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Knowledge and Innovation Support for ADB's Water Financing Program

Pakistan: Water Productivity Measurement-Punjab Irrigated Agriculture Investment Program

Prepared by Xueliang Cai and Wim Bastiaanssen
IHE Delft Institute for Water Education, The Netherlands

For Asian Development Bank

Asian Development Bank

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

Technical report

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Executive summary

The government of Punjab, Pakistan is transferring its water management systems from heavily irrigation focused to more integrated approach, which calls for more efficient irrigation water management. The Punjab Irrigation Department is working to modernize irrigation in the Lower Bari Doab Canal (LBDC) 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 modernization and management, IHE works with ADB and the Irrigation Department to introduce the concept of crop water productivity (CWP) and use of remote sensing technology for assessing the same.

This report describes the application of, pySEBAL, a remote sensing approach to assess crop CWP in LBDC. Baseline conditions were established by means of mapping the crop type, water consumption, water shortage, crop water deficit, crop yield, and the crop water productivity in the reference period of the 2016-7 Rabi season at resolution of 30 m by 30 m using publically available imagery and ground-truth surveys. The spatial variability and contributing factors are 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 open source remote sensing tool.

The 2016-7 Rabi season baseline conditions of selected areas in LBDC on water consumption, shortage and crop production are revealed. A total wheat production area of 664,311 ha consumed 3,049 MCM of water and produced 2.7 million ton of grain. Orchard (Citrus and mango) occupies 281,307 ha of areas, and consumed 991 MCM of water during the same Rabi season. Clearly orchard consumes significant amount of water, which is currently not included in water supply plans.

Water shortages and adequacy were determined at pixel level for wheat. A crop water shortage, in the form of ET deficit, of 239 MCM (8% of current consumption) exists. However another finding shows that the water consumption is already 11% higher than total crop water requirement. It is therefore necessary to optimize and improve current irrigation scheduling instead of increasing water supply to fill up this gap, as what the departments are planning to do.

The CWP of wheat is low with moderately high spatial variability. The average CWP of wheat is 0.89 kg/m^3 with a CV of 13%. The average yield and ETa are 4.1 ton/ha (CV 15%) and 459 mm (CV 6%) respectively. The low WP is mainly attributed to high water consumption. High spatial variability represents non-uniform performance across the system, which represent great potential for farmers to learn from their better-performing neighbours. The overall potential is less in water management and more on non-water related yield factors, as indicated by the differences in CVs.

No significant correlation was found between performance (water consumption, yield and CWP) among irrigation management units, or distance of farms to canals. The analysis did not find significant variations in CWP indicators among different administrative units, or head and tail end farms.

The total canal water supply to two irrigation divisions were lower than total water consumption from the command, but higher than that of wheat. Total water supply was 852 MCM and 1,076 MCM for Sahiwal and Khanewal respectively. It is 34% and 22% more than wheat water consumption, but only 73% and 81% of total water consumption from the two divisions respectively. There was no rainfall observed for the study period. The additional water consumption comes from soil moisture change and groundwater extraction, with the later plays significant role.

There is significant potential for water saving in canal systemoperations. The total water consumption of wheat is 11% higher than the crop water requirement, as analyzed in section 5.3. The actual canal supply in Sahiwal and Khanewal is even higher. So the potential to reduce water supply could be even higher.

On-farm water savings represents another big potential in LBDC. The average ratio of beneficial consumption (Ta) to total consumption (ETa) is 52% for wheat, 43% for mango, and 42% for citrus. They indicate large areas, particularly orchard, with high potential to reduce water losses at farm level by reducing open soil evaporation, through partial soil wetting methods such as bubblers and drips.

The spatially explicit maps could pin-point priority interventions areas. Hotspots can be easily identified on water productivity map and attributed to water or non-water management aspects. On the other side, “hero farmers” can also be identified to help understand why they are doing better and how other can learn.

A CWP and pySEBAL training workshop, organized with the Irrigation Department, was carried out for 19 selected participants. This training was meant to create awareness and interests, and introduce young and eager professionals to the technology. It does not seem to be of sufficient duration to transfer the full modelling capacity for participants to apply on their own. 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 problems from the remote sensing outputs and monitoring of the irrigation system to detect improvements. Nevertheless, all the participants, and the Irrigation and Agriculture Departments, have shown great interests in the ideas and methods. Reflections from the participants are pointed towards the needs for continued learning including self-learning, more in-depth analysis of the irrigated cropping systems, and verification and applications of the results.

Follow up actions are required to ensure smooth uptake and continued use of the water productivity concepts and the remote sensing technology, which is especially relevant in the large contiguous irrigation systems in Punjab. The action points are summarized below:

1. There is a great potential in water savings through both improved system operations and better on-farm water management practices. The irrigation supply can be reduced at least 11% at canal level. Even bigger potential exists through on-farm water saving irrigation strategies. This needs to be verified at individual canal command level, with consideration of groundwater use and the recharging effects of irrigation supply;
2. The on-farm management practices for wheat represent the biggest potential for water savings. But the large area of orchard, which is not included in current irrigation planning, has lower beneficial consumption ratio, hence high potential for improvement per unit of area. It is probably also easier to implement water saving practices in orchard gardens.
3. It is highly recommended that the data, results, and findings be critically reviewed by the Project Management Unit at the Irrigation Department and ADB and incorporated into current planning. The on-going effort by the department to assess irrigation shortage (adequacy) using remote sensing, for example, is aimed at increasing supply while the current supply already far exceeded what is required. Crop water requirement may be met through conversion of irrigation methods from flood to bubblers, and optimized rotation of distributaries, instead of supplying more water from canals.
4. Scaling up the assessment to the entire LBDC command. A full system level analysis, including that from remote sensing and measured irrigation and drainage data, will be more relevant for management. The trained participants could take the lead and IHE Delft provides backstopping role.
5. The Irrigation Department and Agriculture Department build up a joint capacity on remote sensing crop and water monitoring and diagnosis, using the free software packages provided by IHE Delft. The continued exercises will provide opportunities for self-learning, but perhaps also identifying more advanced trainings and/or master/PhD scholarships.

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 in water scarce regions 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 irrigation managers, or profits for farmers. 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 found 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 and rainfall in a system and the ability of irrigation systems to turn water supply into food production. Figure 1.1 shows that irrigation efficiency (including conveyance efficiency and application 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.

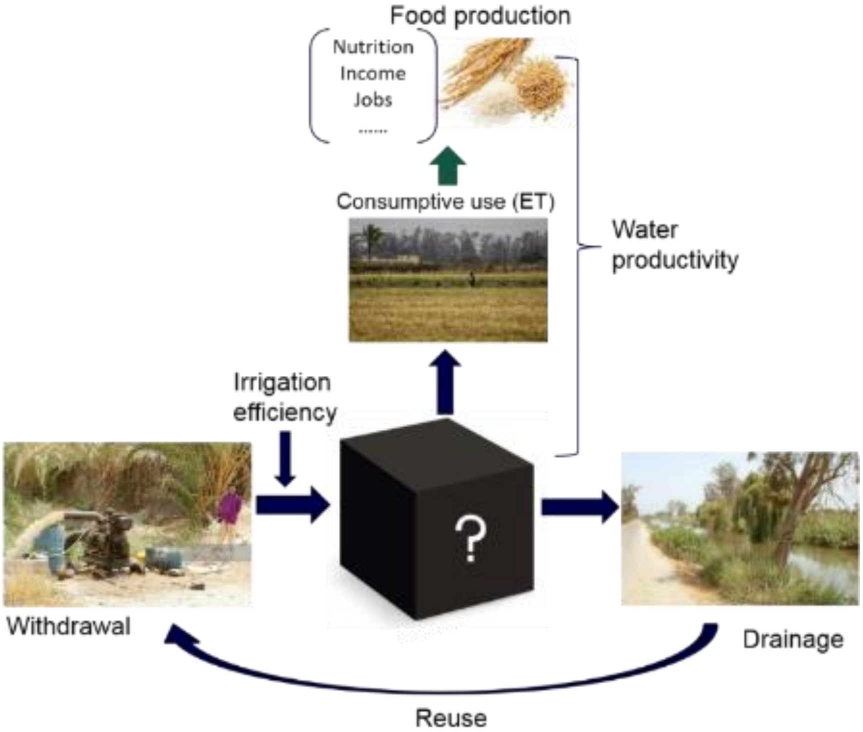

Figure 1.1 The irrigation efficiency and water productivity indicators for irrigation systems. The two indicators are complementary while WP covers more advanced and broader components of irrigation performance.

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).

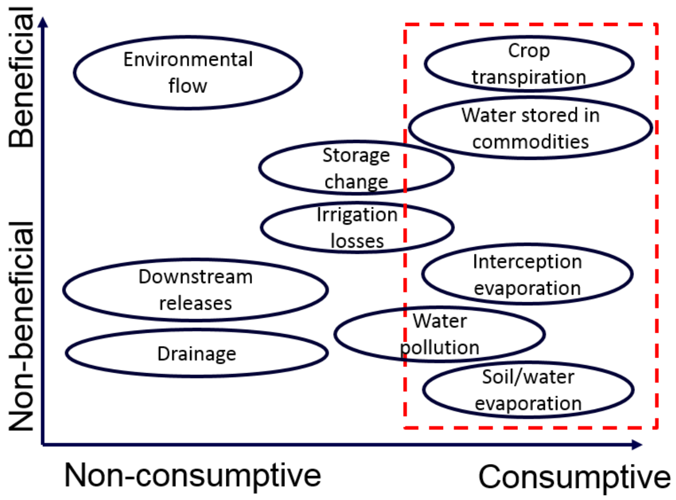

Figure 1.2 Remote sensing approach focuses on the beneficial and non-beneficial consumptive use of water.

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 contribute to addressing water and food crisis in water scarce areas, in reality it is difficult to improve crop water productivity at farm level, partially because target values are not available to farmers/irrigators to guide them. They often associate water savings with a lower amounts of applied water, fewer irrigation turns, or a higher on-farm conveyance efficiency. They do not consider the consumptive use of water and the production that is associated with that use.

Various strategic programs ranging from United Nations to National Departments assume that CWP 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).

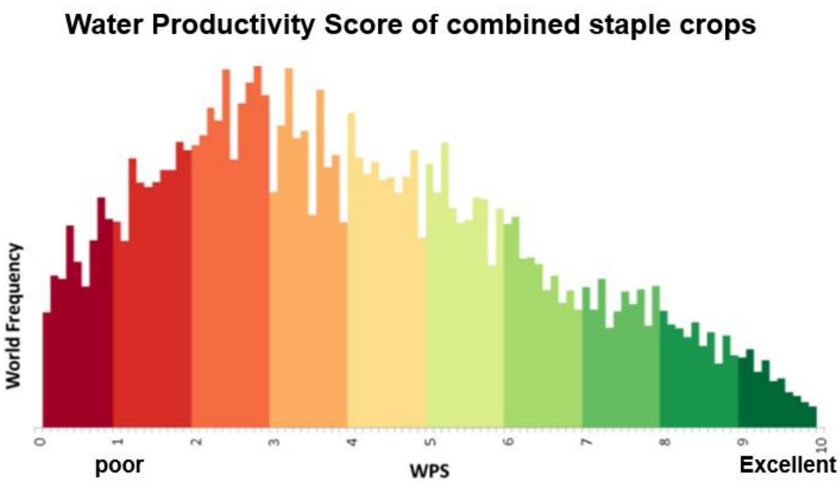

Figure 1.3 Frequency distribution of the Global Water Productivity Score (GWPS) reflecting wheat, rice and maize crops at the global scale. This graph could be created due to climate and crop normalization. A GWPS of 1 is poor and of 10 is excellent (Bastiaanssen and Steduto, 2016)

1.3 The collaboration between IHE Delft, ADB and Punjab Irrigation Department 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 lending projects. 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 Pakistan the team is working with Punjab Irrigation Department with pilot study being carried out in selected areas in the Lower Bari Doab Command (LBDC). The irrigation department was actively involved in setting the scope, designing of field survey, and coordinating of the training workshop.

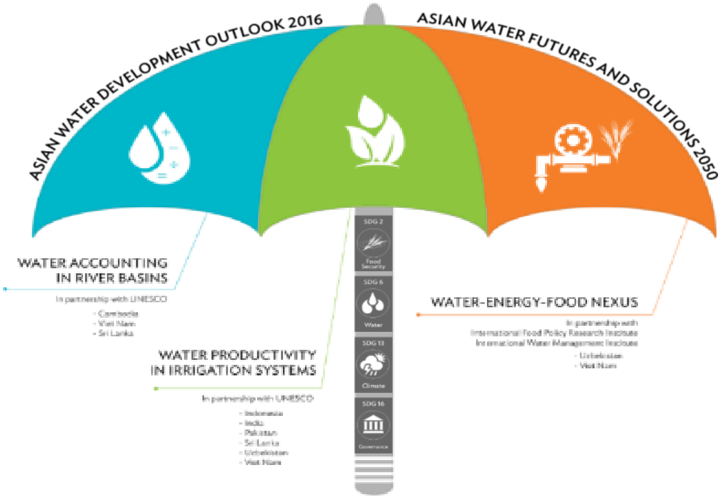

Figure 1.7. The role of Water productivity in irrigation systems, the single biggest water user, to support ADB initiatives for Asian water security. (Source: ADB, 2016)

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, organized with Irrigation Department and ADB, was conducted at the Flatties' Hotel in Lahore from 16-20 April 2018. A total of 19 participants (17 male and 2 female) joined the training. The participants were from the Irrigation Department, and Water Management of the Agricultural Department. 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 the LBDC area 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.

An interactive discussion session on the last day of the training workshop was organized. The discussion session is opened with an introduction to current water shortage mapping activities at the Irrigation Department using remote sensing by Dr. Wakas Karim. Dr. Sanmugam Ahembaranathan Prathapar facilitated the discussions with all participants given their reflection on what can be improved at Irrigation and Agriculture Departments, as well as that at IHE. There's a general agreement that the logic and steps of the methodology used to map water productivity is sound. The following comments were made in response to PID's presentation on how their DSS can be improved:

1. ***Improving Team's skills/data sources***
   a. PID could increase use of open-access software for GIS/RS analysis, as in the case of IHE.
   b. PID's Technical capacity has room for improvement. Invest time on Self-learning.
   c. Use of higher resolution images will improve crop identification and crop-area mapping.
   d. Use of satellites with more frequent passes is recommended.
2. ***Improving execution of methodology***
   a. Validating crop identification by increasing (sampling sites) ground truthing. It is unclear how intercropping is affecting crop signatures. Another source of data for crop verification is the data collected in 2003 by PID. This will also lead to better estimation of cropping area.
   b. There's also scope to increase estimates of water consumed. Kc-current estimates used can be refined by including the knowledge and understanding of on-farm irrigation practices. Current estimates appear to be lower, resulting in higher estimates of water deficit. How about setting up and monitoring pilot areas? Is the variation in Kc with variation in Days After Planting a concern? How does the deficit spreads over the season – was the water availability reliable (from canal and groundwater sources)?
3. ***Application of Results***
   a. Estimate water deficit at distributary levels since they are the control points for water delivery.
   b. Use results to redefine cropping pattern and calendars.
   c. Link IRSA sanctioned water allocation to water deficit estimated by PID's WRM DSS. This will be beneficial to re-visit water sharing among canal commands in the Province.
   d. Revise allowances made during the British Era using new tools and conjunctive water use within canal commands.
   e. Refined crop areas can be used to verify estimates made by Patwaris and Abiana assessed.
   f. Verify whether the 15-year data set (2003-2017), is applicable now? Can this be used to evaluate the impact of rehabilitation of LBDC?
4. ***What can IHE do?***
   a. Algorithms used to estimate ET0 (RET) needs checking.
   b. Are the KC estimates done by FAO 56 remain valid?
   c. Can we separate the impact of irrigation method on water deficit, based on Ta?
   d. Currently ETa is estimated and Ta separated from ETa. Will it be possible that despite estimated ETa deficit, the Ta is met? Probably the case in drip irrigated orchards. It was recognized maximizing Ta and minimizing E will require major changes to irrigation practices, such aa\s a shift from gravity irrigation to pressurized irrigation.
   e. Develop an educational tool to understand water use efficiency.
   f. Determine what contributes to water deficit? Groundwater availability and quality, canal water supply (quantity and frequency), traditions of farmers.

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).

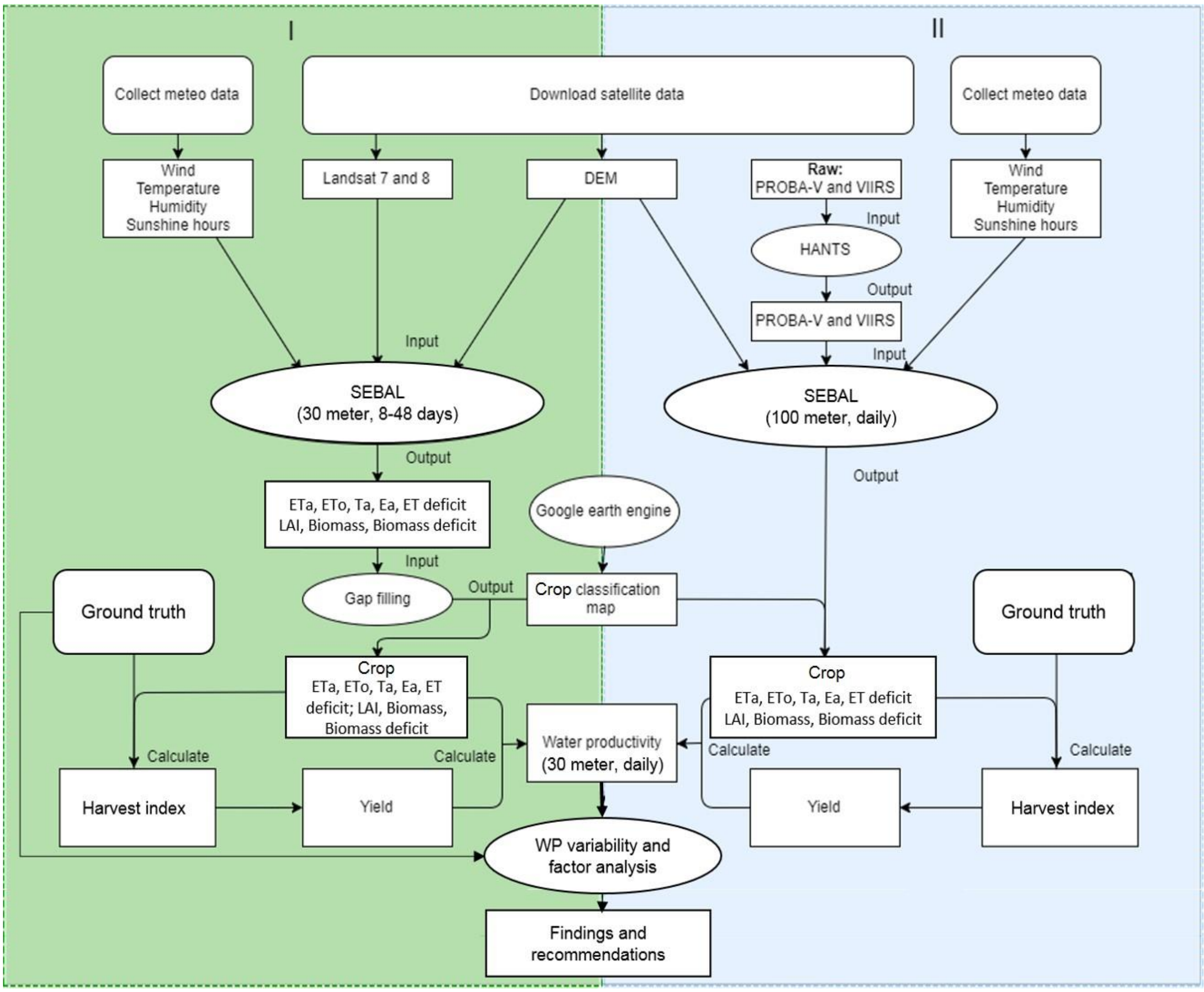

Figure 2.1 The methodological framework of CWP assessment. In the case of LBDC, clouds had negligible effects on image availability, therefore only Landsat images, and no Proba-V/VIIRS images, were used to calculate CWP.

Clouds had negligible effects on the Landsat 8 images in the LBDC area during the 2016-7 Rabi season. A good quality 16-day repeat of Landsat 8 images were found for the LBDC area during the selected study period. The 16-day repeat is good enough to capture seasonal dynamics of crop water consumption and growth. Therefore only Landsat 8 images were used in this study (corresponding to the green box in figure 2.1).

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.

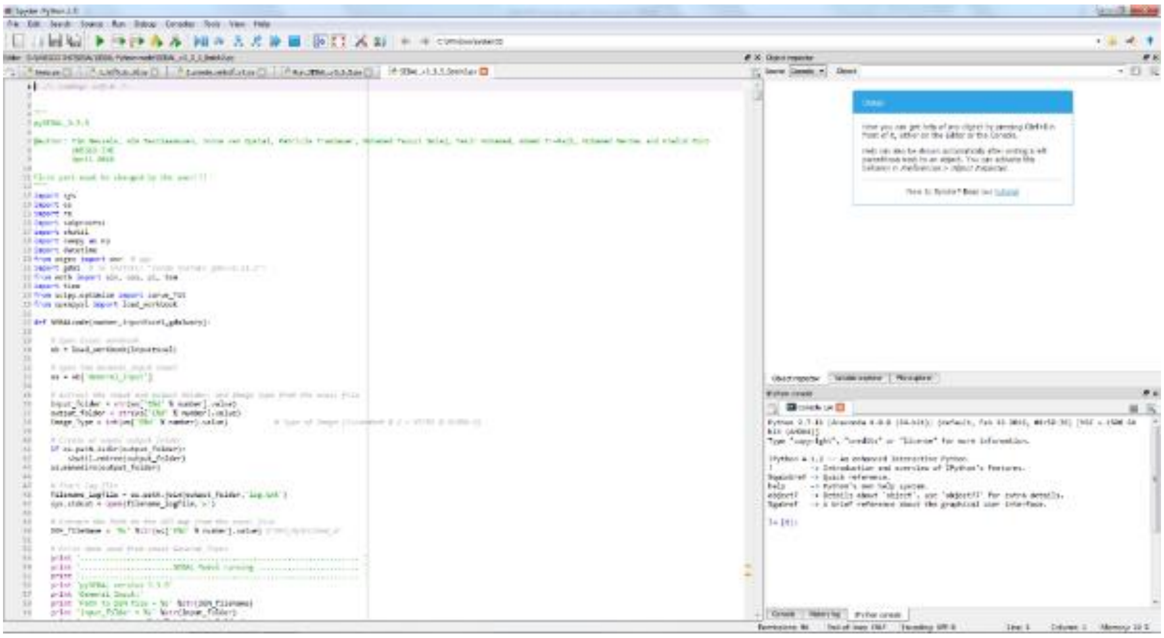

Figure 2.2 Screenshot of the Spyder2 (a version of Python) software as platform for implementation of pySEBAL

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 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 LBDC the dominant irrigated crops in the Rabi season are wheat, mango and citrus, the latter two was not in initial assessment plan but was found to have significant implications due to their large spread areas in the system.

The crop classification is performed using a supervised classification approach with the Maximum Likelihood algorithm. A Landsat 8 image of 13 February 2017 from the peak wheat growing season is chosen as basis of crop classification. Training samples were developed from groundtruth and Google Earth high resolution zoom-ins.

2.4 Smart phone based field survey

Ground truth (GT) survey was conducted using smartphone application. A digital GT survey form was developed 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 Lower Bari Doab Canal (LBDC) is a large diversion from the Ravi River at the Balloki Barrage in Punjab, Pakistan. LBDC was commissioned in 1914, well over 100 years ago. It serves a cultivable command area of about 688,000 ha, supporting the livelihoods of about 275,000 farming families in the areas. The total length of the canals is approximately 2,670 km, including 201 km of main canal, 54 km of branch canals, and 2,414 km of distributary and minor canals (http://lbdcip.irrigation.punjab.gov.pk/).

The LBDC is an intensively cultivated system with diverse crops. Main crop calendars are divided into Kharif and Rabi seasons. Wheat and rice are the dominant crops for Rabi and Kharif season respectively. But other crops including maize, cotton, sugarcane, fodder, flowers, vegetables, and citrus and other orchard crops are increasingly popular for farmers.

The scope of the pilot study, including site, crop season, and crop types were agreed through a series of consultation with Punjab Irrigation Department. The LBDC is too big to be covered by a single Landsat tile. A trade-off is therefore made to cover the areas from downstream Multan to Sahiwal, which falls under the Landsat 8 path number 150 and row number 039 (figure 3.1). The assessment period was chosen for the 2016-7 Rabi season from 1st November 2016 to 13th April 2017. For this period the dominant crop wheat is chosen as the focus crop.

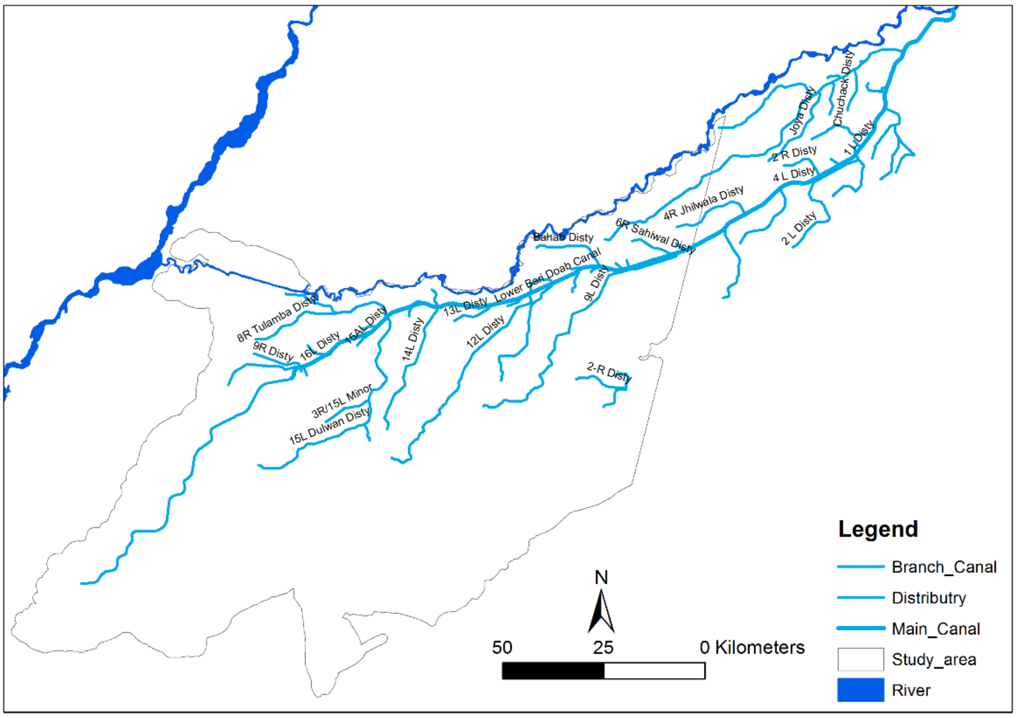

Figure 3.1 The LBDC area and study site in Punjab, Pakistan

3.2 Data

Landsat 8

The Landsat 7 and 8 imagery is one of the most widely used for remote sensing applications in natural resources and agriculture. Both sources have a 30 meter resolution in multispectral bands and 100 meter in thermal bands. Each has a 16-day repeat cycle and together, they form an 8-day cycle, providing data at great spatial and temporal details. A total of 16 Landsat images, nine from Landsat 8 and seven from Landsat 7, with path/row number 150/039 were downloaded from USGS EarthExploerer (https://earthexplorer.usgs.gov/) for the 2016-7 Rabi season from 1 November 2016 to 13 April 2017. The image tile covers the LBDC area from Sahiwal to Multan (Figure 3.1). Clouds in the season are overall negligible. In pySEBAL areas affected by small patches of clouds are filled up using a linear interpolation algorithm.

Weather data

Daily weather data from two meteorological stations (one in Multan and another in Sahiwal) was collected for the study period. The command area in between these two weather stations are flat with a gradient in elevation from 123 meter in Multan to 170 meter in Sahiwal above mean sea water levels. The average weather of the two stations were therefore used to create a virtual station in the middle. This data on temperature (Min, Max), relative humidity, wind direction and sunshine hours from 1 November 2016 to 13 April 2017 is used as inputs. The instantaneous temperature, relative humidity, wind speed, and transmissivity at image overpass time, in this case often around 10:40 AM, is generated from morning (8:00 hours) and afternoon (17:00 hours) observations using linear interpolation.

Ground truth

The GT data was collected using ODK Collect for the study area. The field trip collected a total of 124 observations in quick mode and 67 in normal mode from 27 February 2016 to 9 March 2017 (figure 3.2). The number of points were significantly lower than most other sites which use the same methods, especially in quick mode which does not require interview with farmers. As a result, the ability to distinguish crops are limited, although the relative dominance of wheat crops help reduce the requirement on more GT points.

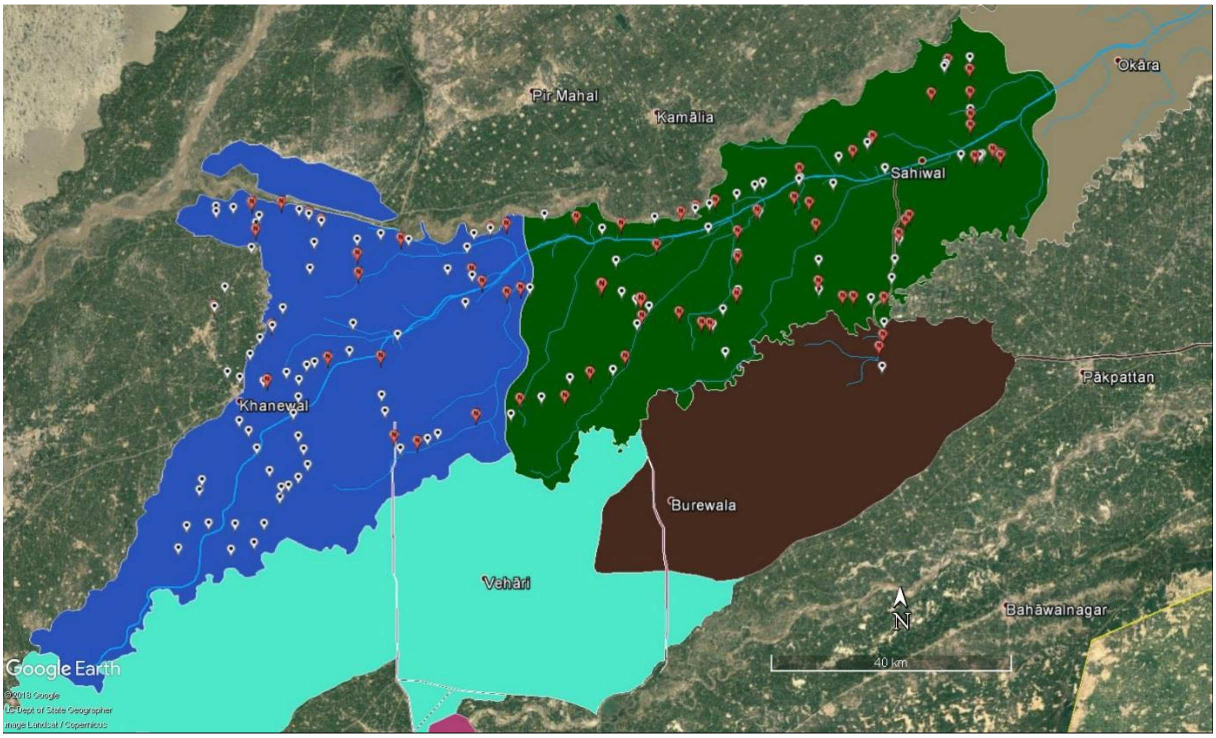

Figure 3.2 The ground truth points in the LBDC area collected from 27 Feb 2016 – 9 Mar 2017. The normal mode points (red) are those with farmers interviewed, the quick points (white) are those only with crop type and no farmers' interviews.

4. Water consumption, yield, and CWP in LBDC

This section presents the results from image analysis on the 2016-7 Rabi season from 1 November 2016 to 13 April 2017. Seasonal total evapotranspiration and biomass production were mapped for Landsat image 150/039. They were then extracted using a crop mask layer to focus on areas of individual crops within the LBDC command.

4.1 Crop type map

The LBDC has a wheat dominant cropping system. The classified map is shown on figure 4.1. A total of six classes, including three for crops, were identified. The three crop types (groups) are wheat, mango, and citrus. Other classes are waterbodies, settlements, and a combination of desert and fallow croplands. Wheat is distributed all along the study area and especially to the tail-end of the system. Fruit plantations, including citrus and mango, is more prominent towards upstream area surrounding the town of Sahiwal.

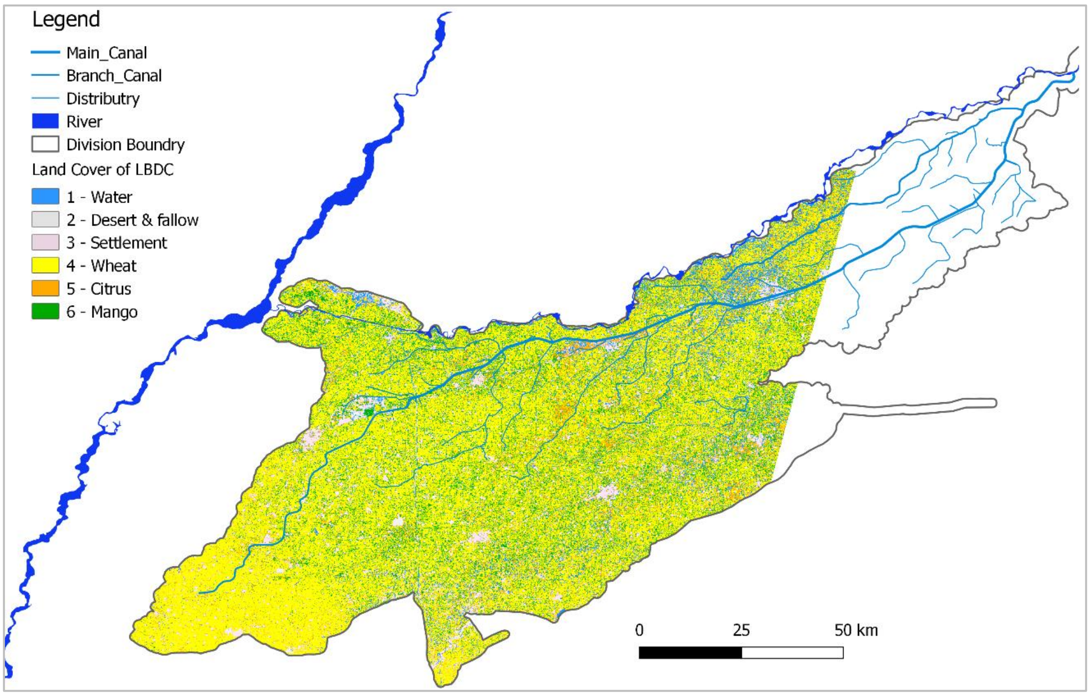

Figure 4.1 A combined map of crop type and land cover for LBDC in the 2016 -17 Rabi season.

Wheat is the dominant crop for the season. Total wheat area is 664,311 ha, very close to the design command area of 688,000 ha for the entire LBDC. There is another 157,316 ha of mango trees, and 123,991 ha of citrus areas. In total, the cultivated agricultural areas including fruits are 945,617 ha, or about 82% of total geographic area at the study site. There is barely cropland left fallow, which together with sandy desert areas, accounts for only 0.6% of total land area.

Table 4.1 The land cover area of the LBDC for the 2016-7 Rabi season

LC type	Areas (ha)	Percentage
Water	85,015	7.3%
Desert & fallow	7,040	0.6%
Settlement	119,664	10.3%
Wheat	664,311	57.4%
Citrus	123,991	10.7%
Mango	157,316	13.6%
Cultivated area	945,617	81.7%
Total area	1,157,336	

4.2 Crop water consumption and deficit

The consumptive water use (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 images for the period of 1 November 2016 to 13 April 2017, extracted for individual crops using the crop 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 the entire command area. The ETa ranges from 0 to 659 mm with an average of 440 mm and a coefficient of variation (CV) at 13%. The total water consumption in the command area, including those from waterbodies, cropland, settlement areas, was 5,092 Million cubic Meters (MCM) for the study period. The seasonal average ETa rate is high. A parallel study in Madhya Pradesh, India, for example finds the average seasonal ETa of a wheat dominant system was only 307 mm, 30% lower than that of LBDC, although the average yield of wheat in India site was also 7% lower.

The variability of water consumption in the area is low. CV is an indication of variability across the area. The average CV of 13% is low compared with similar studies in India (>30%) and Sri Lanka (17%). Lower variability implies more equitable access to water. LBDC seems to be doing relatively well in delivering water throughout the systems. It is observed though that areas closer to Sahiwal to the east have slightly higher variability in ETa.

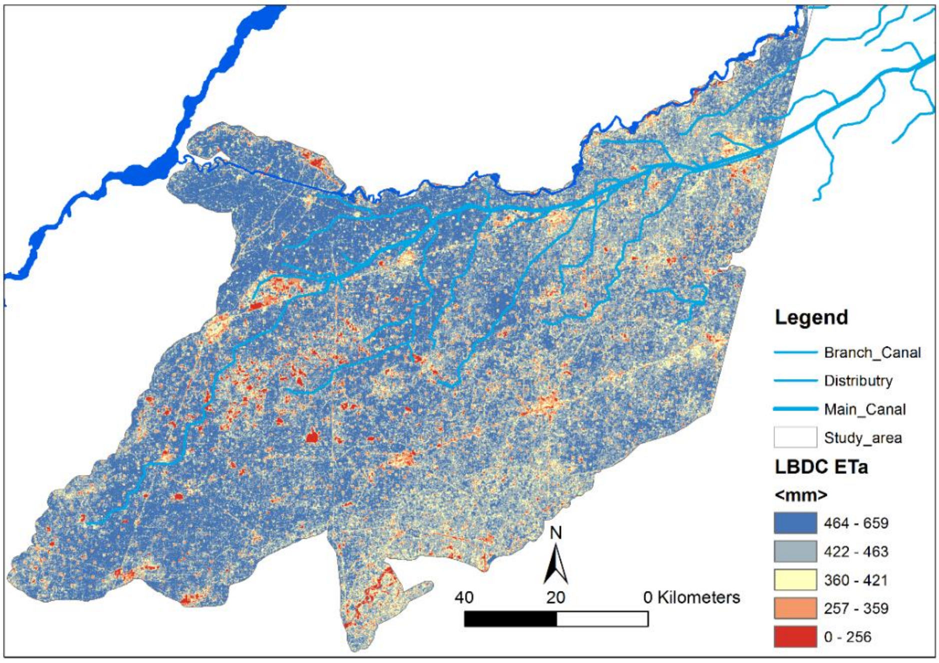

Figure 4.2 Map of actual Evapotranspiration (ETa) for the LBDC study area, 01 Nov 2016 – 13 Apr, 2017. The right part was left out due to insufficient image cover.

Crop specific ETa was extracted from the above map using the crop type map. Figure 4.3 shows the ETa maps of wheat, mango, and citrus. The average ETa of the three crops are 459 mm, 439 mm, and 445 mm respectively. Wheat consumes more water than fruit trees although the difference is small. The total water consumption from these crop are 3,049 MCM, 691 MCM, and 552 MCM for wheat, mango, and citrus respectively. Together the total water consumption of the three crops combined are 4292 MCM, or about 84% of total water consumption from the study area, which is slightly higher than the percentage of cropland to total area (82%).

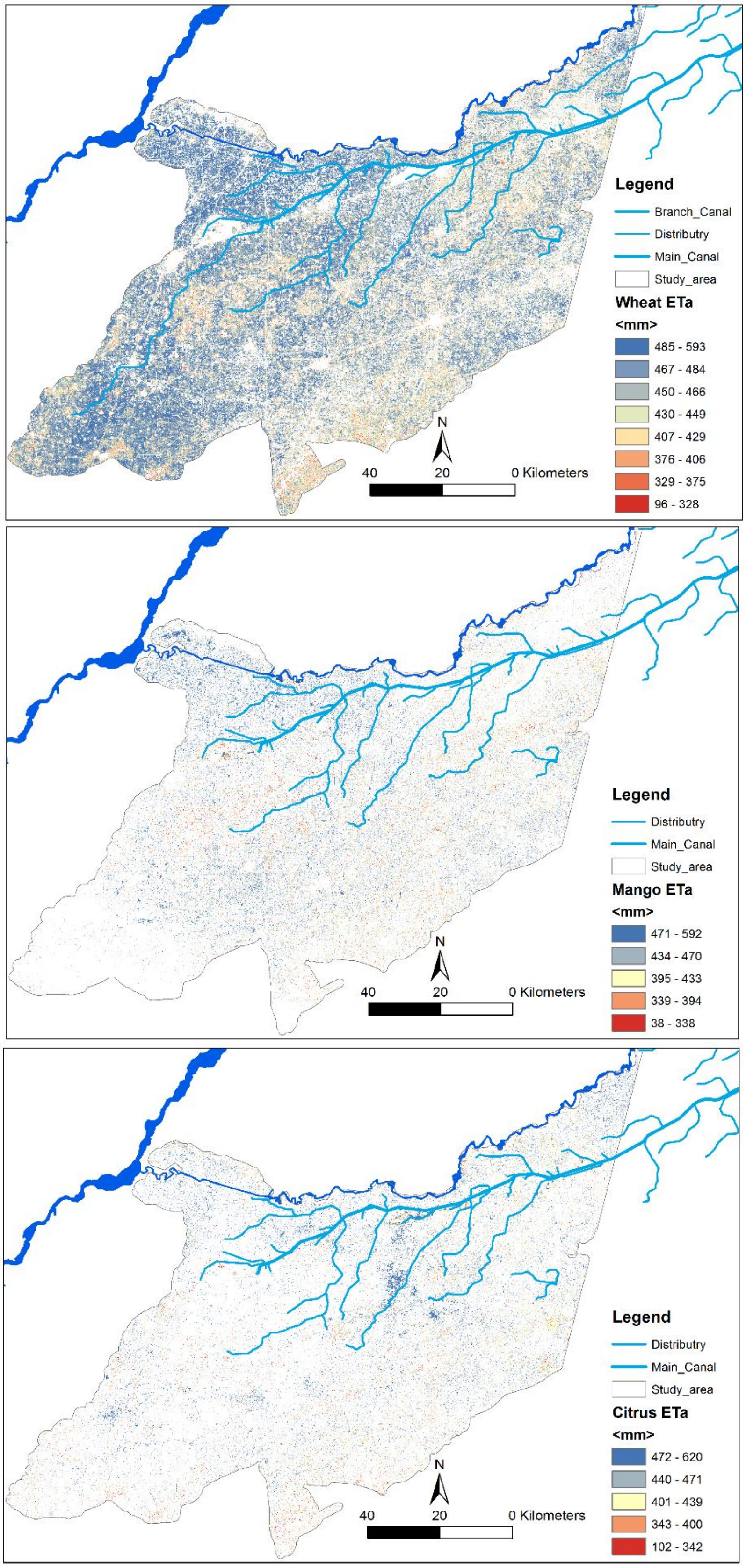

Figure 4.3 Seasonal ETa of wheat, mango, and citrus in LBDC command area, 1 Nov 2016 – 13 Apr 2017.

Relatively low spatial variability in water consumption by each crop is observed in the command area. The CVs of wheat, mango, and citrus are 6%, 10% and 9% respectively. This is much lower than that of the command area ETa. Pockets of low ETa for wheat are observed on the map. But there are no apparent variability in relation to canals.

The beneficial water consumption (Ta)

The actual crop water consumption (ETa) can be further separated into transpiration (Ta) and evaporation (Ea) by pySEBAL model. Transpiration is the water consumed by crops through canopy photosynthesis process. It is therefore considered beneficial for the plant to grow. The evaporation, while helping regulate micro-climate and cool down crop temperature, is considered as non-beneficial from efficiency point of view. The maps of the transpiration can be found in figure 4.4. The average values of transpiration are 238 mm, 188 mm, and 188 mm for wheat, mango, and citrus respectively.

Strong variability is observed in Ta for different crops. The CV of wheat is 18%, compared with 6 of ETa. The CV of mango and citrus are both 35%, compared with 10% and 9% of ETa. High variability means different capability in the field to turn water consumption into beneficial consumption through transpiration. But rather, some areas spend much more water on evaporation instead of transpiration.

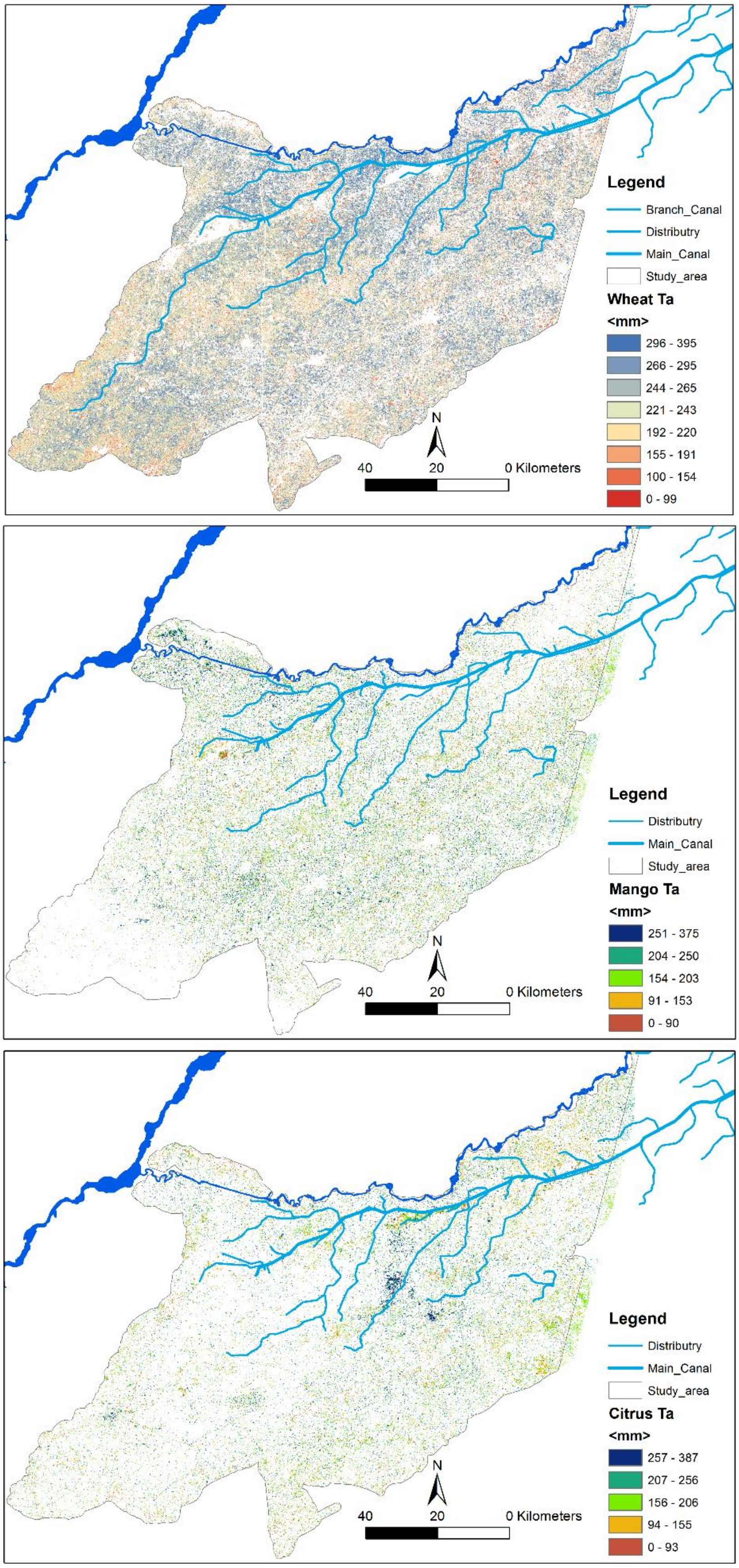

Figure 4.4 the beneficial consumption of water through transpiration for wheat, mango, and citrus in LBDC, 1 Nov 2016 – 13 Apr 2017

Crop 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 of crops) and actual ET (ETa). ET deficit is opposite to adequacy indicator and a direct expression for water shortage the crop experiences on a pixel by pixel basis (figure 4.5). It helps assess, without any information on canal flows or field measurement, whether crops from certain fields have sufficient moisture in the root zone.

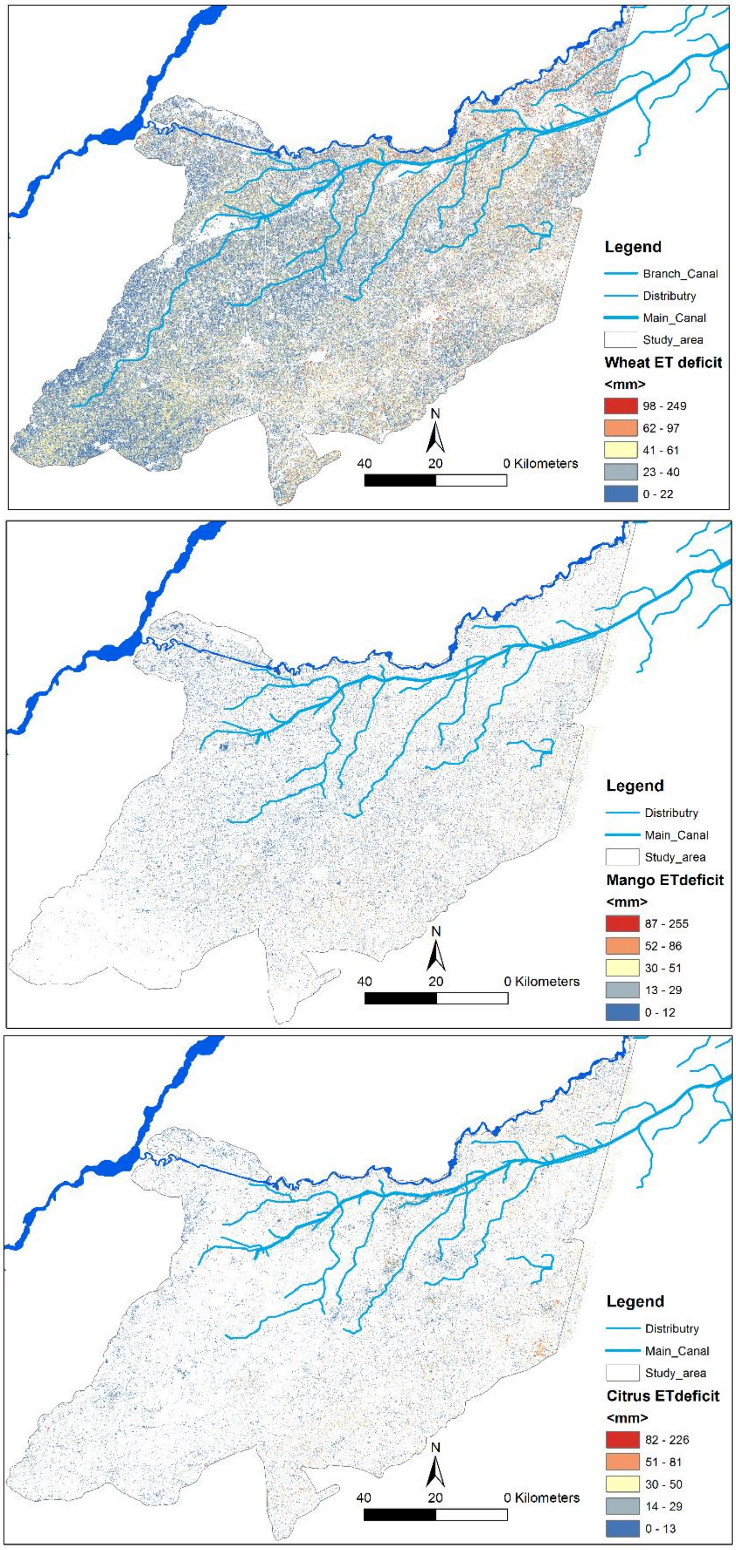

Figure 4.5 Water shortage as measured in ET deficit for wheat, mango, and citrus.

Overall water shortage is low in the system for the studied period. The average ET deficit is 36 mm for wheat, 22 mm for both mango and citrus. This is 239 MCM shortage of crop water requirement for wheat, 35 MCM for mango and 27 MCM for citrus. Altogether the 2016 Rabi season had a water shortage of 301 MCM from the three types of cultivated croplands. However, one must realize that this shortage is water stress expressed by crops, and not the overall water supply shortage as further analysis reveals that great water waste (excess water consumption) co-exists along with water shortage.

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 specific crop 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 biomass of the LBDC area is mapped and shown in figure 4.6. The average biomass across landscape, i.e., all areas including crops and non-cropland, is 7.5 ton/ha with a CV of 37% for the 2016-7 Rabi season. Strong variability is observed for the biomass production, much higher that of ETa (13%).

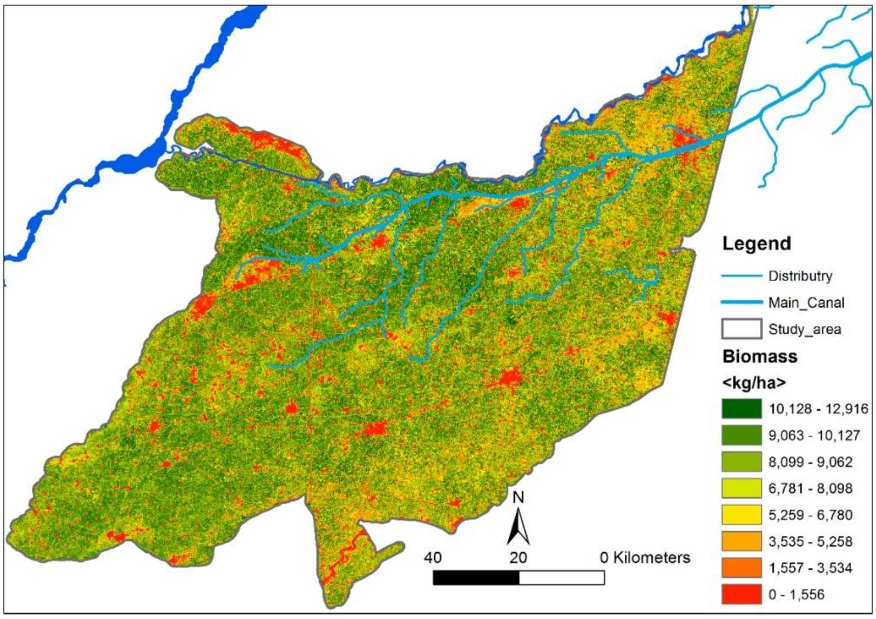

Figure 4.6 Biomass production of the study area in LBDC for the period 1 Nov 2016 to 13 Apr 2017

HI of crops are determined using biomass and field survey data. The field survey collected estimated yield data of 60 farmers with their location, of which 54 of the samples were found to have valid data for correctly identified wheat pixels. The average yield of the 57 wheat samples is 4.1 ton/ha while the corresponding average dry biomass production is 8.9 ton/ha. If an average moisture content of 15% is assumed, then the HI for dry yield divided by dry biomass is 0.396, slightly above an average of 0.37 reported in literature. No harvest index for mango and citrus is established. The current pilot study covers only the Rabi season while the fruit trees are perennial plantation. The detailed GT yield and harvest index calculation can be found in annex 4.

The yield map of wheat is produced using biomass maps and harvest index. Figure 4.7 shows the yield map of wheat. The average yield is 4.1 ton/ha with a CV of 15%. The CV of crop yield is higher than that of ETa (6%) and close to that of Ta (18%). The higher variability in crop yield is therefore not explainable with the variability in ETa, but probably in non-water related issues. The total production of wheat for the 2016-7 Rabi season was 2.7 million ton from the 664,311 ha of wheat areas.

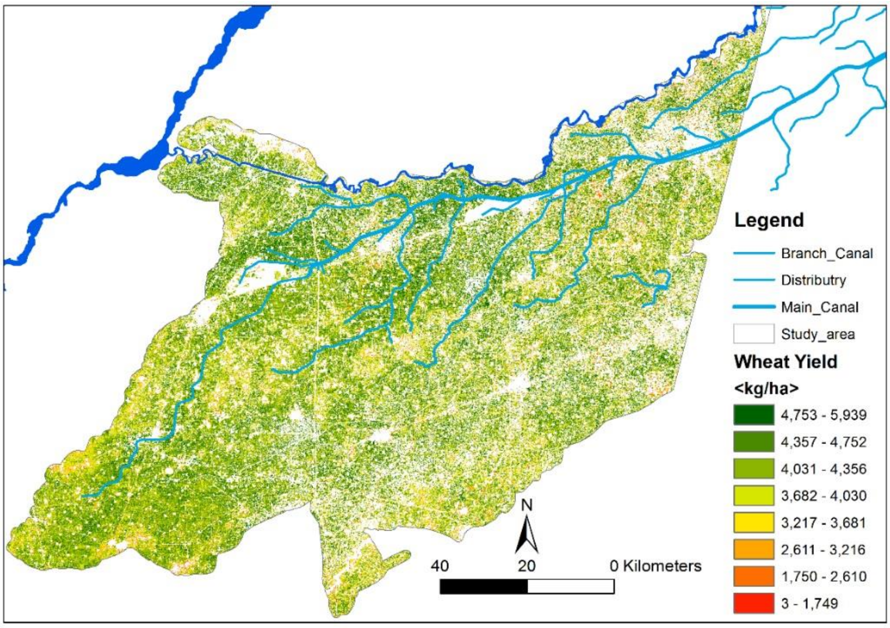

Figure 4.7 the yield map of wheat for the 2016-7 Rabi season

4.4 Crop water productivity

Water productivity maps of wheat and vegetables were produced using the yield map divided by ETa maps, after the units were converted. Figure 4.8 shows the WP map of wheat for the study area.

Low WP with high variability were observed for the wheat crop. The average WP of wheat is 0.89 kg/m^3 with a CV of 13%. The average WP in LBDC is lower than the average for wheat reported in international literature (about 1 kg/m^3). The crop yield is not low for other comparable countries including India. The low CWP is attributed to high water consumption.

High variability of wheat WP is observed. The WP map shows significant variability across the study area. High WP and low WP areas are very often found along with each other. Pockets of blue (high WP) and orange (low WP) pixels are found from upstream to downstream, with no clear pattern of distribution. The low WP areas clearly illustrate the need for priority action, either on water management side to reduce water consumption, or on non-water management side to increase productivity.

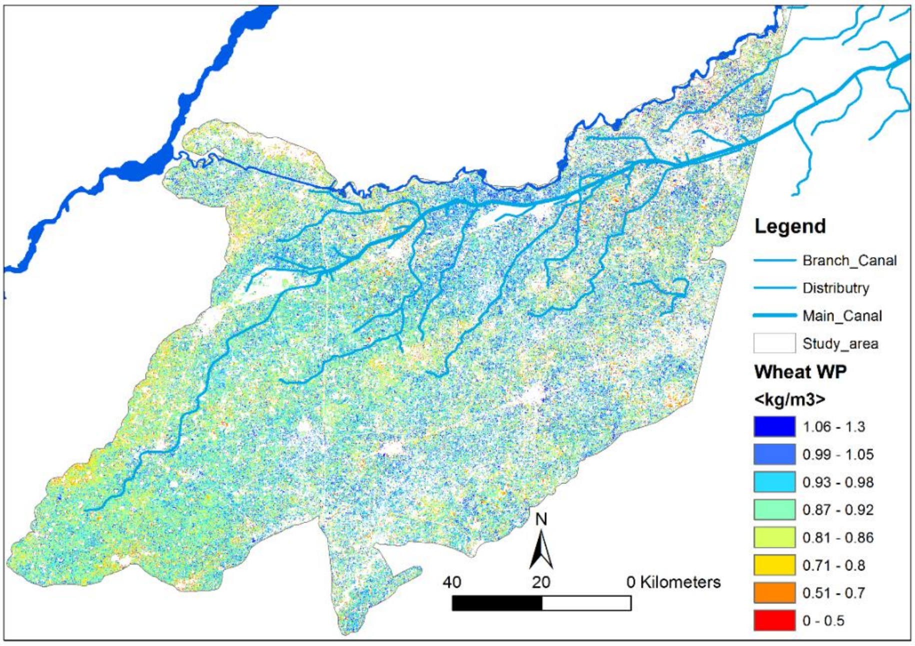

Figure 4.8 the crop water productivity map of wheat in LBDC for the 2016-7 Rabi season

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, slope, soil type, fertilizer applications, irrigation sources and irrigation methods. 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 Administrative boundaries

The spatial variability of CWP, yield and ETa are assessed using the administrative boundaries of irrigation divisions. The study area falls in six irrigation divisions, namely Sahiwal, Easter bar, Khanewal, Western Bar, Okara, and Mailsi Syphon Division. However the last two divisions only had a small area falling in the study area. They are therefore excluded from the analysis.

The CWP, yield and ETa of each division shows little differences in different irrigation divisions. Figure 5.1 shows that variations in average values can be observed across divisions. The water consumption of Khanewal division is the highest while that of Sahiwal is the lowest, although the difference is only 11 mm, or about 2% of total water consumption. The wheat yield of Khanewal is also the highest, followed by Sahiwal. The water productivity of wheat in Sahiwal is the highest due to its low ETa and relatively high yield, about 2% higher than that of Khanewal. Overall, the differences in ETa, ET deficit, yield and WP are small across divisions.

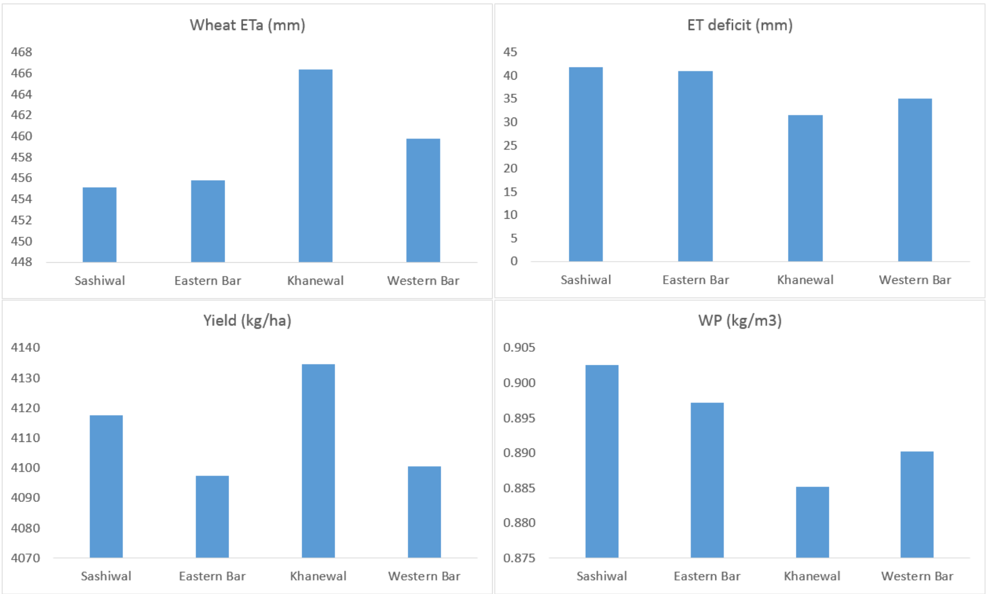

Figure 5.1 Average CWP, yield and ETa of wheat and vegetables by Taluks

5.2 Distance to canals

The spatial distribution of CWP, ETa, yield and the ratio of Ta to ETa in relation to the distance to canals are analysed. The main, branch, and distributary canals are combined and buffer zones at 500 meter, 1 km, 2 km, 5 km, and 10 km to canals are generated. These buffer zones are then used to summarize average values of the above mentioned variables within each zone. Distance to canals provides an indication on the conditions of the infrastructure, and the ability of the infrastructure to deliver water to farmers.

The average values of CWP, yield, ETa, and Ta/ETa showed declining trend but the differences are negligible. Figure 5.2 shows that for all the four parameters, the overall trend is that the values decreases with increases in distances to canals. However, it has to be noticed that all differences from 500 meter to 10 km are small, ranging from 0.6% to 1.6%. It can therefore be safely concluded, that the variability has little to do with distances to canals.

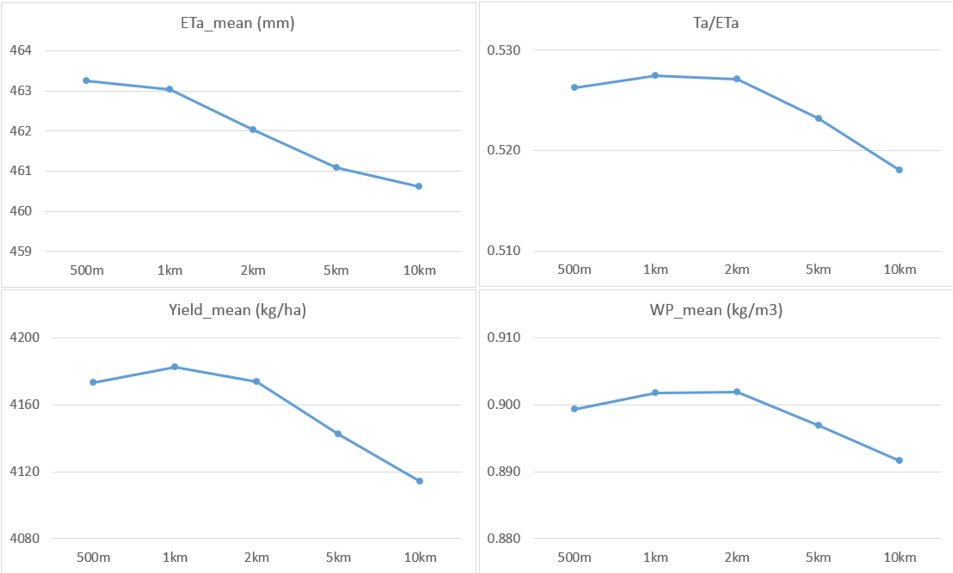

Figure 5.2 The variations of CWP, yield, ETa, and the ratio of Ta to ETa for wheat in relation to distance to canals

5.3 Adequacy of irrigation supply

Adequacy is an indicator to measure if irrigation supply is sufficient to meet crop water requirement. The remote sensing approach enables assessment of adequacy by calculating ETa divided by Wheat crop ET (ETc). ETc is calculated using the FAO 56 approach by multiplying ETo with crop coefficient Kc. Kc values are adopted from values recommended by IWMI (Ullah et al., 2001). The general assumption is, if ETa is smaller than ETc, then the adequacy of irrigation supply is not sufficient.

The map of irrigation adequacy is produced and shown in figure 5.3. The seasonal ETo and ETc for wheat are 502 mm and 412 mm respectively. The average ETa for the seasonal for wheat was 459 mm. The average ratio of ETa/ETc, or adequacy indicator, is therefore 1.11. That is, the actual water consumption was 11% higher than crop water requirement for wheat. Excessive water consumption is observed at the early stages of wheat growth, when too much water is applied and the evaporation from open soils exceeds ETc.

High adequacy, however, does not exclude crop water stress. Even though the ETa exceeds ETc for the entire growing season, a deficit of 36 mm was observed in earlier analysis. This is because water stress still occurs in some parts of the system, and the timing of irrigation supply does not always meet the requirement of crops, causing water stress in short duration of time.

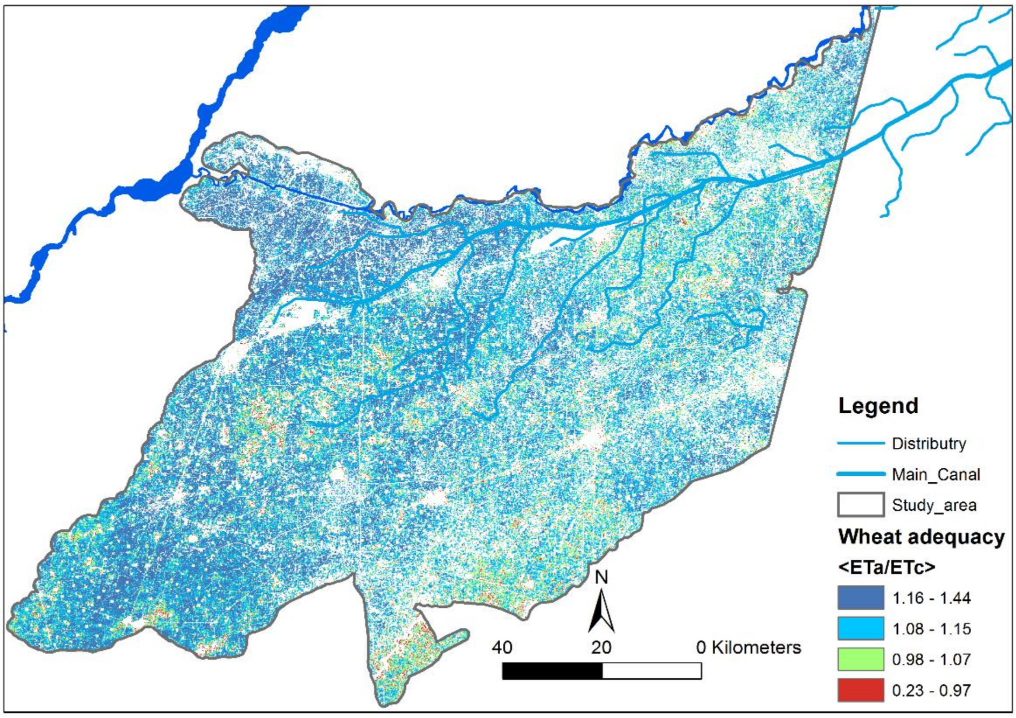

Figure 5.3 Adequacy of irrigation supply for wheat crop. The adequacy is measured as ETa/ETc.

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 introduces WP concept and demonstrates its applications in LBDC, Punjab. WP is a simple and attractive indicator to assess whether intended processes go well. In this study, we introduced WP together with crop yield, ET deficit and beneficial consumption (Ta) to help make a first diagnosis on how irrigation systems function.

A novel yet practical remote sensing approach was applied to the LBDC area. The computation 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 2016-7 Rabi season baseline conditions of LBDC of water consumption, shortage and crop production is revealed. Table 6.1 and 6.2 summarize the results for LBDC by crop types and irrigation divisions. Cropland accounts for 82% of total land areas. A total wheat production area of 664,311 ha consumed 3,049 MCM of water and produced 2.7 million ton of grain. Citrus occupies 123,991 ha of areas, and consumed 552 MCM of water. Mango also occupies 157,316 ha of land and consumes 439 MCM of water during the same period. However due to the limited scope of the study the full harvest cycles of orchards were not assessed. Clearly orchard consumes significant amount of water, which is currently not included in water supply plans.

Water shortages were determined at pixel level for wheat. A crop water shortage, in the form of ET deficit, of 239 MCM (8% of current consumption) exists. Cautions are however needed as the total actual water consumption is already 11% higher than total crop water requirement. It is therefore necessary to optimize and improve current irrigation scheduling instead of increasing water supply to fill up this gap.

The CWP of wheat is low with moderately high spatial variability. The average CWP of wheat is 0.89 kg/m^3 with a CV of 13%. The average yield and ETa are 4.1 ton/ha (CV 15%) and 459 mm (CV 6%) respectively. The low WP is mainly attributed to high water consumption. High spatial variability represents non-uniform performance across the system, which represent great potential for farmers to learn from their better-performing neighbours.

Table 6.1 Summary of crop area, CWP, yield and water use information by crop type from remote sensing for the 2016-7 Rabi season in LBDC area.

	Wheat	Citrus	Mango	Cultivated area	Water	Desert & fallow	Settlement	Total area
Areas (ha)	664,311	123,991	157,316	945,617	85,015	7,040	119,664	1,157,336
Percentage	57%	11%	14%	82%	7%	1%	10%	
ETa (mm)	459	445	439					440
CV of ETa	0.06	0.09	0.10					0.13
Volume (MCM)	3,049	552	691					5092
Ta (mm)	238	188	188					
CV of Ta	0.18	0.35	0.35					
Volume (MCM)	1,581	233	296					
ET deficit (mm)	36	22	22					
ET deficit (MCM)	239	27	35					
Yield (ton/ha)	4.1							
CV of yield	0.15							
Production (ton)	2,723,673							
CWP (kg/m3)	0.89							
CV of CWP	0.13							

Figure 6.2 Summary of crop area, CWP, yield and water use information by irrigation division from remote sensing for the 2016-7 Rabi season in LBDC area.

	Sashiwal	Khanewal	Eastern Bar	Western Bar
Total area (ha)	270,696	302,859	152,633	315,195
Wheat area (ha)	140,084	189,000	75,845	201,379
Total water consumption (MCM)	1,165	1,336	657	1,371
Canal supply PMIU (MCM)	852	1,076		
Canal supply - Total water consumption (MCM)	-312	-260		
Wheat ETa (mm)	455	466	456	460
Water consumption (MCM)	638	881	346	926
ET deficit (mm)	42	31	41	35
Water shortage (MCM)	59	59	31	71
Ta/ETa	0.45	0.43	0.44	0.44
Yield (kg/ha)	4,118	4,135	4,098	4,101
WP (kg/m3)	0.90	0.89	0.90	0.89

The factors potentially linked to water consumption, yield and CWP are investigated for irrigation management units, distance to canals, and adequacy of irrigation supply. The analysis did not find significant variations in CWP indicators among different administrative units, or head and tail end farms. Seasonal water adequacy indicator is 1.11, which means the actual water consumption is 11% higher than crop water requirement calculated using the FAO recommended approach.

Canal water supply data was compared against total water consumption. The total canal water supply to two irrigation divisions were obtained from the Irrigation Department. Total water supply was 852 MCM and 1,076 MCM for Sahiwal and Khanewal Irrigation Divisions respectively. It is 34% and 22% more than wheat water consumption, but only 73% and 81% of total water consumption from the two divisions respectively. The additional water consumption comes from soil moisture change and groundwater extraction, with the later plays significant role.

6.2 Assessing the potential and determining the priorities

There is significant potential for water saving in canal systmoperations. The total water consumption of wheat is 11% higher than the crop water requirement, as analyzed in section 5.3. The actual canal supply in Sahiwal and Khanewal is even higher. So the potential in reducing water supply could be even higher.

System level WP potential could be analyzed based on WP – yield relationship. 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 wheat 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, and a polynomial line on top. The bottom line is defined by the potential ET that is controlled by atmospheric conditions. For a given farm with certain yield, the water consumption cannot be higher than that corresponding to a WP value defined by the lower line. The upper line is defined by local water management practices, especially on-farm practices which affect the proportion of beneficial consumption. This graph demonstrates the possibilities of farmers who produces the same yield but with different levels of WP (vertical), due to varying amount of water consumed. On the other side, they could have same level of CWP even if their yields are different, which reflects broad ranges of production constraints. 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.

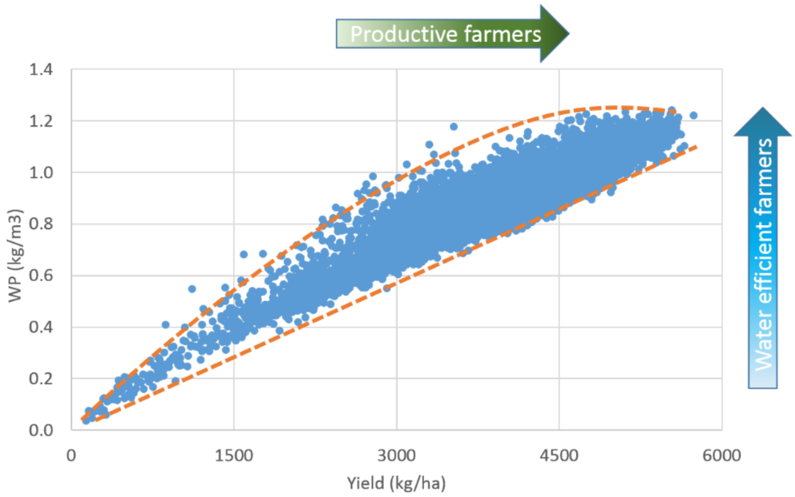

Figure 6.1 Water saving and WP potential analysis by identifying water use efficient farmers and productive farmers in LBDC.

On-farm water savings represents another big potential in LBDC. The average ratio of beneficial consumption (Ta) to total consumption (ETa) is 52% for wheat, 43% for mango, and 42% for citrus. They indicate large areas, particularly orchard, with high potential to minimize water losses at farm level by reducing open soil evaporation. Figure 6.2 shows such potential in a spatially explicit manner for wheat.

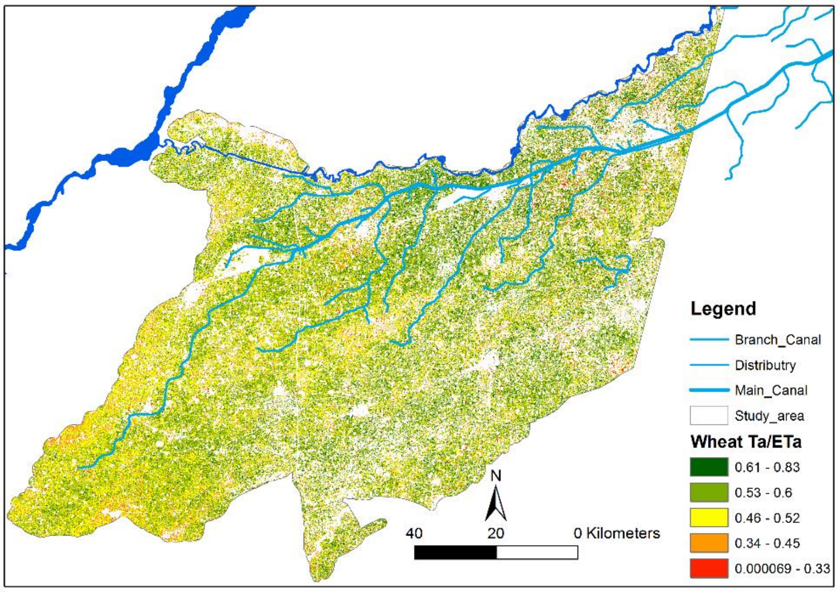

Figure 6.2 The ratio of beneficiary consumption (Ta) to total water consumption (ETa) as an indication of on-farm water management efficiencies for the 2016-7 Rabi season

Managing field water consumptions are ultimately linked with system. Figure 6.3 shows the relation between wheat CWP and ETa (left) and CWP with Ta/ETa ratio (right). As similar in other studies, CWP shows no apparent relation with ETa values, but near linear relationship with the ratio of Ta to ETa. It is clear that in order to increases CWP, it is necessary to increase the Ta/ETa, adopting more water saving irrigation practices such as partial soil wetting, reducing irrigation application and increase frequency, and increase canopy cover.

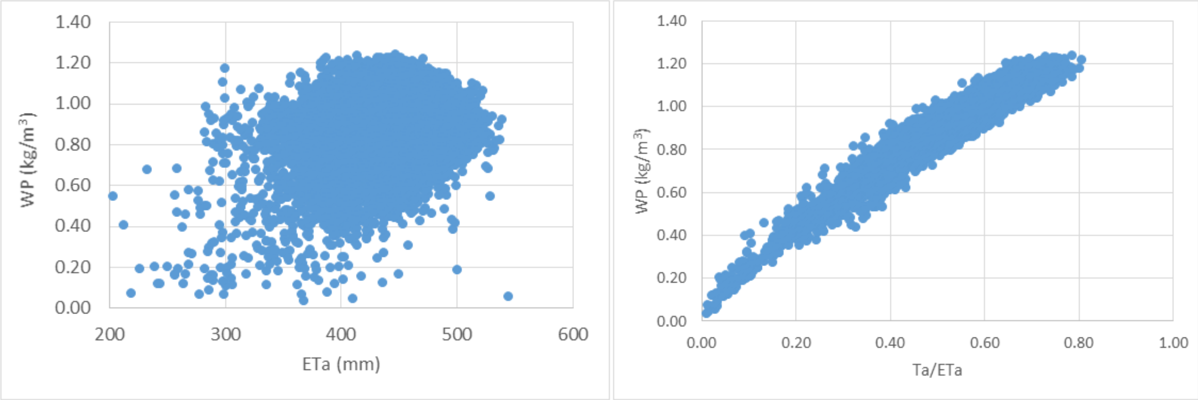

Figure 6.3 the relation between wheat CWP and ETa (left), and CWP and Ta/ETa ratio (right)

Adoption of water saving in the system should however also consider the effects on groundwater. Currently the excess irrigaiton supply may also help recharge groundwater, which is used for irrigaiton purpose in some areas. An evaluation on the dynamics are required should the water saving targets be implemented.

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 one standard deviation (SD) below average, areas with average, and bright spots/hero farmers for those well performing areas with CWP one SD above average. The hotspots (Red) are not expected to achieve the same results as the bright spots (Green), but could learn from the hero farmers. Areas closer to waterbodies seem to be least efficient therefore requiring more attention to reduce water consumption.

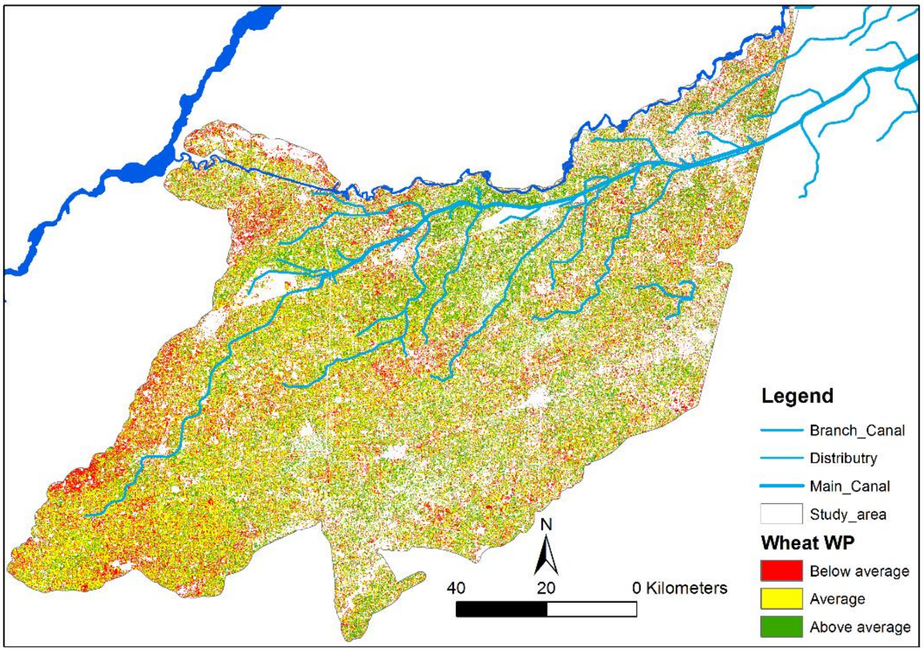

Figure 6.4 The CWP map of wheat help determine priority intervention areas where CWP is very low (red), average (yellow), and above average (green).

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 CWP in agricultural areas and analyze priority areas for improvement. The efforts are embedded in the government and ADB efforts to revitalize the Punjab irrigation systems. Synergies were also found with on-going initiatives in the department, for example, the remote sensing based irrigation water shortage monitoring in the department.

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 practices and identifying 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 maps produced with field visits to discuss with local stakeholders.

A CWP and pySEBAL training workshop, organized with the Irrigation Department, was carried out for 19 selected participants. This training was meant to create awareness and interests, and introduce young and eager professionals to the technology. It does not seem to be of sufficient duration to transfer the full modelling capacity for participants to apply on their own. 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 problems from the remote sensing outputs and monitoring of the irrigation system to detect improvements. Nevertheless, all the participants, and the Irrigation and Agriculture Departments, have shown great interests in the ideas and methods.

Follow up actions are required to ensure smooth uptake and continued use of the water productivity concepts and the remote sensing technology, which is especially relevant in the large contiguous irrigation systems in Punjab. The action points are summarized below:

1. There is a great potential in water savings through both improved system operations and better on-farm water management practices. The irrigation supply can be reduced at least 11% of current levels from canals and groundwater. Even bigger potential exists through on-farm water saving irrigation strategies. This needs to be verified at individual canal command level, with consideration of groundwater use and the recharging effects of irrigation supply;
2. The on-farm management practices for wheat represent the biggest potential for water savings. But the large area of orchard, which is not included in current irrigation planning, has lower beneficial consumption ratio, hence high potential for improvement per unit of area. It is probably also easier to implement water saving practices in orchard gardens.
3. It is highly recommended that the data, results, and findings be critically reviewed by the Project Management Unit at the Irrigation Department and ADB and incorporated into current planning. The on-going effort by the department to assess irrigation shortage (adequacy) using remote sensing, for example, is aimed at increasing supply while the current supply already far exceeded what is required. In fact, better satisfying crop water requirement can be met through improved water saving and optimized scheduling, instead of supplying more water from canals.
4. Scaling up the assessment to the entire LBDC command. A full system level analysis, including that from remote sensing and measured irrigation and drainage data, will be more relevant for management. The trained participants could take the lead and IHE Delft provides backstopping role.
5. The Irrigation Department and Agriculture Department build up a joint capacity on remote sensing crop and water monitoring and diagnosis, using the free software packages provided by IHE Delft. The continued exercises will provide opportunities for self-learning, but perhaps also identifying more advanced trainings and/or master/PhD scholarships.

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