigation system is not low but with high spatial variability for the 2016 Kharif season. The average CWP of the TLBC is 1.44 kg/m^3 with a CV of 13%. The average yield and ETa are 6.4 ton/ha and 448 mm respectively. The command areas of RBHL and RBLL has slightly higher CWP at 1.5 kg/m3 by using less water (437 mm) and producing higher yield (6.5 ton/ha). There was a shortage of 25 MCM, or 3% of current consumption, for TLBC to satisfy full crop water requirement. However, this does have to come from additional supply. In fact, only 268 mm, or 60%, of total ETa is consumed through transpiration (Ta), meaning significant potential for improvement (Table 6.1).

High spatial variability represents non-uniform performance across the system. The up to mid- streams of TLBC, areas along the main river, and the RBLL command have high water consumption of 475 mm or more. However, the crop yields are not high, leading to moderate CWP. Large area of low ETa is found in the command of RBHL which also has high yields, and therefore high CWP. The tail end of TLBC has low water consumption and very low yields, which leads to low CWP. The areas along the main river, which are fed with direct diversions from the river, also have very relatively high water consumption but very low yields.

Table 6.1 summary of CWP results for TLBC and RBHL/RBLL

	TLBC	RBHL & RBLL
Total command area (ha)	365,681	314,106
Total paddy area (ha)	195,202	164,499
ETa mean (mm)	448	437
Ta mean (mm)	268	279
ET_def mean (mm)	13	16
ETa sum (MCM)	875	718
Ta sum (MCM)	523	458
Ta/ETa (-)	0.60	0.64
ET deficit (MCM)	25	27
Yield mean (kg/ha)	6,412	6,515
Production (ton)	1,251,649	1,071,646
WP mean (kg/m^3)	1.44	1.50

The factors potentially linked to water consumption, yield and CWP are investigated for location, slope, soil, crop pattern, fertilizer application, and seeds. The analysis did not find significant correlation between the CWP indicators and the distance to canals. But the distance to the main dam, as a measure of head – tail effect, is affecting CWP, yield and ETa. The 20-50 km zones in the middle reach have the lowest CWP with high total water consumption (but low beneficial consumption) and low yield. No significant correlation is found between the CWP parameters with slope. The sandy soils have the lowest CWP due to low yields from similar water consumption. Cropping patterns also have an effect on CWP of the assessed Kharif season, the higher the intensity, the lower the CWP is found. For single cropping intensity, areas performing Rabi season farming has higher CWP than that of areas with Kharif season farming. When farmers apply both N and P at recommended level, they have the highest CWP compared with those applying less or more. And the research seed variety produces higher CWP than other varieties.

6.2 Assessing the potential and determining the priorities

A combined analysis of ET, yield and WP provides a comprehensive picture of the results of irrigation land, water, and crop 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 Tungabhadra irrigation system is illustrated to demonstrate how the planners and mangers can best embrace these technologies.

Yield – often referred to as land productivity – and water productivity should both score high in an ideal situation. Figure 6.1 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. This graph demonstrates the possibilities of farmers who produces the same yield but with low and high WP, or on the other side, they could achieve different levels of CWP even if their yields are the same. 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 the space.

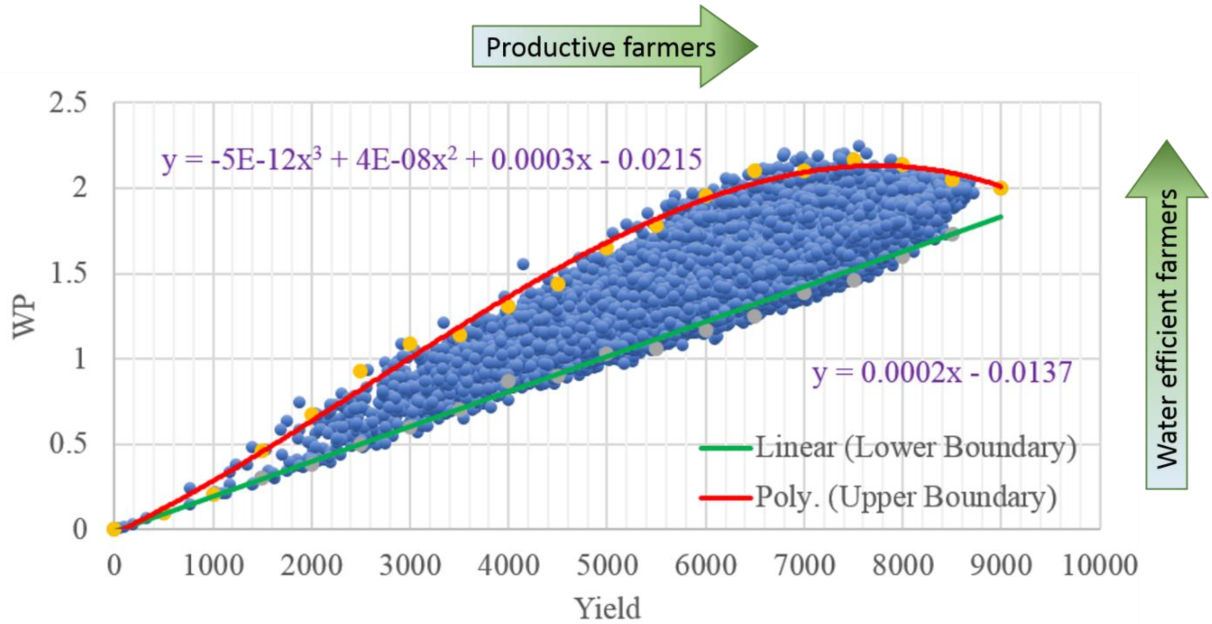

Figure 6.1 Water saving and WP potential analysis by identifying water use efficient farmers and productive farmers.

Significant potential exists for on farm water savings. The average ratio of beneficiary consumption (Ta) to total consumption (ETa) is 60% for TLBC and 64% for RBHL/RBLL. While these values are already high and they don't equate to water saving potential, they still indicate areas where higher potential exists. Figure 6.2 shows such potential in a spatially explicit manner. The highest water saving potential is along the main river where the beneficiary consumption ratio is only 40-50%, a 10-20% potential for improvement if we just take system average of 60% as a modest target. Large areas in the upper to middle stream of TLBC also show lower ratio with a potential of about 5-10% improvement.

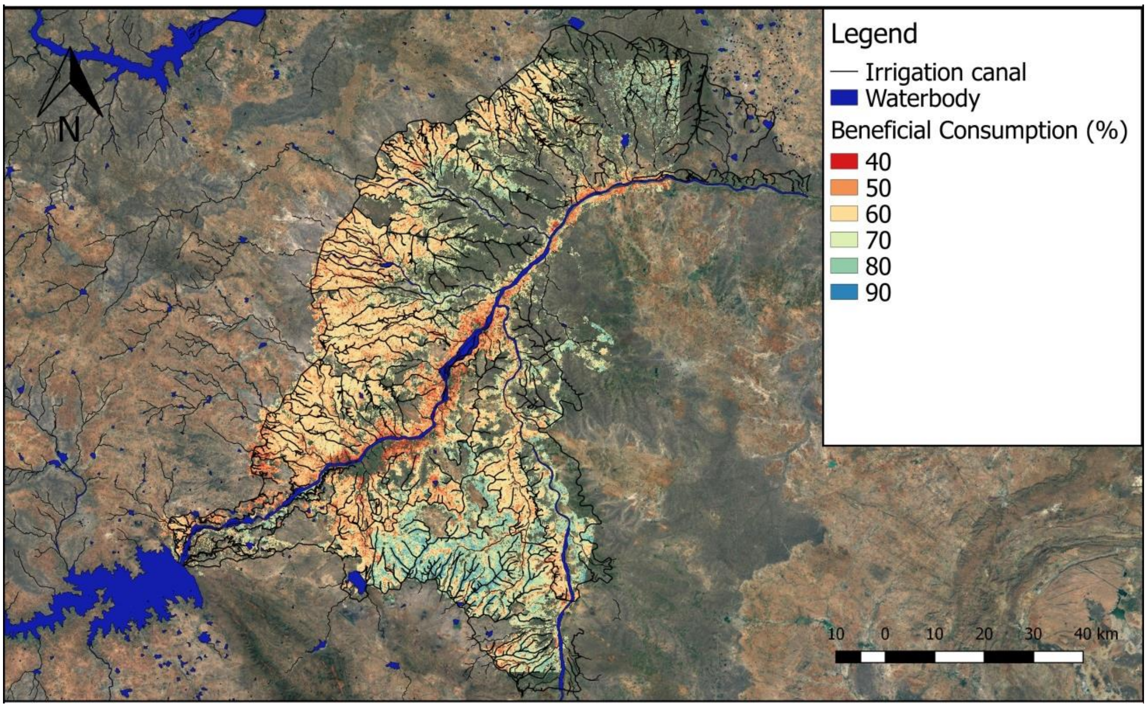

Figure 6.2 The ratio of beneficiary consumption (Ta) to total water consumption (ETa) as an indication of on-farm water management efficiencies for the 2016 Kharif rice

Managing field water consumptions are ultimately linked with system performance through measurement of CWP. Figure 6.3 shows the relation between rice CWP and rice Ta to ETa ratio. Increases in CWP is linearly related to the increases in Ta/ETa value through on-farm water management improvements.

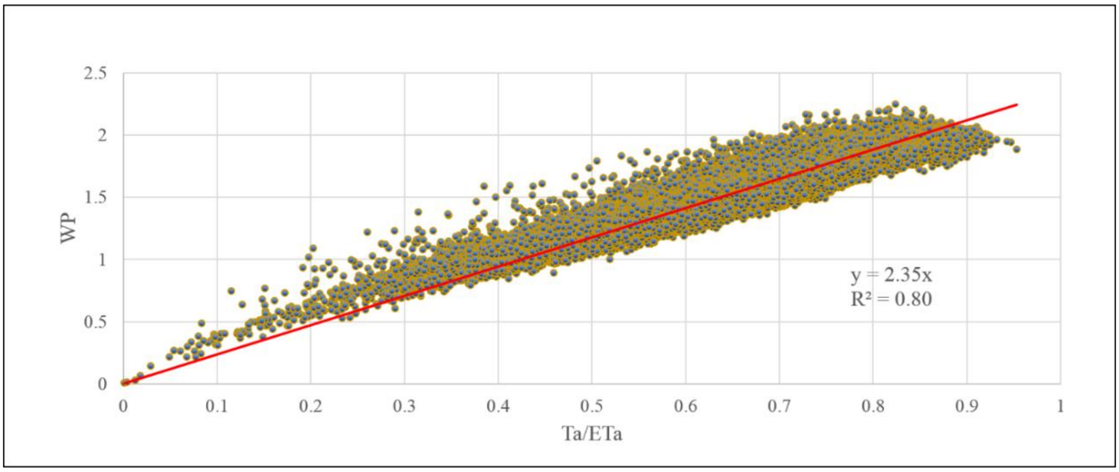

Figure 6.3 the relation between rice CWP and rice seasonal Ta to ETa

There are always a need to determine priority interventions areas due to constraints in resources. Figure 6.4 illustrates this can be easily done using the CWP map classified in 3 categories: hotspots or poor performing areas with CWP 1 standard deviation (SD) below average, areas with average, and bright spots/hero farmers for those well performing areas with CWP 1 SD above average. The hotspots are not expected to achieve the same results as the bright spots, but could learn from the hero farmers. Unsurprisingly, the tail end of TLBC (upper right) are mostly green. Higher CWP here does not imply better performance, but rather, farmers used the little water available to them more efficiently.

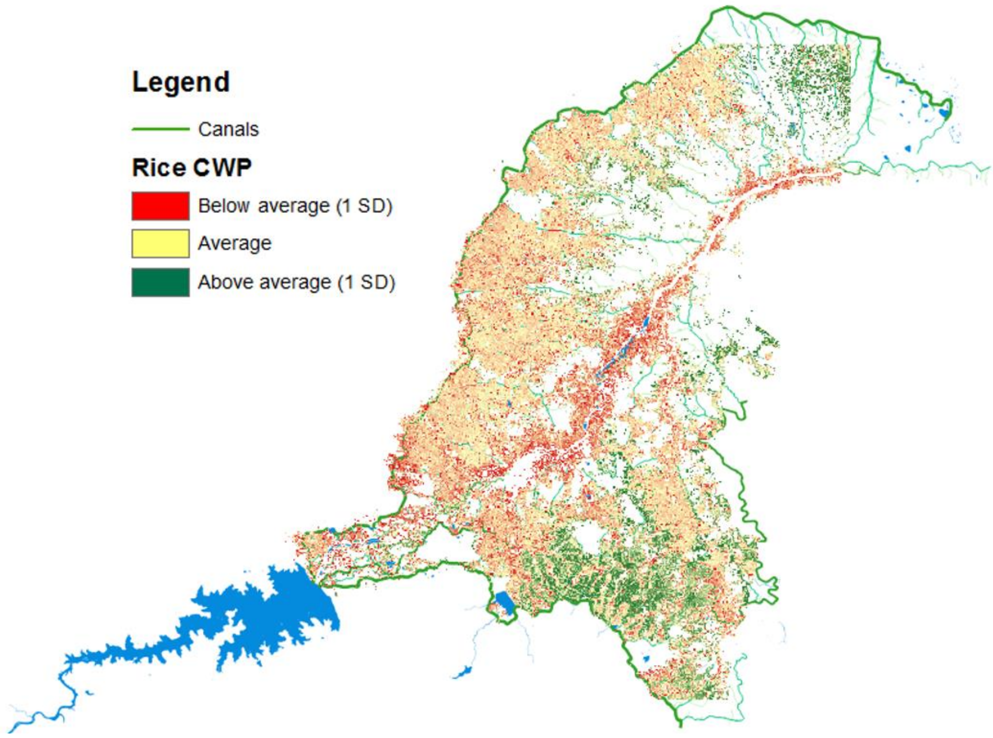

Figure 6.4 Rice CWP map to help determine priority intervention areas where CWP is very low (red), average (yellow), and above average (green).

6.3 The way forward

This report presents the demonstration part of a capacity building project on integrating CWP into irrigation development and management. The project introduces and demonstrates the concept of WP and use of state-of-art remote sensing technology to assess rice CWP in agricultural areas where the government and ADB are working with farmers to develop and rehabilitate irrigation projects. While rehabilitation and modernization are essential to keep pace with the rapid changes in challenges facing farmers, the effectiveness of investments depends on the main constraints to improve yield and WP. It is recommended that any interventions have to be location specific considering current water use, yield and CWP conditions.

A genuine shortage of water due to lack of rainfall and low storage in reservoir can be the primary reason for low productivity. The effects on individual fields are however different. The Tungabhadra irrigation systems exhibits great local variabilities in both yield and ET, reflecting various factors but especially that related to water availability at field level. Factors such as irrigation infrastructure, canal and field water management practices, soil, cropping pattern, fertilizer and seeds all have direct effects on water consumption, yield and CWP. Hence remote sensing is excellent for detecting local situations, but follow-up field investigation should be initiated to define a package of measures that could generate location and factor specific interventions. Such value-adding exercises need to be carried out through collaborations with irrigation engineers/managers, agronomists, extension services, farmers and farmers groups.

A CWP and pySEBAL training workshop, organized with ACIWRM, was successfully carried out for 31 selected participants. 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 learning and hands-on exercises, preferably with individual investment projects. In particular, emphasis should be given to diagnoses of the causing problems and monitoring of the irrigation system to detect improvements. ACIWRM is already working with the state agricultural universities to take the concept and method forward. The collaborations between water and agriculture will add more value to the uptake of the theory and technology.

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List of annexes

Annex 1. pySEBAL user manual
Annex 2. SEBAL list of publications
Annex 3. Groundtruth
Annex 4. Validation and bias correction of crop yields
Annex 5. The training workshop