

OPERATIONALIZING WATER PRODUCTIVITY FOR BETTER INVESTMENT IN THE POST IRRIGATION DEVELOPMENT ERA

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ABSTRACT

Investment in Asia's irrigation is shifting away from expansion and rehabilitation and enters is entering a post development era of modernization. The concept of water productivity (WP) became popular as it focuses on linking irrigation water supply to crop production which is the intended output of modernization. This paper describes a framework for operationalizing water productivity in irrigation. Using remote sensing and modern information and communications technology (ICT) approach and by focusing on actual evaporation and transpiration, the framework incorporates beneficial/ nonbeneficial water uses to assess and diagnose both infrastructural and management challenges at spatial and temporal details. It can provide practical insights on actual water consumption, crop water stress, their variability, and water and non-water related contributing factors for practical investment and management. The aim is to apply research approaches to provide operational results. Pilot studies were carried out in six countries, e.g., India, Indonesia, Pakistan, People's Republic of China, Sri Lanka and Viet Nam. Results show that the framework helps not only to assess the baseline performance, but also identify factors affecting water productivity, assess the potential for improvement, and determine priority interventions. Crop patterns and irrigation infrastructure designed through a top-down approach can quickly be outdated with farmers' own initiatives. A switch to high WP (expressed in USD/m³ water used) crops are observed in Viet Nam, India, China, and Pakistan. As much as 21 times differences in WP were observed in Vietnam between traditional crops such as rice and coffee and new cash crops such as mango. The largest water savings and WP improvements exist by farmers adopting improved on farm water and land management practices. The proposed framework can be adopted by engineers and managers for performance evaluation and diagnosis for more targeted investment strategies.

1. INTRODUCTION

Decades of irrigation development in Asia has led to major improvement in food security and poverty alleviation. The achievement is underpinned by massive expansion of irrigation and the areas under agricultural water management. Various studies show that actual irrigated areas can be three to ten times of statistics and literature values, which implies limited scope for further development of new irrigation areas, even in many of the less developed countries (Ajaz, 2016; IWMI, 2016). Countries like China are already transitioning from massive infrastructure building to a more holistic approach in accordance with broad economic development, demographic change, and increasing demand on sustainable development.

The WP concept is developed in recognition of the constraints of 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 (Lautze, 2014). Figure 1 shows that irrigation efficiency in effect represents only a small portion of hydrological processes in a

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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.

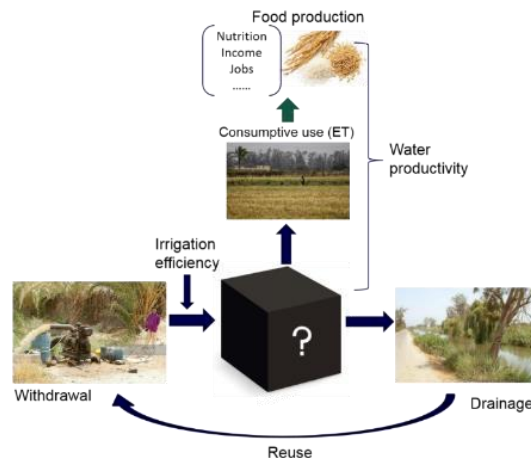


Figure 1. The irrigation efficiency and water productivity indicators for irrigation systems. The two indicators are complementary while WP covers more advanced and broader components of irrigation performance.

WP indicators are complementary with 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 from natural conditions, leading to complex water cycling processes, which is further convoluted by management practices including irrigation and drainage. Remote sensing-based WP assessment focus on actual evapotranspiration (ET_a) – the water actually consumed. Further, the ET_a 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 2).

2. A FRAMEWORK TO OPERATIONALIZE CROP WATER PRODUCTIVITY

There are many well established approaches to use satellite images and weather data to map agricultural water consumption (actual evapotranspiration) and crop yields. The pySEBAL is the latest development of the earlier SEBAL model, a remote sensing algorithm for estimating actual landscape evapotranspiration (SEBAL stands for Surface Energy Balance Algorithm for Land, Bastiannssen et al., 1998; Teixeira et al., 2008). It is based on Python, an open source language, and consists of a crop growth simulation model. The model is developed at IHE Delft Institute for Water Education through a collaboration with the Asian Development Bank. The model is

freely available online at <https://github.com/wateraccounting/SEBAL> (last access 30 May 2019).

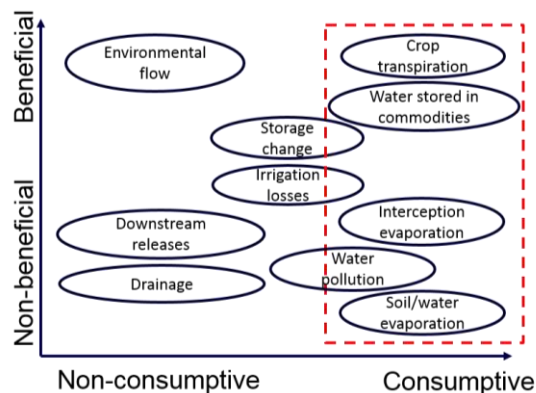


Figure 2. Remote sensing approach focuses on the beneficial and non-beneficial consumptive use of water.

Key improvements to the SEBAL model include automatic selection of hot and cold pixels and biomass production estimate. The group of hot and cold pixels are identified using a combination of cloud mask, NDVI, and thermal images (Bastiaanssen et al., forthcoming). The biomass production is also incorporated into pySEBAL model based on the method published by Bastiaanssen and Ali (2003). The method uses Monteith's model to calculate absorbed photosynthetically active radiation (APAR), which is then coupled with a light use efficiency estimate and the land wetness conditions estimated by SEBAL. The crop yield is then estimated using harvest index and crop type map from ground survey and other methods.

Open source tool and data are the key approach in the proposed framework. The satellite images used by pySEBAL are currently all public domain data including Landsat series, Proba-V, VIIRS, and MODIS. The model is capable of producing outputs at 30 meter resolution when using Landsat images, 100 meter using Proba-V and VIIRS images, and 250 meter when using MODIS. To improve the usability in tropical and humid areas where heavy cloud presence is expected, a cloud removal algorithm Harmonic ANalysis for Time Series, or HANTS ((Alfieri et al., 2013), is adopted to filter out cloud contaminated pixels and smoothen the time series. The methodological flow chart of pySEBAL and related inputs and outputs processing is illustrated in figure 3.

Ground truth survey is critical for validation of yield estimate and interpreting remote sensing images. Smartphone application was developed for GT survey which can record the coordinates, text description, multi-choice selection, and multimedia such as pictures, voice recording and videos.

3. APPLICATIONS IN ASIA AND THE PACIFIC REGION

Pilot applications were carried out in six countries with an aim to link with investment decision making. These countries are India, Indonesia, Pakistan, People's Republic of China, Sri Lanka and Viet Nam. Figure 4 illustrates the locations of the study areas. They are all areas with medium to large existing irrigations systems, except in the case of Madhya Pradesh in India where a large irrigation system is being planned. A total of nine crops were assessed across all the sites, including rice, wheat, sugarcane, mango, apple, grape, dragon fruit, pepper, rice and coffee. This section presents selected results to demonstrate the capabilities with more also introduced in the next section during discussions.

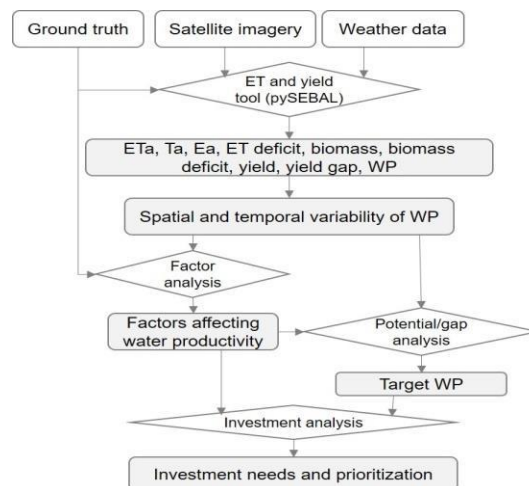


Figure 3. The methodological framework for operationalizing crop water productivity for investment using remote sensing.



Figure 4. the pilot sites in six Asian countries

3.1 Crop Water Productivity Assessment

The pySEBAL is capable of producing a range of outputs including seasonal actual evapotranspiration (ETa), potential ET, Transpiration (or beneficial consumption for production point of view), evaporation, ET deficit, biomass, crop yield, and finally CWP for various crops, both aggregated in monetary terms and disaggregated in physical yield terms. Figure 5 illustrates the ETa, yield and CWP of rice in the Tungabhadra irrigation system, Karnataka, India. They were then extracted using a rice crop mask layer to focus on the paddy areas within the command area.

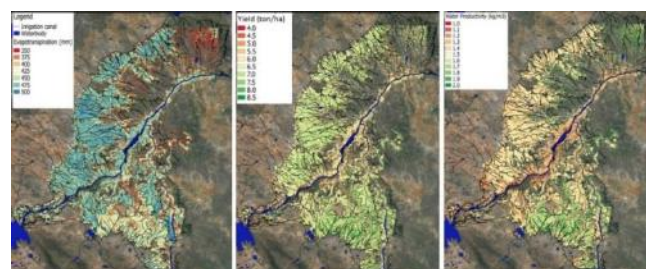


Figure 5. Actual ET, yield, and water productivity of rice in the Tungabhadra Irrigation System for period 01 Sept - 31 Dec 2016.

The 30 meter resolution ETa map reveals the level of water consumption as well as their spatial variability across canal command area. 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 the left main canal command and 718 MCM for the right canal command.

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 the right canal command area, even though the ETa is relatively low. The areas along the main river has low yield in general despite high ETa. The total rice production for the studied growing season is 2.32 million ton, with 1.25 produced from the left canal command areas and 1.07 million ton from the right canal command areas. The WP ranges from 0.14 to 2.2 kg/m³. The average CWP is 1.47 kg/m³ with a CV of 13.6%. The average WP is relatively high compared with values frequently reported in literature.

WP diagnosis also provides an opportunity for crop optimization during agriculture modernization process. The WP assessment was carried out for 7 crops in the drought affected central highlands and coastal areas of Vietnam. Table 1 shows that rice and coffee, being traditional staple food and cash crops, have the lowest WP in terms of market values per unit of water consumed. Emerging new agricultural products, especially fruits, provide much higher returns. The high-quality mango achieves 110,000 Vietnamese dong (or about 5 USD) per cubic meter of water in 2017 market prices, 22 times that of coffee and 16 times that of rice.

Developing market oriented new irrigation facilities requires reconsideration of target crops, their characterises of irrigation water requirement, and associated infrastructure and management needs. It highlights the major economic benefits to farmers who switch to higher WP crops. It also suggests that development interventions can use such data to highlight to government agencies and water users how benefits can be achieved by making more productive use of water resources.

The Landsat series images date back to 1980s, which allows for opportunity to perform long time series assessment. Figure 6 shows the WP results of the Ganfu Irrigation system in the Jiangxi Province, People's Republic of China from year 2002 to 2017. The assessment was performed for the paddy rice, the main irrigated crop. It can be observed that from 2003 the rice WP gradually increased over the study period. The average WP increased from 1.13 kg/m³ to 1.38 kg/m³, representing a 22% increase. The histogram distribution of the two years reveals that in 2003 there is much more variability among the irrigated paddy rice fields than in 2017. The variability in 2017 is so low that the best performing fields are not much better than the worst ones, implying low potential for further improvement.

3.2 Factors Affecting WP, Yield and Water Consumption

The remote sensing-based approach provides a detailed “picture” of what is happening on the ground. To understand what factors contribute to the variability between fields and command areas, causal analysis between the pySEBAL outputs (WP, yield, ETa, Ta) and biophysical, infrastructural, and management options are performed. The factors include, but are not limited to, administrative boundaries for potential effects on extension services, distance to water bodies, distance to canals and rivers, slope, soil quality and type, sowing seasons and seed quality.

Table 1. Crop area, water consumption, yield, and water productivity for seven crops in central highland and coastal provinces in Vietnam.

Crop	Season	Area [ha]	Average ETa [mm]	Total Water consumption [1000 m ³]	Average yield [ton/ha]	Pro- duction [ton]	Water productivity	
							[kg/m ³]	000 VND/m ³
Mango	May - Apr	8,061	1,118	90,122	27.9	224,902	2.52	110
Apple	Oct - Sep	14	555	78	30.2	423	5.33	64
Grape	Oct - Sep	21	602	126	22.2	466	2.29	32
Dragon fruit	Oct - Sep	1,824	1,059	19,316	24.1	43,958	2.29	28
Pepper	Sep - Aug	2,718	1,161	31,567	1.8	4,956	0.16	22
Rice	Dec - Mar	10,713	399	42,725	5.4	58,358	1.37	7
Coffee	Nov - Mar	3,569	1,087	38,801	1.4	5,067	0.13	5

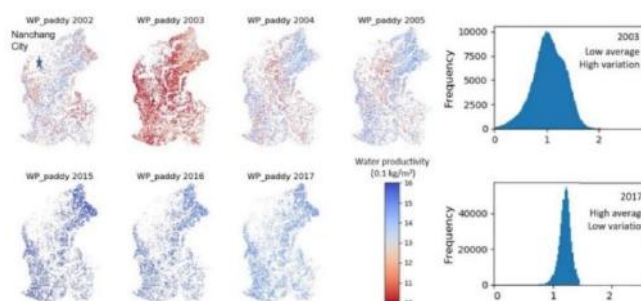


Figure 6. Water productivity of paddy rice in the Ganfu Irrigation System in Jiangxi, China for the period 2002 to 2017. On the right is the histogram distribution rice WP (Number of pixels versus WP values)

The distance to canal and water sources is a measurement of the impact of canal infrastructure. It is useful in determining the conditions of canal networks for reliably supplying adequate water. Figure 7 is an example from the Tungabhadra irrigation system in Karnataka state, India. It shows that the WP, yield, ETa, and Ta from areas with varying distances to the head canal intake at the reservoir. It can be observed that although the dependent variables change with the changes in distances, no significant trend can be detected, implying the conditions of canals are not determining factor. Similar results are observed in Indonesia, Pakistan, Vietnam and Madhya Pradesh of India.

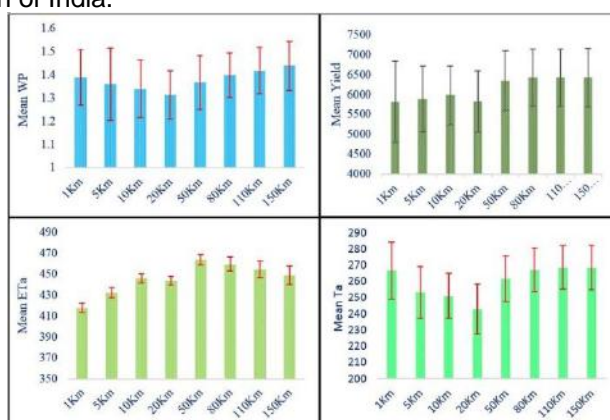


Figure 7. The relationship between water productivity, yield, ETa, and Ta of rice and their distance to water sources (head intake) in Karnataka, India.

Distance to salt waterbodies is also useful in determining the effects of salt water intrusion. Figure 8 shows left shows the WP of rice in West Java, Indonesia, and right shows the relationship between WP and the distance to salt waterbodies. It can be observed that the WP rapidly increase further away from the salt water bodies for the first 600 meters of buffer zones.

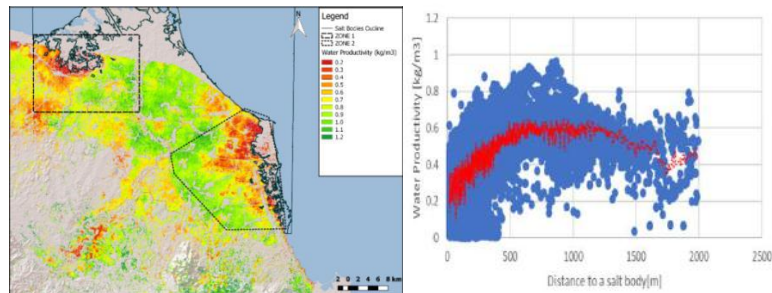


Figure 8. The relationship between WP and salt waterbodies in West Java, Indonesia.

Non-water related factors can also be analysed. Figure 9 illustrates WP, yield, ETa in relation to seed and fertilizer types in Karnataka. The research variety seed has the highest WP. Using grain as seed is comparable with certified seeds while the formal is much cheaper for farmers. Combined fertilizers with both nitrogen and phosphorus gave the best boost for WP while adding potassium does not help.

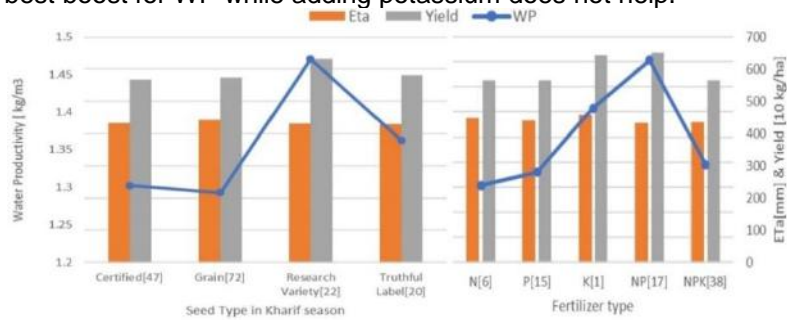


Figure 9. Non-water related factors: seed types and fertilizer types.

Some other factors are also analysed based on applicability in different sites. Biophysical factors such as soils and slope are found to have site specific relations with yield, water consumption and WP. While these factors could be difficult to manage, the relation point to opportunities during crop and irrigation planning phases. Shifting in crop calendar will also have a positive effect on overall WP. Water quality is also positively linked to WP in Indonesia. The explanation is however not directly in water quality itself, but probably other associated input efforts which accompany the source of supplied water.

3.3 Determining Potential For Improvement And Areas Of Priorities

The potential for improvement in any irrigation system should be site specific, related to local inputs and biophysical and climate conditions. Yield – often referred to as land productivity – and water productivity should be high in an ideal situation when there is no water scarcity. If water scarcity does exist the optimizing the best trade-off acceptable to farmers, water managers and other stakeholders becomes important. Figure 10 shows yield and WP of rice for every 30 m x 30 m field in System H, Sri Lanka. Most of the pixels fall in a shape that is defined by a straight line at the bottom, and 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. This graph demonstrates vertically farmers can achieve the same yield but with varying water use and WP. Farmers should move up from the bottom to the top. The horizontal shows that even for the same level of WP, yield can be vastly different, underscoring the importance of local conditions. Not all farms have the same potential due to soil, water, and other limitations. Importantly it is not possible to push all farms towards the top-right corner.

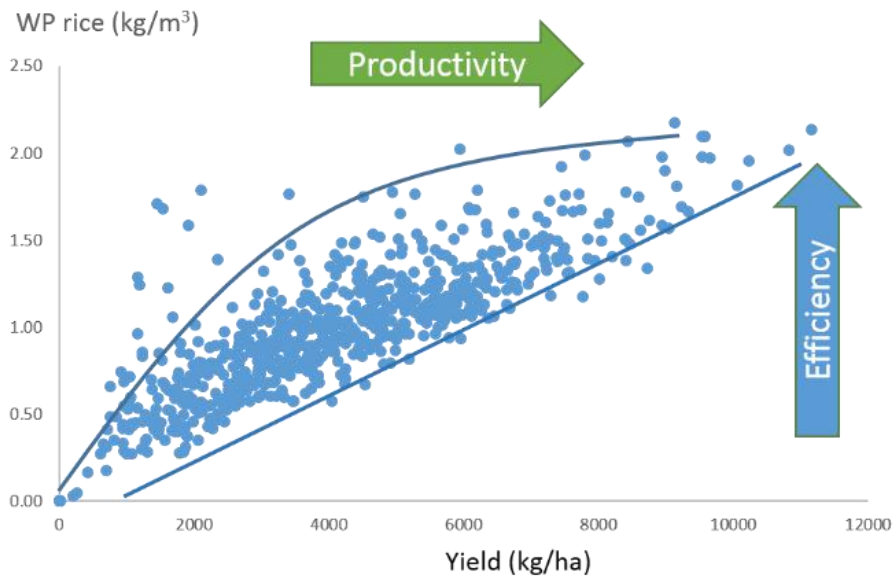


Figure 10. The Relationship between CWP and yield of rice in System H, Sri Lanka.

On-farm water savings represents the biggest potential in improvement. In the Lower Bari Doab Canal, Punjab, Pakistan, the average ratio of beneficial consumption (T_a) to total water consumption (ET_a) 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 11 highlights the potential in a spatially explicit manner for wheat. It can be observed that along the main canals, the T_a/ET_a ratio tends to be higher i.e. water losses are minimized. The lower reach to the bottom left is much lower. If we simply take 71%, the average ratio in the top bracket, as a practically achievable target ratio, then the water saving potential is 23% of current supply level.

There is always a need to determine priority interventions areas due to constraints in resources and capacity. This can be achieved by classifying the CWP map into three categories: (i) poor performing areas with CWP one standard deviation (SD) below average (hotspots); (ii) areas with average CWP; and; (iii) well performing areas with CWP one SD above average (champion farmers). The hotspots are not expected to achieve the same results as the champion farmers but could learn from them. Figure 12 shows that champion farmers (green) are in the right canal command (bottom). The farmers along the river stream in the middle tend to have the poorest performance, probably because they have unlimited access to the river water. A notable exception is in the tail end of left canal command (upper right). Higher CWP here does not imply better performance in terms of crop yield, but rather, farmers used the limited water available more productively.

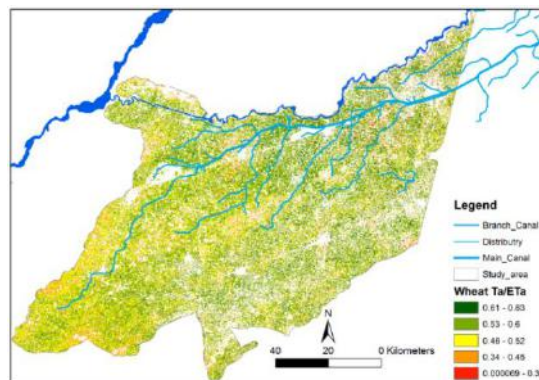


Figure 11. The ratio of beneficiary consumption (Ta) to total water consumption (ETa) for the 2016-7 Rabi season in Punjab, Pakistan

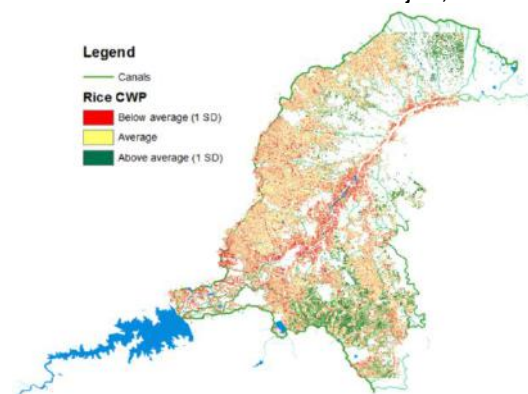


Figure 12. Rice CWP map of Tungabhadra system (India) to help determine priority areas where CWP is very low (red), average (yellow), and above average (green).

4. CONCLUSIONS

Asia has long been investing to modernize its water and agricultural systems – with much focus on main system investments. To avoid being caught in the rehabilitation cycle, we need to shift our investments to delivering the required level of service to farmers based on their crop water requirements. This concept of modernization includes investing in policy making, capacity building for improved management and infrastructure resulting in a higher level of service delivery. Water productivity represents such a shift towards linking outcome with water management in irrigation systems. Assessing the WP of major crops cultivated on an irrigation system is useful for setting the baseline conditions and comparing with local performance (or “control” areas) along time. It is in a way a useful monitoring indicator for policy and management purposes. However, with the use of remote sensing data and processing tool, new capabilities of CWP analysis allows one to move beyond simple assessment. It is now possible to operationalize the concept for practical decision-making during investment planning. A Remote sensing-based framework approach was proposed and demonstrated in this paper. The framework combines analysis of ET, yield and WP components and provides an analytical approach to diagnose irrigation performance, identify factors affecting water productivity, assess the potential for improvement, and determine priority intervention areas. It is based on open source models, toolkits, and uses publicly available data. It is semi-automated requiring least interventions from modellers and can be easily adopted by non-research community, such as GIS, irrigation, water and agriculture engineers from operational management departments and institutions. The remote sensing-based approach does not exclude expert knowledge and field information. Interpretations of

outputs require extensive field knowledge and understanding of local water practices that cannot be seen on an image. More importantly, increasing the acceptance of such a new concept, indicators, and tools by policy makers and managers still has some way to go.

By strengthening the links between knowledge, innovations and operations, multilateral development banks like the Asian Development Bank is demonstrating how latest tools can be used for determining baseline conditions. The future looks brighter as more information is disseminated to water service providers and users about the results that can be achieved and water savings that can be made. Working more closely with water users at the field level could be one of the biggest drivers of change – particularly when we can now visualize and share the beneficial outcomes of more judicious water use.

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