
Water productivity assessment of rice paddies in Indonesia

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List of abbreviations

| Abbreviation | Explanation | Abbreviation | Explanation |
|--------------|--|--------------|--|
| ADB | Asian Development Bank | LE | Latent Energy |
| B | Biomass | LUE | Light use efficiency |
| BBWS | Balai Besar Wilayah Sungai (River Basin authority) | NDVI | Normalized Difference Vegetation Index |
| BC | Beneficial Consumption | NIR | Near Infrared |
| BOD | Biochemical Oxygen Demand | PIRIMP | Participatory Irrigation Rehabilitation and Improvement Management Project |
| BP | Biomass production | PROBA-V | Project for On-Board Autonomy - Vegetation |
| COD | Chemical Oxygen Demand | PSDA | Pengelolaan Sumber Daya Air (Water management) |
| cp | Specific heat of air | QGIS | Quantum Geographical Information System |
| CWP | Crop water productivity | rah | Aerodynamic resistance to heat transport |
| DEM | Digital Elevation Map | RI | Longwave radiation |
| DO | Dissolved Oxygen | Rn | Net radiation flux at the ground surface |
| DS | Dry Season | Rs | Shortwave radiation |
| E | Evaporation | SAVI | Soil-adjusted Vegetation Index |
| EF | Evaporation factor | SEBAL | Surface Energy Balance Algorithm for Land |
| ET | Actual Evapotranspiration | SWIR | Shortwave Infrared |
| FAO | Food and Agriculture Organization | T | Transpiration |
| G | Soil heat flux | TIFF | Tagged Image File Format |
| GDP | Gross domestic product | TIR | Thermal Infrared |
| GEE | Google Earth Engine | Ts | Surface temperature |
| GT | Ground truth | VIIRS | Visible Infrared Imaging Radiometer Suite |
| H | Sensible heat flux | WP | Water productivity |

| | | | |
|-------|----------------------------------|----------|------------------|
| HANTS | Harmonic Analysis of Time Series | WS | Wet season |
| L | Latent heat of evaporation | α | Surface albedo |
| L7 | Landsat 7 | ρ_w | Density of water |
| L8 | Landsat 8 | ρ_z | Air density |
| LAI | Leaf area index | | |

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Executive Summary

IHE-Delft in cooperation with the Asian Development Bank (ADB) conducts a pilot project on assessing Crop Water Productivity in Asia, aiming to contribute to sustainable development in Asia's irrigation sector, and create more value from scarce water resources. Indonesia is one of the 6 pilot countries where advanced technologies to measure Water Productivity (WP) from satellite data were introduced. Indonesia is the third largest rice producer of the world. Given the challenges such as growing population, degrading land and increasing water scarcity in upcoming decades, the Indonesian government aims to rehabilitate its irrigation systems. More insights in the spatial distribution of irrigation water and water productivity of rice paddies could contribute to decision-making in future rehabilitation investments.

This report describes the assessment of Water Productivity (WP) of paddy rice in Indonesia using the Surface Energy Balance Algorithm for Land (SEBAL). SEBAL is a tool that translates raw satellite measurements into maps of actual evapotranspiration and crop production, among others. The actual crop water consumption (i.e. actual evapotranspiration) and crop yield can now be estimated for every 30 m x 30 m, even if data on irrigation water application is not available. With this information, rice production per unit of land (kg/ha) as well as per unit of water consumed (kg/m³) can be computed.

Focus of this study are sites in Bali, West Java and Lombok. Fieldwork is conducted in Bali and West Java to support the maps with 'ground truth' data. Data is collected from local governmental institutes and farmers to verify the remote sensing outputs.

The WP maps show a distinct distribution in all study sites, which implies that poor and good irrigation management practices coincide everywhere. The average WP was 1.1, 0.76 and 1.4 kg/m³ for Bali, West Java and Lombok respectively. Hence, Lombok is the most efficient in converting water to food. The consumptive use during the dry season was 506, 473 and 374 mm/season respectively. Bali thus has the highest water consumption per unit area. The paddy yield was 5.6, 3.6 and 5.0 ton/ha respectively. The higher water consumption in Bali resulted also into more yield and income for the farmers. But the simultaneous higher values for yield and water consumption on Bali takes care that WP is 1.1 kg/m³ (while Lombok reaches 1.4 kg/m³). The world-wide average value for WP is 1.1 kg/m³. Hence Bali is representing the global average value, Lombok is higher and West Java is lower.

Maps with below-average WP performance are created and can be used to indicate potential investment areas where opportunities for improving WP are likely present. In Bali a clear zone with predominantly WP values below average is found in the south-west of districts Badung and Tabanan. Factors that seem to be influential in Bali are drainage problems, erosion, poor water quality and three rice rotations per year. Interviews with institutes and in-field observations support the theory of a surplus of water in the downstream coastal regions. Water quality issues have been discovered in the urban sub-district Kuta, where crop production is low. Areas with insufficient irrigation water supply were also detected from this new remote sensing technologies. Especially the northern part of the island is plagued with water shortage.

As stated by institutes and observed in the field, one influential factor in the Rentang irrigation scheme on West Java is water availability. Tertiary, and sometimes even secondary, irrigation channels are often dry due to clogging or insufficient maintenance. In West Java a clear relation is found between the WP distribution and distance to primary and secondary irrigation canals. Also, areas that cope with yearly occurring floods seem to have lower crop production. Finally, areas adjacent to salt bodies show a pattern of lower crop production values and thus lower WP.

Lessons learned in Bali and West Java are applied to examine the WP conditions for the Lombok region. Low WP around the city Mataram and Bandar Udara airport trigger the suspicion of water quality issues because of pollution, based on the analyses for Bali. The region around the Waduk Batujai reservoir seem to have low WP values as well. The existing reservoir indicates abundant water availability, being supported by the high ET values throughout the whole zone.

This research shows promising results linking SEBAL outputs with the ground truth even though the amount of fieldwork was limited. The inclusion of the new HANTS algorithm will create the technical opportunity to make daily WP reports for all rice fields in Indonesia, also under cloudy conditions. This could be a big information boost to support irrigation managers with their daily services of bringing water to farmers. Whereas some key explanatory reasons were detected (i.e. distance to canal, salt water intrusion, water quality, erosion), it is recommended to further explore relations between WP and influencing factors in the local context together with local irrigation officers. Even though the research revealed some limitations causing uncertainties, this new remote sensing technologies can support an efficient and effective investment purposes on modernization of irrigation. It is recommended that the Directorate of Irrigation and Lowlands recognize WP as a new policy instrument and implement it both at central level and irrigation district level.

Introduction

The Indonesian government, in recognition of the challenges facing the country's irrigation sector, is working towards more efficient management and use of water by devoting major investments into development, rehabilitation, and modernization of its irrigation systems. The efforts have been focused on rice which is the most important food crop of Indonesia, and as it requires a vast amount of water. Over 90 percent of the world's rice is produced and consumed in Asia¹ and Indonesia is the 3rd largest rice producer in the world². Despite this large amount of production, the demand of the crop is growing faster than the increase of production. Producing more rice with the same amount of water, or better, even more rice with less water, is therefore an important goal of the government.

IHE-Delft in cooperation with the Asian Development Bank, is working on a pilot project to promote efficient water use in the agricultural sector of Asia. Until recently, there is limited data of water usage of the considered areas. This project introduces a relatively new method of mapping the water consumption of crops in relation to the crop yield produced: measuring the Crop Water Productivity (CWP) using Remote Sensing. Crop Water Productivity is a performance indicator for monitoring, evaluating, and diagnosing irrigation water management. It refers to the ratio between agricultural yield and water consumed. Mapping the Crop Water Productivity of a certain area, allows for examining differences in water productivity in the agriculture sector, and discover high potential areas for possible investments.

The prime driver of the new method, is the Surface Energy Balance Algorithm for Land (SEBAL). SEBAL models Evapotranspiration and Biomass production per unit area. In addition, a classification map is produced by applying a classification algorithm on Landsat images in Google Earth Engine (GEE). Combining the outputs of both SEBAL and GEE results into Crop Water Productivity maps of the considered area.

All data and software required are open source and free to use. This makes the SEBAL method easily applicable on a larger scale and therefore a promising tool to get further insights into potential investment areas in a relative easy way.

The Indonesian Government has shown interests in the use of water productivity and remote sensing technology to aid the investment in irrigation. Pilot study sites have been identified by the Ministry of Public Works and Housing. These sites are in West Java, Bali and Lombok (Landsat tile 121/64 and 116/66). The project aims to map water productivity of paddy rice in these sites. Additionally, an in-depth enquiry on the status of WP is conducted and the reasons behind the outcomes are explored. The results feed into the government's decision-making processes for better investment and management of its irrigation systems. In addition, the project aims to identify the limitations as well as opportunities of the WP method in Indonesia.

Key to this study is the close cooperation with various Indonesian partners (e.g. Ministry of Public Works, IPB university, and local governmental bodies). The project team works closely together with two young professionals from IPB university, such that thorough knowledge exchange takes place. After the study is

¹ FAO report Bridging the rice yield gap in the Asia-Pacific region (2000)

² FAOSTAT 2014

completed, training will be given to multiple local partners. The goal of this training is to expand knowledge on working with WP software, as well as to increase understanding about the use of WP.

Sharing knowledge on the WP method with local partners opens the opportunity to apply the WP method on a larger scale. This allows for further development of SEBAL and therefore increasing insights in water productivity.

Scope

This report contains the output of the pilot study conducted in West Java, Bali and Lombok. Background information on Water Productivity, rice production and study sites are given in the first sections. In chapter 3 the methods of the study are explained. All results can be found in chapter 4, and an analysis of the Water Productivity maps in chapter 5. In Chapter 6, the results and analyses are discussed based on case studies. Finally, chapter 7 provides limitations and recommendations for the further application of SEBAL in Indonesia.

1. Background

1.1. Background on WP

Crop water productivity, also known as “crop per drop”, is an indicator of the amount of crop produced per unit of water used. The amount of crop which is produced is often expressed in yield. The amount of water used is a more complicated concept and can be approached on different scales (farmer level, basin level) and aspects of the water cycle (transpiration, total evaporation, water in- outflow). For the scope of this study the water productivity (WP) is based on the amount of crop produced per amount of water *consumed*. Figure 1 provides an overview of which factors are accounted for as consumed water.

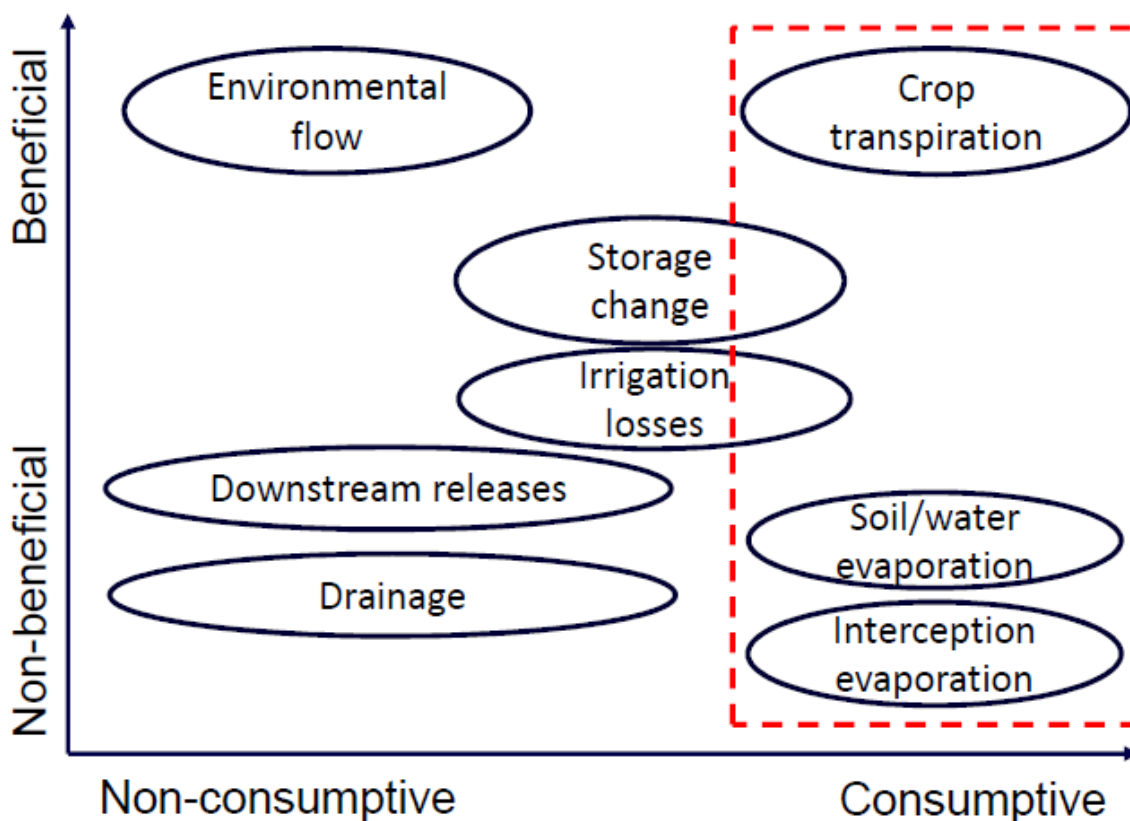


Figure 1 Overview of types of water. The red box around the consumptive water types are the forms which will be focused on in this WP research.

The focus is on the consumptive water, namely evapotranspiration (ET), as it can be argued to be a loss at an agricultural level. Since the focus of the stakeholders of this project is to optimize water use in the agricultural sector, it is desirable to limit the consumptive water amount as much as possible. On farmer plot level downstream releases, drainage and other non-consumptive water types may be considered as a loss, however, as the farmers downstream often reuse this water, it can be seen as a source too and is

therefore not taken into account in this research. Additionally, water types related to environmental flow may function as water source too and are therefore not accounted as a loss either.

The formula for the type of crop water productivity which is used in this research is the following:

$$WP = \frac{Y_a}{ET_a}$$

Where:

WP = Water Productivity

Y_a = The Marketable yield

ET_a = Actual Evapotranspiration

Ideally, when aiming to increase the water productivity, the goal is not only to decrease the consumptive water use, but additionally increase the yield. So, more crop with less water.

There are many factors which may influence the WP. Each factor may influence either the yield, or the ET, or both. These factors are related to the hydrology of the study area (sub-catchments, water quality, rainfall distribution, floods), the topography of the area (altitude, slope, erosion level, distance to the sea), the timing of the seasons, and the condition and types of irrigation system. As WP depends on many factors, these factors should be analysed to obtain a better understanding of the cause behind the spatial distribution of the various WP values.

WP differs from the concept of water efficiency as it gives more information about the amount of crop produced with the amount water available and does not only focus on the required water. However, when aiming to optimize WP it is useful to analyse the efficiency of field level application, and upstream/downstream allocation at various levels. WP is a useful tool of obtaining a first indication on a large scale of which region may be worth investing into, to save water and increase yield. Nevertheless, low WP is not necessarily bad and field research to understand which factors influence WP should be conducted in order to truly understand what is happening on the ground.

1.2. Rice production in Indonesia

This section explains the basics of rice cultivation in Indonesia and its factors relevant to Water Productivity.

1.2.1. Rice environment

In general, four environments are distinguished in which rice is grown: upland, rainfed lowland, irrigated, flood-prone environments (IRRI, 1993; Prasad et al., 2017). The majority of rice fields in Indonesia (50% of rice fields worldwide) are irrigated. The main advantage of irrigated rice fields is that it assures water supply throughout one or more cropping cycles in a year. This is an advantage since rice production is very sensitive to water shortage.

Although most rice fields in Indonesia are irrigated systems, often it is a combination of 'irrigated' and 'rainfed'. Two seasons can roughly be distinguished in Indonesia, which are the Dry Season (DS) and the Wet Season (WS), from April – September, and October – March respectively. During the WS in particular, rainfall is a significant part of the water source in rice paddies. Rainfed lowland rice field systems are

characterized by alternating aerobic and anaerobic soil, with rainfall as only water source. However, in rainfed environments in combination with irrigation water sources, this is not the case. The combination of both assures continuous shallow flooding (anaerobic conditions) of the rice field throughout the entire growth stage.

1.2.2. Growth stages

Before rice seeds are planted, field preparation is necessary. In clay soils, which are prominent in Indonesia, wet preparation is most appropriate. The duration of field preparation and amount of water used depends on field conditions. In general, field preparation takes 3 – 4 weeks. However, this can vary up to 2 months when, for example, cracks are prominent in the soil caused by drought.

A rice cycle has different growing stages (Figure 2): the Vegetative Phase, Reproductive Phase and the Ripening Phase. Rice is transplanted (in few cases directly seeded) in puddle soil. After transplanting the field is flooded either continuously or in intermitted stages throughout the three phases to maintain anaerobic conditions (IRRI, 2017). The water depth is increased with biomass growth, ranging from 3 to 10 cm. Flooding the field reduces the risk of the crop receiving too little water, as rice is very sensitive to water shortages, and controls the weeds. To maintain a shallow flooded field, irrigated rice fields are levelled and embanked. Up until 7 days till 3 weeks before harvesting the field is drained.

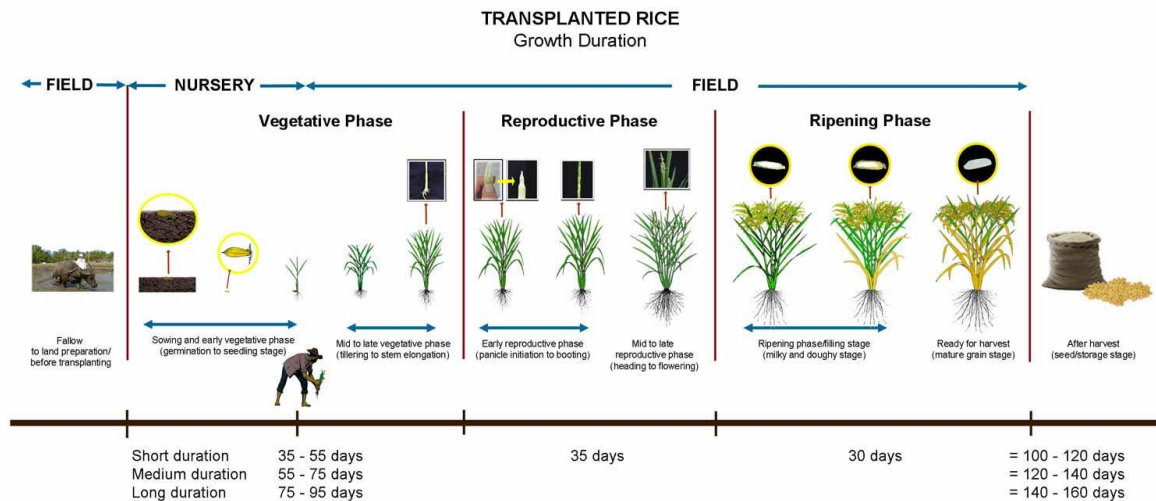


Figure 2 Growing stages of a rice cycle [Source: IRRI, 2017]

Depending on rice type, the duration of a rice cycle (vegetative phase – ripening phase) varies from 100 – 160 days. In general, the cycle of hybrid rice varieties is shorter in comparison to local rice varieties. In addition, hybrid rice has higher yield (approximately +20-30%) compared to local rice.

Rice is grown 1, 2, or 3 times in a year. This often depends on water availability and weather conditions (Prasad et al., 2017). Cultivating rice requires high amounts of water and labour compared to other crops. Therefore, when 1 or 2 rice cycles are grown, other crops are often grown in between. Examples are soy beans, corn and water melon. Other reasons for growing less than 3 cycles are limiting pests, insects, and weeds (Riar et al. 2013), to enhance the fertility of the soil and finally, because of money restrictions.

1.3. Site Description

In this section the sites which are selected to conduct the research are described. The characteristics of the site, especially those relevant for the WP and rice production are briefly explained.

1.3.1. Site selection

Two main research regions in Bali and West-Java were selected in cooperation with the Indonesian Government and IHE-Delft. To achieve an as decent, and detailed, performance as possible within this 8 weeks lasting pilot project, a realistic area size is selected. Next to that, for field data collection regions are selected strategically based on borders of districts (Kabupatens), sub-districts (Kecematans) and river basin authorities, to ensure that the data is correlating as well as comparable. Finally, to reduce the amount of data required for this pilot study, boundaries of satellite images are followed.

A third area of interest, the island of Lombok, will be taken into account when computing the WP calculations, but due to time limitations of this pilot study Lombok will not be investigated further.

Bali

The first site is the island of Bali. The main focus is on the south part of Bali situated in the districts (Kabupatens) Badung, Gianyar, Tabanan and, the capital, Denpasar (Figure 3). There are several rivers in Bali, each with its own catchment area, as shown in Figure 4.

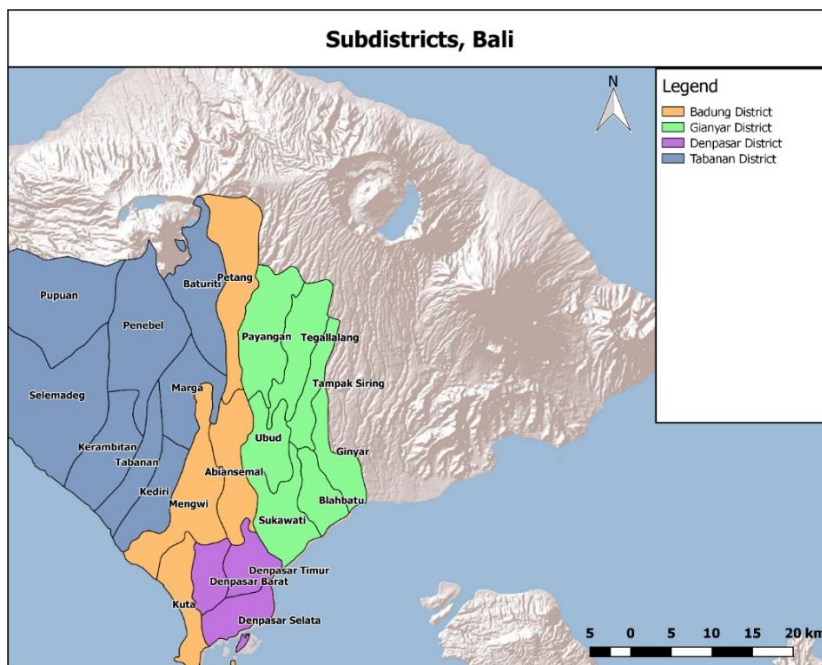


Figure 3: Subdistricts of interest in Bali

Java

The second study area is in the north of the island Java close to the cities Cirebon and Indramayu, in the Rentang irrigation scheme. The Rentang irrigation scheme is administratively covered by 3 districts, namely Majalengka, Cirebon and Indramayu. These districts contain 40 sub-districts: 2 sub-districts of Majalengka, 14 sub-districts of Cirebon and 24 sub-districts of Indramayu (Nippon Koei Co., 2011). Some of these sub-districts exceed the boundaries of the WP-maps and are therefore excluded. The relevant sub-districts are shown in Figure 5.

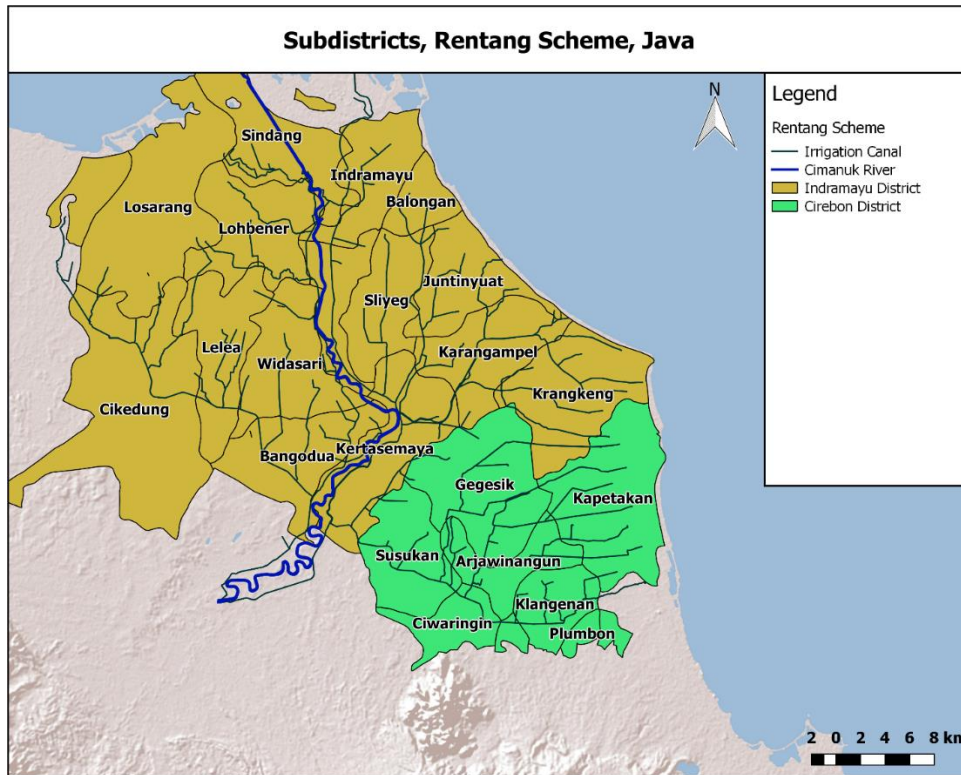


Figure 5: Relevant sub districts in the Rentang scheme

1.3.2. Site characteristics

Bali

Bali reaches 140km by 90km and has an area of 5,632 km². An east-west orientated chain of volcanic mountains separates a narrow coastal plain to the north, from a broad gently sloping, fertile, plain to the south. It has a warm, humid climate with two seasons: the wet season from October to March and the dry season from April to September (Cole et al. 2015). The mountain range in the middle of the island divides the island into lowlands, ranging from zero to 500 meters, covering 56% of the island, and highlands. Besides elevation, these zones also differ in their average annual rainfall. Yearly rainfall in the southern lowlands ranges between 1500 and 2300 mm and is on average less than 900 mm in the northern highlands (Widjana & Sutisna, 2000). The rainy season in Bali is relatively short compared to other Indonesian islands, so droughts are a potential danger, especially in the northern and eastern highlands (Takama et al., 2007).

Together with East Java, Bali produces 22 % of the rice produced in Indonesia (Naylor et al. 2007). 43% of the employment in Bali is based in the agricultural sector, but agriculture only accounts for 24% of the island's GDP. Tourism on the other hand accounts for almost 9.3% of the GDP and 8.4% of the employment (WTTC, 2015). Tourism is a large factor in the Balinese day-to-day life and has grown heavily in the last thirty years. Bali profits from this tourism. However, it is estimated that 85% of the tourism economy is in the hands of non-Balinese (MacRae, 2005). These non-Balineses may not be directly affected by tourism's negative impacts, including the declining quality and quantity of water. It is estimated that tourism accounts for 65% of water consumption (Cole et al. 2015).

Java

The Rentang irrigation scheme is situated in the alluvial plain of the Cimanuk River and some other small rivers. It is mostly covered by clay to loam soils, but also fine sand to loam soils occur. The slope varies between 1/3000 to 1/5000, flattening towards the sea. At the coast salt intrusion into groundwater occurs and therefore it cannot be used for domestic use. The total area of the Rentang irrigation scheme is 123.611 ha, of which approximately 70% is paddy field. Most of the farmers choose for the cultivation of one paddy in the rainy season, one paddy in the dry season and finally a third fallow-period or other crop. A high-scale modernization project of the Rentang irrigation scheme, part of the Participatory Irrigation Rehabilitation and Improvement Management Project (PIRIMP) which started in 2011, strives to upgrade the water availability in the whole region so every farmer can cultivate three cycles, paddy or other crop, per year in the year 2020. The most common secondary crops are respectively green bean, cassava, soy bean and maize. Around 2.2 million people live in the Rentang irrigation scheme and more than 50% work in the agricultural sector (Nippon Koei Co., 2011).

The climate in the Rentang irrigation scheme is characterized by two seasons, one rainy season from October to April, where 90 percent of the annual precipitation occurs, and one dry season from May to September. Average annual rainfall is about 1900 mm, spatially varying from 1500 mm in the coastal region to 2500 mm in the hills. Average temperature is quite constant through the whole year and ranges from 26 to 28 °C (Nippon Koei Co., 2011).

1.3.3. Site management

Bali

Bali is a single Indonesian Province and is split into nine districts (kabupaten), each with a regent (bupati), or area head. At the local level Bali is divided into hamlets (banjars). Only Balinese people are allowed to join these Banjars. The head of a Banjar is democratically elected and decisions are made democratically, but only by male heads of households (Cole et al. 2015). Banjar is the “most important corporate institution related to social organization” (Lorenzen, 2005, pp. 3). It can be viewed as a “moral community” in which “every member has the same responsibility towards the group”. Violations of the regulations of banjar can lead to group exclusion. Another organizational structure is the Subak. A Subak is an organization around a water source which distributes the water among its members. The water is allocated depending on the size of the fields. “Subak are socio-religious organisations responsible for irrigation management and religious activities within a defined geographical area” (Lorenzen 2005, pp1). Though the banjar and the Subak are not directly related, many members of the same banjar are often also members of the same Subak. *Awig-awig* is a set of laws which are part of the Subak and contain the rights and duties of the members. These rights and duties are related to “public obligations, regulations concerning land and water use, legal transactions of land transfer, and collective religious ceremonies” (Lorenzen, 2005, pp. 1).

Java

The operation and maintenance of the Rentang irrigation scheme is controlled by two organizations, namely the BBWS and the Balai PSDA CC. The BBWS is responsible for the operation and maintenance of the Rentang dam and the primary canals. The Balai PSDA CC performs routine works of operation and maintenance on secondary canals and structures. Data about agricultural production is registered at the agricultural offices in Indramayu and Cirebon.

On Java, local rural neighbourhoods are organized in peasant groups, so-called Kelompok Tani, whose membership is based on the location of their farmland. Each Kelompok Tani represents about eighty farm household and are led by a person called the Ketua Kelompok Tani. Adjacent Kelompok Tani unite in so-called Gabungan Kelompok Tani, or Gabpoktan (Pradoto, 2012).

2. Method

In the flowchart of Figure 6 the methods for this research are presented. There are two paths which can be followed to compute the WP. Option 1 uses Landsat data, meteo data and a Digital Elevation Model (DEM) in the SEBAL model. The SEBAL output needs to be gap filled to create complete evapotranspiration (ET) and biomass production maps without signs of clouds. For option 2, daily PROBA-V and VIIRS data is processed in a cloud removal algorithm HANTS. The output of HANTS together with meteo data and a DEM is used in SEBAL. The resulting ET and biomass production maps do not need to be gap filled. Next, both ET and biomass production maps are clipped for the crop of interest, using Crop Classification. The biomass production maps together with ground truth data and interviews are used to calculate a yield factor to create a yield map. Then, the ET map and yield map are used to calculate the Water Productivity (WP). Finally, the WP, ET, and yield maps are analysed to obtain a better understanding of the spatial distribution of the outputs. The steps for these methods will be discussed in further detail in this chapter.

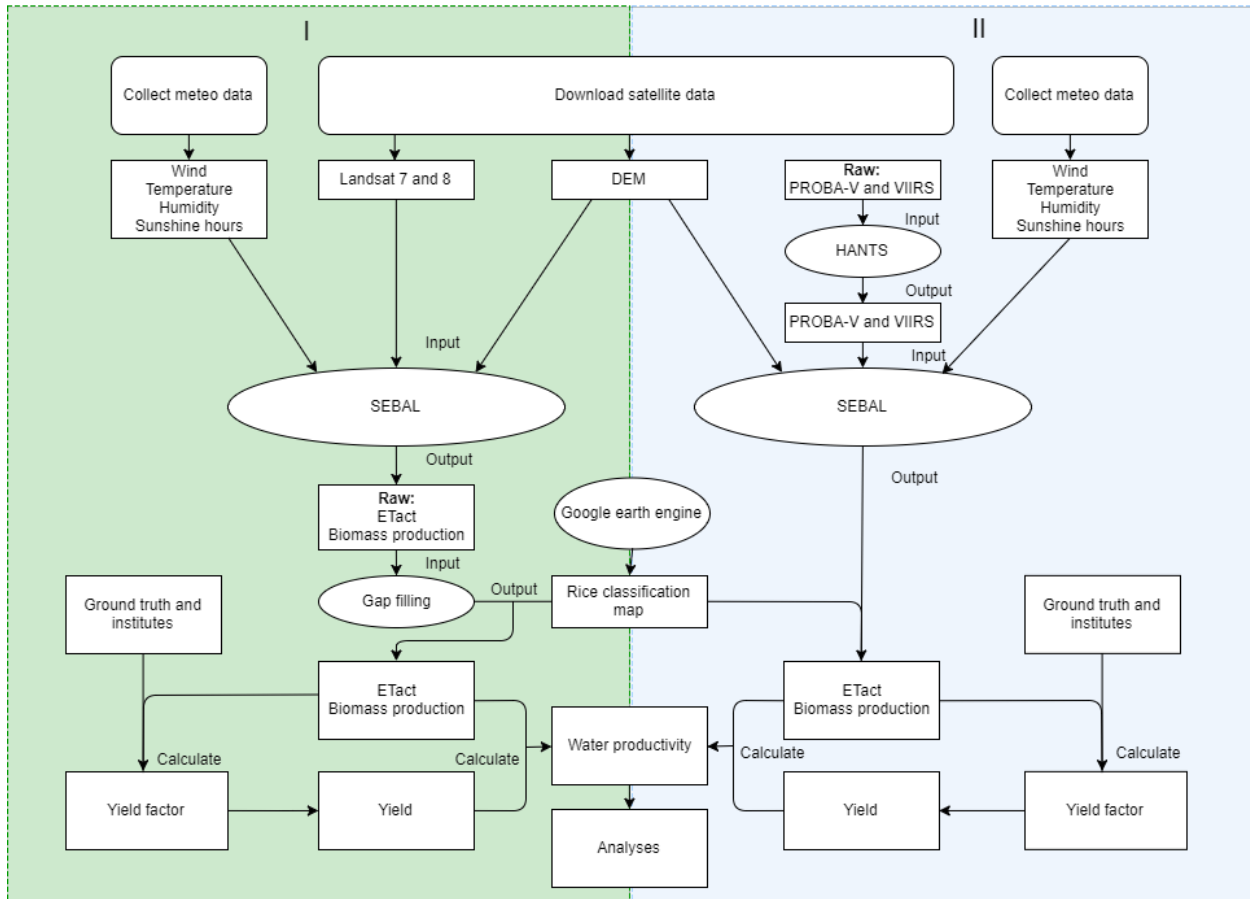


Figure 6 Flowchart of the methods

2.1. SEBAL

SEBAL is a complex model which forms the backbone of this research. This section explains the main theories and applications of SEBAL. For a more elaborate explanation the articles by Bastiaanssen *et al.* (1998a, b) can be consulted.

2.1.1. Theory

Flux calculation

The SEBAL algorithm is based on the Surface Energy Balance for Land (SEBAL). It was first published by Bastiaanssen *et al.* (1998a, b). SEBAL is based on modelling the surface energy balance using remote sensing data. Satellites do not measure ET or Biomass directly but the spectral bands of the satellites can be related to these processes. The energy balance can be expressed in terms of Radiation, Soil heat flux and the Sensible heat flux:

$$LE = R_n - G - H$$

Where LE is the latent heat flux (W/m²), R_n is the net radiation flux at the ground surface (W/m²), G is the soil heat flux (W/m²) and H is the sensible heat flux (W/m²). From LE the evapotranspiration (ET) can be calculated using the latent heat of evaporation (W/kg), L, and the density of water (kg/m³), ρ_w, using the following formula:

$$ET = \frac{LE}{L \cdot \rho_w}$$

The Net Radiation flux (R_n) is calculated using the balance for the surface radiation:

$$R_n = R_s^\downarrow - \alpha R_s^\downarrow + R_L^\downarrow - R_L^\uparrow - (1 - \epsilon_0)R_L^\downarrow$$

Where R_s^\downarrow is the incoming shortwave radiation (W/m²), α is the surface albedo (-), R_L^\downarrow is the incoming longwave radiation, R_L^\uparrow is the outgoing longwave radiation and ϵ_0 is the surface thermal emissivity (-). The parameters in this equation can be calculated using satellite and weather station data. More information about how the formulas are solved in SEBAL can be found in (Bastiaanssen, 1998a; Bastiaanssen, 1998b).

The ground heat flux G , can be calculated using an empirical formula developed by Bastiaanssen (1995), the formula for G is:

$$G/R_n = T_s \cdot (0.0038 + 0.0074 \cdot \alpha) \cdot (1 - 0.98 \cdot NDVI^4)$$

Where T_s is the surface temperature (°C), α is the surface albedo (-) and NDVI is the Normalized Vegetation Index calculated using the satellite data (Bands B5 and B4 when using Landsat 8 data, this can differ for each satellite). Then using the net radiation, the ground heat flux can be calculated.

The sensible heat flux H is the heat loss to the air due to convection and conduction caused by a temperature difference. It is calculated using the following formula:

$$H = \frac{\rho_a \cdot c_p \cdot dT}{r_{ah}}$$

In this formula ρ_a is the air density (kg/m³), c_p is the specific heat of air (1004 J/kg/K), dT is the temperature difference (K) between z_1 and z_2 , these two heights are based on Bastiaanssen (1995), and r_{ah} is the aerodynamic resistance to heat transport (s/m).

The equations which are used in SEBAL to calculate the various components of the energy balance can be found in Bastiaanssen et al. (1992a, 1992b). SEBAL uses satellite data, weather station data and a digital elevation map (DEM) to calculate all parameters.

To change the energy balance from an instantaneous to a daily value an evaporation factor (EF) is used. The formula for the EF is:

$$EF_i = \frac{LE}{R_n - G}$$

This is then converted by SEBAL into a 24-hour factor using the formula:

$$EF_{24} = \Omega \cdot EF_i$$

Where EF_{24} is the evaporation factor for 24 hours and Ω is an advection factor that is used to make a correction on the EF_i factor. Ω is determined by an empirical formula (Teixeira et al. 2008; Hong et al. 2014).

The 24-hour latent heat flux can be calculated using the following formula:

$$LE_{24} = EF_{24} \cdot (Rn_{24} - G_{24})$$

The G_{24} is negligible small, due to the heating up of the topsoil during the day and the cooling down of the soil during the night. This results into the following formula:

$$LE_{24} = EF_{24} \cdot Rn_{24}$$

The Rn_{24} term in the equation is calculated using the formula as described in FAO56 (Allen et al., 1998).

SEBAL automation

With the huge amount of data available and the need to be able to run SEBAL and provide data on a large spatial scale, the model needs to be automated. This requires the model to calibrate automatically. The calibration of SEBAL requires the selection of hot pixels ($LE \approx 0$ W/m²) and cold pixels ($H \approx 0$ W/m²).

The hot pixels represent bare land surfaces, for example roads, bare soil or rocks. These pixels can be determined by finding a NDVI value between 0.03 and 0.125. The pixels which fall within these boundaries are statistically analysed to determine a good calibration value for the temperature of a hot pixel (T_s^{hot}). SEBAL3.0 allows for this to happen automatically without the need for manual selection of pixels. For landsat the formula for T_s^{hot} is:

$$T_s^{hot} = T_s^{dem}_{mean} + 2 \cdot T_s^{dem}_{std}$$

Where $T_s^{dem}_{mean}$ is the mean temperature for all pixels within the NDVI boundaries, and $T_s^{dem}_{std}$ is the standard deviation of these pixels. The value for T_s^{hot} is higher than the mean to avoid picking pixels which are for example wet bare soil, which generally have a lower temperature.

The cold pixels are found by looking at water bodies where $H \approx 0$ W/m². SEBAL will find the water pixels using a water mask. From these water pixels the temperatures are taken. The formula to calculate T_s^{cold} is:

$$T_s^{cold} = T_s^{dem}_{mean} - 2 \cdot T_s^{dem}_{std}$$

Where $T_s^{dem}_{mean}$ is the mean temperature for all water pixels, and $T_s^{dem}_{std}$ is the standard deviation of these pixels. T_s^{cold} is lower than the mean value to avoid picking pixels which are for example half water and half shore which generally have a higher temperature.

The values T_s^{cold} and T_s^{hot} are used in the SEBAL calibration when calculating the sensible heat flux H . For all pixels with $T_s^{dem} > T_s^{hot} - 0.5$, dT is computed from $H = R_n - G$ ($LE \approx 0$ W/m²). For all pixels

associated with T_s^{cold} the dT is 0 K since $H \approx 0 \text{ W/m}^2$. When there are no water bodies present SEBAL switches to find pixels with a NDVI > 0.8 (high vegetation) which are cold (moist vegetation) as a substitute for water pixels.

SEBAL masks

SEBAL requires several masks to perform calculations. The first is a water mask, which is used for the calibration with cold pixels. The water mask is based on two conditions:

- NIR reflectivity $<$ Red reflectivity
- SWIR reflectivity $<$ Green reflectivity

This method is dynamic and allows SEBAL to detect changing water bodies over different images. The double condition takes care that many cells which fulfil one condition, for example wet soil, are still masked.

Snow and ice can influence the SEBAL calculation and must be masked. When the pixels are still present they create an offset in the statistical analyses for the cold pixels which will influence the calculation. SEBAL masks any pixels with a temperature $T < 275 \text{ K}$.

One of the largest problems when working with satellite data is the occurrence of clouds. The clouds affect the reflectance of the bands, making a calculation of the land surface energy balance impossible. SEBAL uses thresholds to detect clouded pixels. The threshold conditions are:

- $T_s < T_s^{\text{water}} + \text{offset}$ (offset is chosen by the user)
- surface albedo $\alpha > 0.4$
- NDVI < 0.7

Because of these three conditions, pixels that are not clouds but do fulfil one or two of these conditions, will not be classified as cloud pixels. An example is a sand pixel with a high albedo or a recently irrigated field with a low temperature.

SEBAL requires the temperature of the land surface T_s . This is obtained through the Thermal InfraRed (TIR) band on the satellite (band 10 and 11 on Landsat 8). The pixel size of these bands is larger than the other bands (100 x 100m). This means that when these bands are used, the resolution of the resulting images is decreased. To prevent this the thermal images are sharpened using the NDVI values as regression variables. The relation between NDVI and T_s has been established (Carlson, 2007, Moran et al. 1994). One relationship between T_s and NDVI would not suffice for SEBAL, this would generalize the image. Therefore, SEBAL creates a unique local relationship for T_s and NDVI for each pixel. This creates a sharpened image (Figure 7) for the surface temperature (T_s).

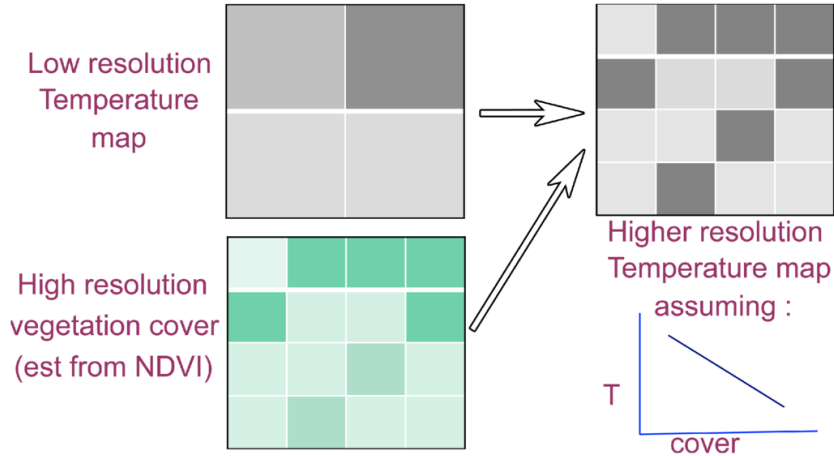


Figure 7 Simplified representation of mapping low resolution pixels using high resolution pixels and the relationship. (Image source: Jones and Sirault, 2014)

The output of SEBAL can be further enhanced by splitting the LE flux into two components, the Transpiration (T) and Evaporation (E). The T flux is generally considered as beneficial and the E flux as non-beneficial, therefore it is useful for the application of SEBAL to distinguish these terms. First the potential T flux must be calculated, this is done using Beer's Law:

$$T_{pot} = ET_{pot} \cdot (1 - \exp(-0.5 \cdot LAI))$$

Where ET_{pot} is the potential evaporation, based on the Penman Monteith equation, and the LAI is the Leaf Area Index. The fluxes for E and T are calculated using the following formulas:

$$T'_{act} = \Psi_{\theta} \cdot T_{pot}$$

and

$$E'_{act} = S_e^{-2} \cdot (ET_{pot} - T_{pot})$$

Where Ψ_{θ} is a factor based on the soil moisture content and its effect on transpiration (Allen et al., 1996) and S_e is the degree of soil saturation of the topsoil scaled between 0 and 1. Because both T'_{act} and E'_{act} are both based on empirical relationships, their relative values are used to breakdown the ET flux. Therefore, the formulas for the corrected T and E flux become:

$$T_{act} = \frac{T'_{act}}{E'_{act} + T'_{act}} \cdot ET_{act}$$

and

$$E_{act} = \frac{E'_{act}}{E'_{act} + T'_{act}} \cdot ET_{act}$$

Additionally, SEBAL provides information on daily biomass production. The biomass production output is important to determine the WP and to derive other results from. The biomass production is calculated based on the Absorbed Photosynthetic Active Radiation (APAR) among other parameters. This is the radiation that is absorbed by the crops and used for photosynthesis. APAR depends on the solar radiation in the atmosphere, the cloud coverage, atmospheric constituents and the presence of green leaves. The APAR is related to the biomass production through the light use efficiency (LUE) (Monteith 1972). The relation can be described using the following formula:

$$B_{io} = \frac{APAR}{LUE}$$

The LUE is dependent on soil moisture, leaf nitrogen content, crop type, leaf temperature, etc. In SEBAL the LUE is calculated using the Jarvis-Stewart model (Jarvis, 1976; Stewart, 1988).

2.1.2. Practical application

The SEBAL model is developed by IHE-Delft in python. This is done for several reasons:

- Python is freely available without high purchasing costs.
- Python speeds up the image processing which is a benefit when applying the method to larger study areas.
- It is possible to link the model to other tools for operational use.
- Python is constantly being developed by volunteers and users.

The model for SEBAL is openly available on Github (<https://github.com/wateraccounting/SEBAL>) where the code for SEBAL and information about the model can be found.

Data

As mentioned SEBAL requires data from several sources. The satellite data that is used in the SEBAL model is the data from Landsat 7 and Landsat 8 (acquired from USGS). In order to calculate the fluxes of the surface energy balance, meteorological data is collected from weather stations near the study areas. Additionally, a Digital Elevation Map (DEM) of the study area is needed for the SEBAL model. This is acquired from Earth Explorer with a resolution of 30x30m (SRTM 1 arc-second). For the area in Java Landsat tile 121x65 is used and for Bali and Lombok tile 116x65. For this study only one tile per area is chosen.

Future application

Currently SEBAL uses data from Landsat 7 and 8 to recreate the daily time series for the Biomass production and the ET. Both satellites have a pass over frequency of ≈ 16 days for each tile. This means large portions of the daily time series need to be interpolated using the available data. This can be further complicated by the presence of clouds on the moment when the Landsat image is taken. If there are too many clouds in a Landsat image it can't be used and more days need to be interpolated. To improve the SEBAL model, data from the satellites PROBA-V and VIIRS will be used in combination with the cloud removal algorithm HANTS. These satellites have a much lower passing frequency (typically one or two days for each site) which makes cloud removal using the

HANTS algorithm possible. The downside of these satellites is that the resolution of the images is 100x100m. The principle of HANTS will be explained in more detail in the next section.

The data of Landsat, PROBA-V and VIIRS can be combined to create a daily cloud free time series with a high accuracy in time and space, to further improve the SEBAL results (Figure 8).

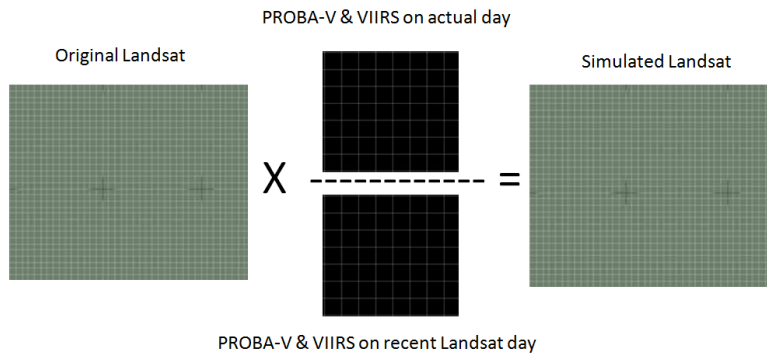


Figure 8 Sketch of the method to correct Landsat output data using PROBA-V and VIIRS.

2.2. HANTS

To overcome the problem of clouds in satellite images the cloud removal algorithm HANTS has been developed. This algorithm works in combination with the PROBA-V and VIIRS satellite to create daily cloud free input data for the SEBAL model with a resolution of 100x100m. As this is a fairly new method with long preparation time, HANTS has only been applied to the Java site. For Java, SEBAL has been run both with and without HANTS in order to analyse the potential improvement.

2.2.1. Sensor selection

PROBA-V

The main aspect of the PROBA-V satellite is the vegetation sensor, which makes this satellite very useful for this research project. The PROBA-V satellite has 4 bands; Blue, red, NIR and SWIR. The satellite is programmed to make images of only land and particular zones in terms that the sea is left out of the data. This is due to the main purpose of the satellite, which is obtaining vegetation data. From the PROBA-V data NDVI, SAVI and Albedo maps are made for this research. The NDVI, SAVI and Albedo will be run through a cloud removal algorithm HANTS to obtain daily cloud free satellite data. This PROBA-V satellite has a resolution of 100x100m which an overpass frequency of approximately one day. The satellite data is freely accessible.

VIIRS

VIIRS is short for Visible Infrared Imaging Radiometer Suite. This satellite uses a whiskbroom scanning radiometer (noaa guide). The whiskbroom scans sideways (cross-track) in aspect to the satellites direction, provides 22 imaging and radiometric bands including applications like sea surface temperature, aerosol and vegetation (noaa VIIRS). In this research, the land surface temperature data of this satellite is used with the application of HANTS. This VIIRS satellite also has a resolution of 100x100m with an overpass frequency of approximately one day, the satellite data is freely accessible.

2.2.2. Hants algorithm to remove clouds from satellite data

One of the main problems of satellite data is the presence of clouds on an image. Clouds can give infested data or even gaps with missing data. For this reason, it is important that clouds can be removed in a way that there is no loss of data or time series. Cloud infested images are not filtered out of SEBAL and will cause incorrect data or missing data. To cope with this problem the algorithm HANTS is used. HANTS uses a mathematical algorithm to remove clouds or abnormalities. In temperature maps, clouds give a significantly low temperature compared to the ground temperatures. For Albedo maps, clouds give a very high albedo compared to the albedo found without clouds. These deviating data points are considered as outliers by HANTS. By using this difference between infested data by clouds and clean data, the cloudy pixels are replaced by an interpolated value created by HANTS. To make the algorithm of HANTS work, a large time series is needed because this increases the amount of cloud free pixels that are used for the interpolation. The overpass frequency of the Landsat satellites is too low and the resulting data series are too small for HANTS to work properly. For this reason, the freely accessible PROBAV-V and VIIRS satellites that have a high overpass frequency are used.

The Harmonic Analysis of Time Series (HANTS) algorithm uses Fourier series for harmonic analysis with curve fitting in iterative steps. The Fourier series is used to find and reconstruct the data as the sum of a sinus and a cosines function. Changing parameters in the Fourier series is the key component to get the best fit for the data. The used Fourier series in HANTS is (Alfieri et al., 2013):

$$y(t) = a_0 + \left[\sum_1^{nf} a_i \cos(2\pi f_i t_y) + b_i \sin(2\pi f_i t_y) \right]$$

The Fourier series above is used to make a signal that fits best for the data where cloud removal needs to be conducted. An off-set threshold (FET) is used to determine the outlying pixels, which are mainly clouds. The Fourier series is applied to the time series of each pixel of the data. This means that all available days are used to find a formula fit for the particular pixel, by excluding the outliers. Finding the best fits means trying a different FET (off-set threshold) but also a different number of frequencies (NF) for the Fourier series. By trying different combinations, a visual inspection can be made to determine the best fit. When the best fit is chosen, the data can be converted to daily TIFF files. The data for a certain pixel where outliers are found are replaced by the data modelled by the Fourier series. Where the data is not seen as an outlier, the original data is used.

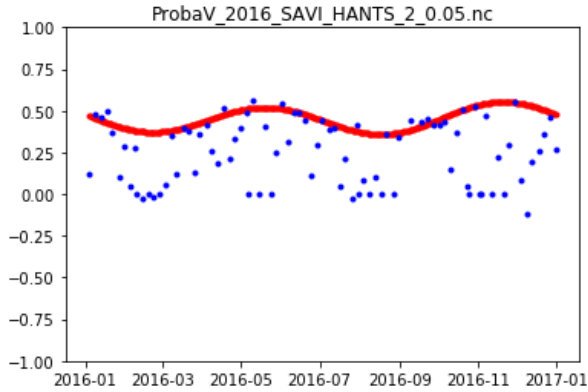


Figure 9 FET=0.05 and NF=2

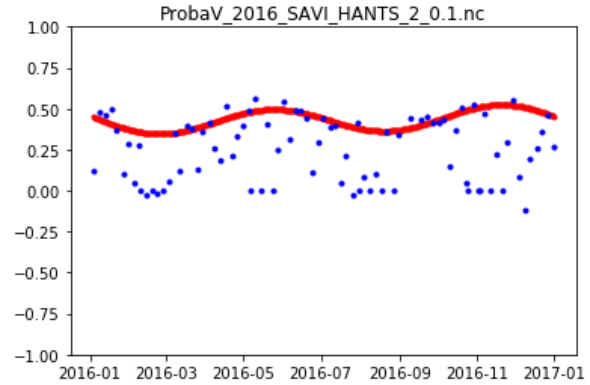


Figure 10 FET=0.1 and NF=2

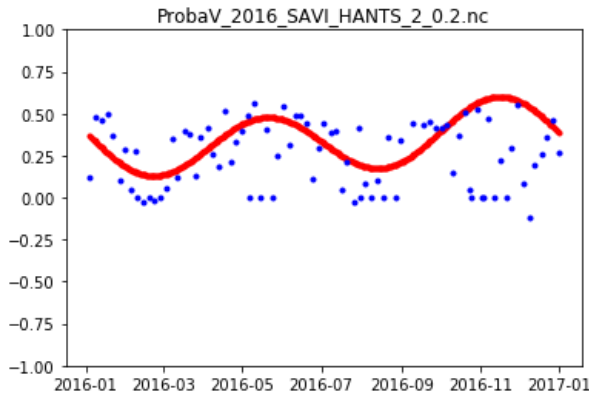


Figure 11 FET=0.2 and NF=2

For Figure 9, Figure 10, and Figure 11 the visual inspection can be done. A best fit should be checked for more than one pixel in order to choose a final best fit.

2.3. Crop Classification

Each food crop has a specific yield factor, which is used to determine the yield from the SEBAL biomass output maps. To determine the yield which is required for the Water Productivity maps, the land use in the concerned area needs to be classified. In the conducted pilot project in Indonesia the focus is on rice paddies. The classification is therefore used to isolate the areas where rice is grown.

The method used for the crop classification is Google Earth Engine (GEE). This software is available online and is free to use. This method has several advantages. Firstly, GEE is run on Google servers. This means that all the data (for example Landsat 8 images) is available and does not require the user to download the data. This means that the area and time frame for which the classification is performed can be easily changed without the need of additional data downloads. The second advantage is that the calculations using GEE are performed on the servers itself, reducing calculation times and the need for workspace on the user's computer. GEE also has built-in algorithms to perform many of the required calculations making the classification easier.

The classification of the rice paddy is performed using Landsat 8 (L8) data. This data is available approximately every 16 days for areas in Indonesia. The data from L8 is filtered on the period of classification and the study area using GEE to reduce calculation times. The resolution of the L8 data is 30m x 30m per pixel. From the L8 data all bands are used except for B10 and B11. This choice has been made as these bands do not yield big enough differences between land use classes to be able to make a classification based on these bands. The L8 images are masked, removing any pixels with a cloud cover above the threshold of 40%.

The next step in the classification process is to create a training map. This training map is used to feed into the algorithm which will determine the classification. In the study area the most important landscape classes are identified, in this case: rice paddies, urban areas, water bodies, forest areas, agricultural areas (all except for rice paddies) and shrimp ponds. These classes can differ per study area. Using GEE, some classes can be identified using visual inspection of the L8 images, for example water bodies and urban areas. For some classes ground truth data is gathered in order to create the training image. In GEE the polygons are drawn for each of the classes. The polygons are combined to create the final training image. The image can consist of data gathered on the ground or of data gathered from satellite data, or a combination of the two.

In GEE the training image is used to create a classification map by using the Classification and Regression Trees (CART) algorithm (Classification and Regression Trees, Stone et al., 1984) This will train the classification using the data from the training map and the L8 data and create a new raster map where all pixels will be assigned a class.

2.4. Creating the Water Productivity map and other outputs

When the output of SEBAL and the Crop classification is combined the Water Productivity maps can be made. This last step is done using QGIS (or any other Geographic Information System software).

The first step in QGIS is interpolating all the biomass maps to determine the biomass for each pixel per day. Hereafter, the biomass is cumulated for the entire growing season, resulting in the total biomass of the concerned growing season per pixel. This is the input for calculating the yield, which is expressed according the following formula:

$$Yield = Bio * H$$

Where B_{io} is the accumulated biomass and H the Harvest Index (or Yield factor). For each pixel in the crop classification layer a certain Harvest Index is given corresponding to the crop type of that pixel. Conducting a raster calculation, using the total biomass layer with the crop classification layer, results into the determined Yield for each pixel.

Finally, dividing the Yield raster layer by the Evapotranspiration map results in the Water Productivity map for the concerned area.

SEBAL produces a wide range of outputs which can be useful for several applications and can be used to complement the WP maps. These outputs may be just as valuable as the WP maps themselves in the analysis of the area. Besides the ET and Biomass production maps SEBAL also produces maps for: Clouds masks, Energy balance, Meteorological data, Radiation balance, Soil moisture and Vegetation. For example,

the E and T fluxes are generated separately as well as combined, both potential and actual. This allows to create a map of the ET-deficit in the study area, or a map of the ratio of beneficial vs non-beneficial water use (T vs ET). Another example is the creation of maps of the different components of the energy balance (as described above) which can be used for analysis or validation of the model. This allows for a wide application of the SEBAL results.

2.5. Ground Truth (GT)

The preliminary Water Productivity maps can give a first impression on what areas have a lower or higher water productivity compared to other areas. To both validate and enhance the WP outputs ground truth measurements are used. Additionally, these ground truth measurements contribute to developing hypotheses on the WP maps.

To improve the crop classification maps, land types must be classified on the ground throughout the concerned area. This will function as additional input in the classification algorithm to enhance the accuracy of the crop classification. The quick analysis of crop type in the fieldwork area is performed by using an app named *ODK Collect*. The collection page called 'quick mode' is used in which crop type, GPS coordinates, and remarks can be added. The quick mode points are collected by driving around through the fieldwork area and filling in the app along the way.

To understand the output of the Water Productivity maps and explain the differences, further in-depth research is conducted on the context of the concerned areas. Important factors which could influence Water Productivity in areas of interest are identified using the same *ODK Collect* app. However, for this analysis other collection pages named 'normal mode – no farmer' and 'normal mode – with farmer' are used, depending on the presence of a farmer in the field. These normal modes include analysis of crop phase, crop conditions, water supply systems, weed presence, and a notation of the coordinates. Additionally, in the normal mode with farmer questions on the yield, pests, water shortage, and planting seasons are asked.

The pages which have been filled in on the app are uploaded to a private webpage in which CSV, KML, and JSON files can be generated and downloaded. The csv files can then be exported as a vector layer in QGIS. All the information which is filled in in the app will appear in the attribute table of the layer. In this way a quick analysis can be conducted on whether SEBAL and the ground data correspond and hypotheses can be developed on the causes of either high or low water productivity.

The information of the quick mode points for the crop classification can be downloaded in a csv file from the private webpage and used as classified coordinates in Google Earth Engine for improvement of the training map.

In addition to the data collection through the *ODK Collect* app, in-depth interviews are conducted with various Klempok Tani chairs, Subak chairs, and institutes such as the PPL of the provinces and the Balai BBWS and PDSA of the catchments. The aim of these interviews is to gain insights into specific topics such as planting seasons in the area, pest outbreaks, water distribution, water shortage, and floods. The relevant information from these interviews will be included in the field data vector layer in QGIS for further analysis. Additionally, any relevant data records are obtained from the institutes, such as records on yield, and maps of soil type. These data sets are used for analysis and for the development of the hypotheses.

2.6. Comparing the SEBAL outputs to the GT

To understand the causes behind the spatial distribution of the SEBAL outputs, the data which is obtained through GT interviews is compared to the SEBAL maps. Understanding the causes is useful for both verifying

SEBAL and generating an impression of which areas are of priority to invest in. As mentioned before, a wide variety of factors affect either the biomass growth, the evapotranspiration, or both. This research focuses only on a selection of these factors. The selected factors are considered to be useful in obtaining a rather quick impression on spatial variation in Water Productivity (WP), while taking into account the relative short time span of the research as well as access to and/or existence of certain data. To illustrate, water availability has a positive relation with both biomass and evapotranspiration. When there is sufficient water, biomass will be higher, as well as the evapotranspiration, compared to a scenario where there is insufficient water. However, it is context dependent to what extent these relations hold. When for example a farmer has sufficient water, and therefore uses more water than is optimum for rice plants, this can result in lower biomass and more evapotranspiration. The interlinkage of all factors and the fact that all factors are context specific, reveals the complexity of the topic. This complexity should be taken into account when aiming to explain what factors are the prime drivers behind Water Productivity values. Therefore, it is most effective to focus on the somewhat more accessible data and knowledge, when aiming to obtain insights in the WP distribution and when evaluating the SEBAL method.

To understand these complex relationships slightly better and thus verify whether SEBAL can give a first impression of areas of interest to invest into, the available ground data is analysed and compared to the SEBAL outputs. This analysis is a *quick and dirty* analysis. Therefore, to be certain of the relationships, further statistical analysis should be conducted of larger data sets. However, this is outside of the scope of this research. The results of the analysis of this research are suitable to get a *first impression* of which factors are worth looking into in the field and conducting further research on.

3. Results – Maps

Below the results from SEBAL are provided for the study areas of Bali, Java, and Lombok. Additionally, the results of SEBAL using HANTS for the Java site are presented. The WP maps and the maps used to produce the WP maps will be presented first, followed by additional SEBAL output maps for a more detailed overview.

3.1. Bali

When aiming to compare WP, ET, and Yield values in one study area, one single paddy season should be considered. After a thorough analysis of the Landsat images, of biomass maps from SEBAL trial runs, and after asking various institutes and Subak members, the decision has been made to analyze a Balinese paddy season from the 12th of June up to including the 15th of October 2016. Therefore, the maps in this chapter correspond to this period.

3.1.1. SEBAL Results Bali

Crop classification

In order to use the SEBAL model for Bali, first a land use classification must be made. As described in the methods this is done using Google Earth Engine (GEE). To improve the training maps ground truth (GT) data is collected for the classification. The data gathered from satellite images is supplemented with this GT data to make the final classification. All SEBAL outputs will be masked with the Rice paddy landscape class for this study, since the focus is primarily on this land use class. The classification map for rice paddies on Bali can be seen in Figure 12.

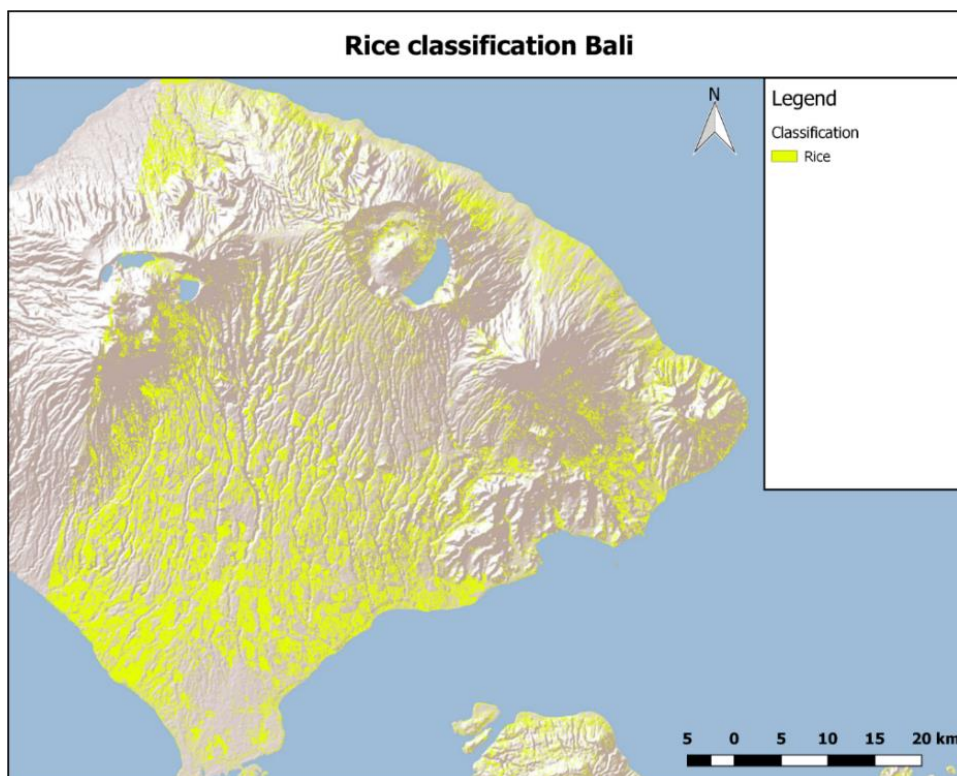


Figure 12: Rice classification map Bali

Evapotranspiration

The map which represents evapotranspiration (ET) is shown in Figure 13. The ET ranges from 207mm to 1041 mm. The mean value for the ET is 506 mm with a standard deviation of 60 mm. As can be seen in the histogram of ET (Figure 14). The majority of the pixels values are between 400 and 600 mm of evapotranspiration for the entire period. Most of the pixels with the higher ET are found in the southwest part of the map near the ocean (Figure 13).

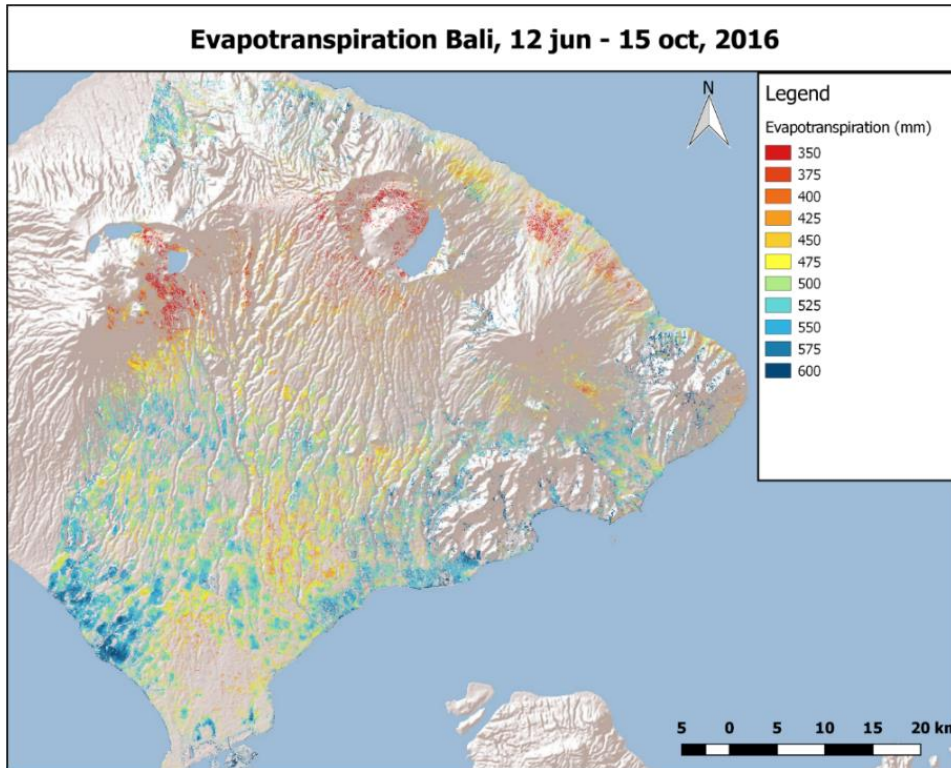


Figure 13: Map of the ET (mm) for Bali, 12Jun – 15Oct, 2016

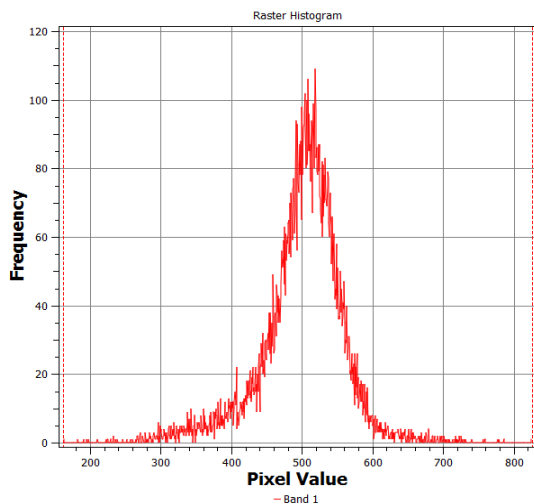


Figure 14: Histogram of the Evapotranspiration (mm) for the Rice paddy pixels Bali, 12 Jun – 15Oct, 2016

Biomass production

The Biomass production (BP) for the cells classified as Rice paddies ranges from 0 until 22.3 ton/ha. An area with a relatively high BP can be found in the southeast of Bali (Figure 15). The mean BP value of the study area is 12.3 ton and a standard deviation is 2.7 ton. The histogram of Figure 16 shows the distribution of the BP for all the classified rice paddy pixels. The histogram shows that the majority of the pixels have a BP between 5 and 18 ton/ha. The results from the total BP map over the period are used to determine the yield map.

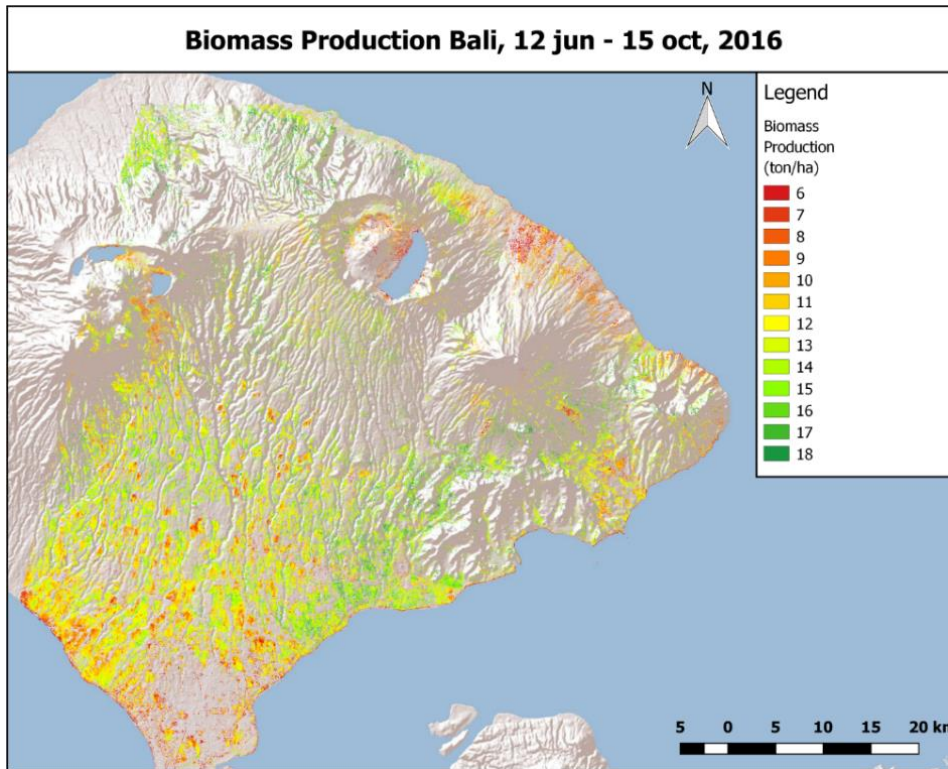


Figure 15: Map of the Biomass Production (ton/ha) for Bali, 12Jun -15Oct, 2016

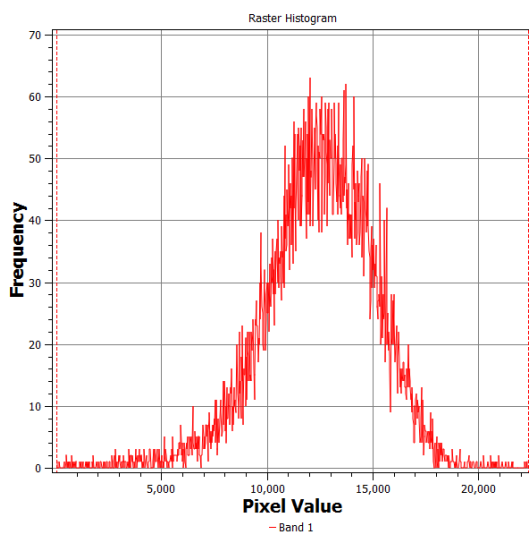


Figure 16: Histogram of the Biomass production (kg/ha) for the Rice paddy pixels Bali, 12 Jun – 15Oct, 2016

Yield

The yield is determined by multiplying the BP map with a yield factor. This factor is determined from the GT collected during the fieldwork (see Figure 104 of the Appendix for the locations of these GT points). By comparing the BP map with the yields found in the field an average yield factor can be determined. For this area the yield factor is equal to 0.45. An overview of the yield factor calculation is provided in Table 2 of the appendix. The resulting yield map is shown in Figure 17. The yield for the cells classified as rice varies between 0 and 9.8 ton/ha. The mean is 5.6 ton/ha with a standard deviation of 1.0 ton/ha.

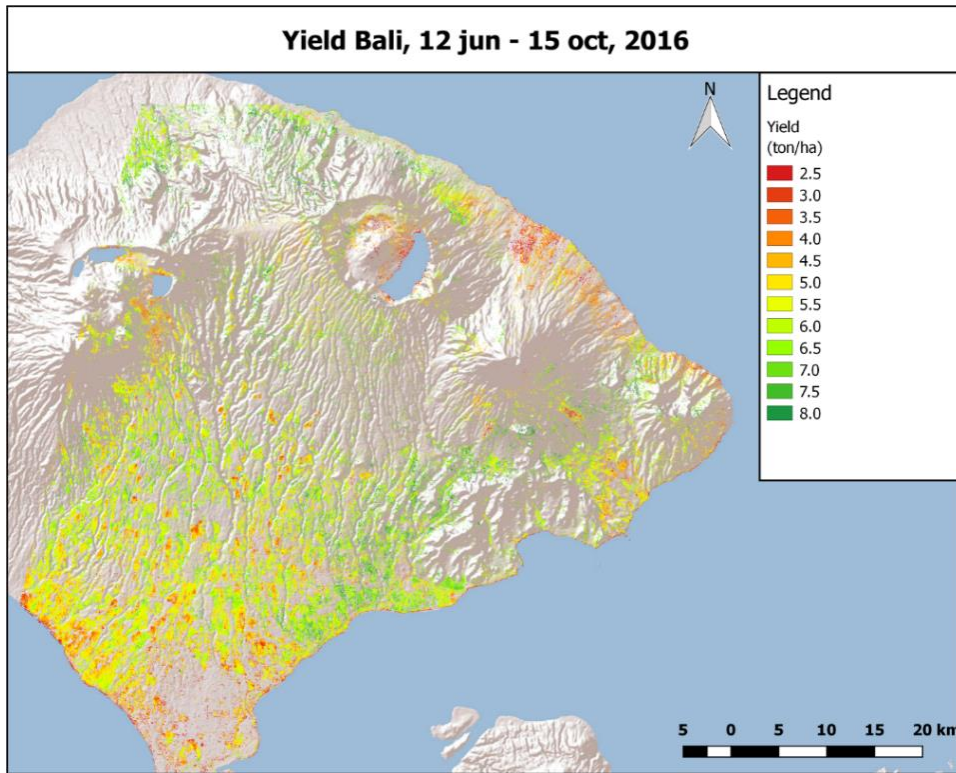


Figure 17: Map of the yield (ton/ha) for Bali, 12Jun – 15Cct, 2016

Water productivity

The water productivity (WP) is determined by dividing the yield by the ET. The map of the WP for the selected paddy season is shown in Figure 18. The WP ranges from 0 to 1.95 kg/m³. The mean is 1.1 kg/m³ with a standard deviation of 0.25 kg/m³. The histogram of the map values (Figure 19) shows the distribution of the WP for all the points classified as rice. It can be seen in Figure 18 that the southwest of Bali shows a concentrated area of low water productivity.

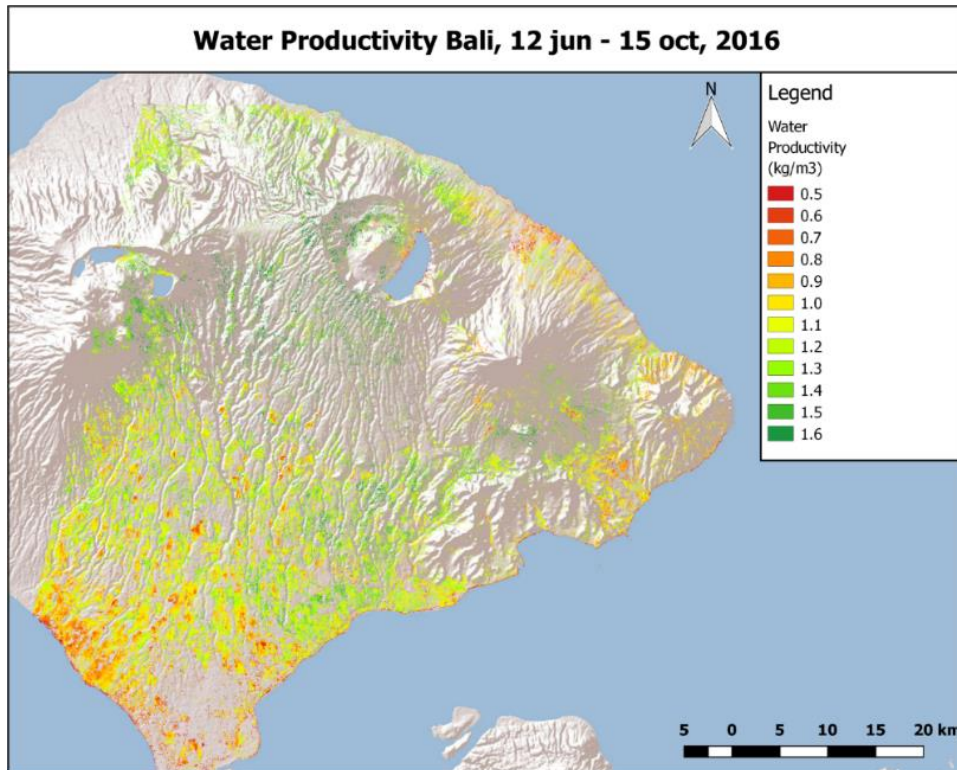


Figure 18: Map of the Water Productivity (kg/m³) for Bali, 12Jun - 15Oct, 2016

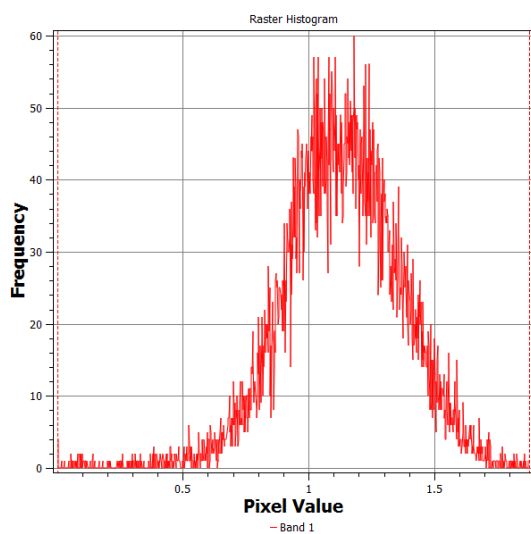


Figure 19: Histogram of the Water Productivity (kg/m³) for the Rice paddy pixels Bali, 12Jun - 15Oct, 2016

ETdeficit

The ET deficit can be found in Figure 20. The Evapotranspiration deficit ranges between 0 and 130 mm. The average is 17 mm and the standard deviation is 17 mm. Normally for irrigated rice the ET deficit of a rice period is between 0 and 30 mm.

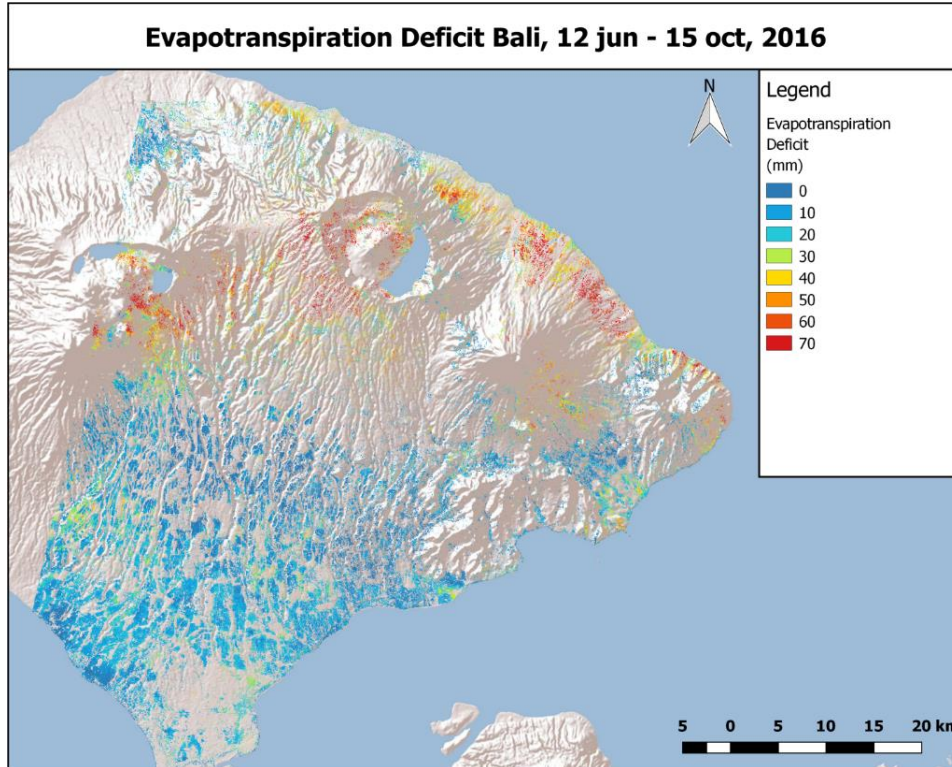


Figure 20: Map of the Evapotranspiration Deficit (mm) of Bali, 12Jun - 15Oct, 2016

Transpiration

The transpiration map can be found in Figure 21. The transpiration ranges from 0 - 450 mm. The average transpiration is 230 mm with a standard deviation of 65 mm. The transpiration can be used to compute the beneficial consumption. The transpiration of the rice plants is the beneficial evaporation which is used for the plant to grow. The transpiration map shows that in the southeast of Bali a higher evaporation rate by transpiration. This is the same area where there is a higher biomass, as can be seen in Figure 15.

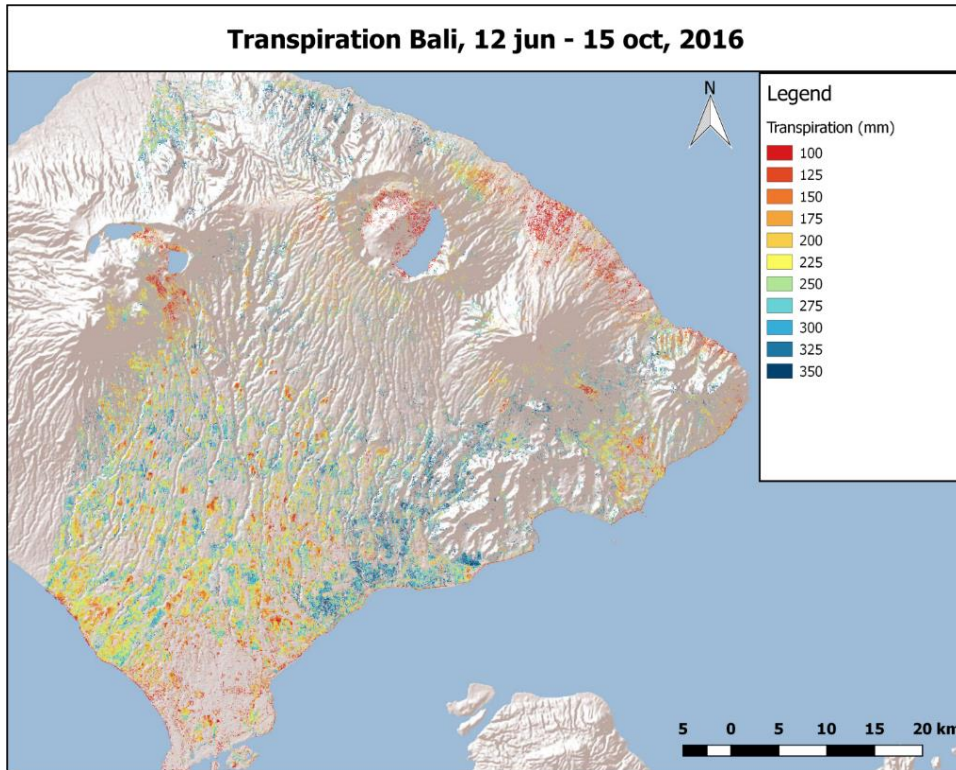


Figure 21: Map of the Transpiration (mm) of Bali, 12Jun – 15Oct, 2016

Beneficial consumption

The beneficial consumption (BC) (Figure 22) is the percentage of the water that is used for the plant to grow (transpiration) compared to the total ET of the field. The BC can be calculated by dividing the transpiration (Figure 21) by the ET. The beneficial consumption varies between 0 and 82%. The average beneficial consumption is 45% with a Standard deviation of 12%.

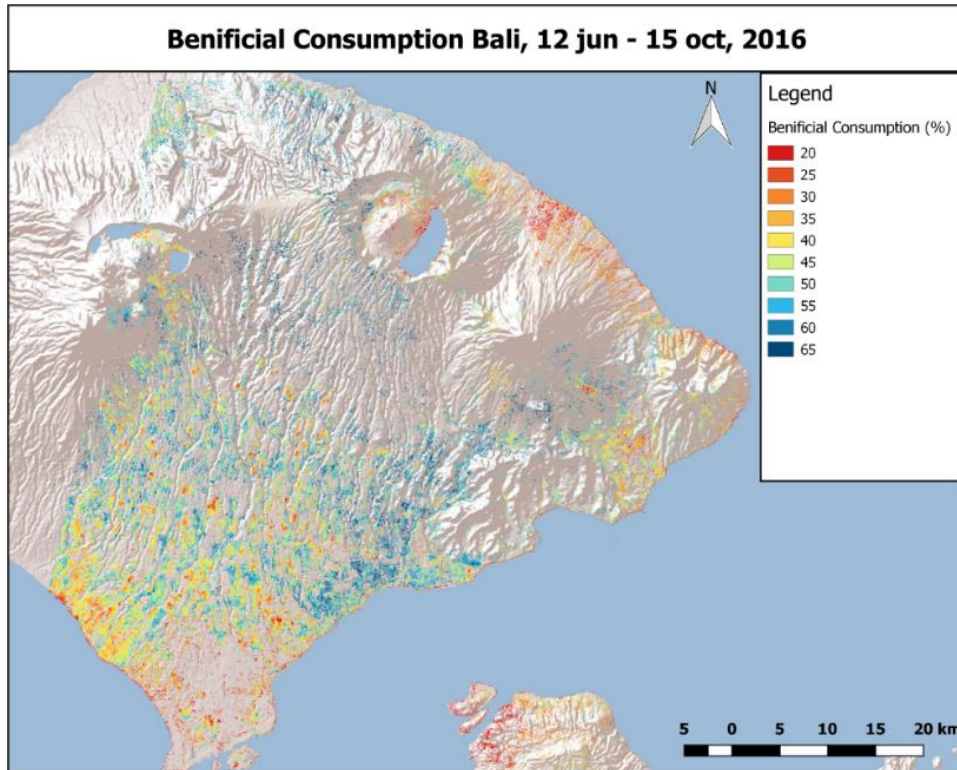


Figure 22: Map of the beneficial consumption (%) of Bali, 12Jun - 15Oct, 2016

3.1.2. Statistical comparison of WP maps

Together the analysis of the ET, yield and WP can provide an overview of the overall performance of an irrigation system and its potential. Maps are made to give a quick overview of the total system and areas of interest can be identified. This can be areas with a high or low ET, yield or WP. Once these areas are identified, extensive research is necessary to get a clear understanding of the situation at a specific location and why it is performing the way it does. In this pilot study a start has been made with the analysis of the study areas to get an idea of the possible causes for a high or low ET, yield and WP.

In Figure 23 the WP is plotted versus the yield of the pixels identified as rice for Bali. The graph clearly shows that all points fall in a shape that is defined by a linear line at the bottom and a nonlinear line at the top. This plot shows that there are farmers which are more water efficient with the same yield and thus have a higher WP. Additionally, there are farmers which are more productive, but also use more water. They produce more yield with the same WP. Furthermore, there are many farmers with a low yield and a low WP (the points close to (0, 0)).

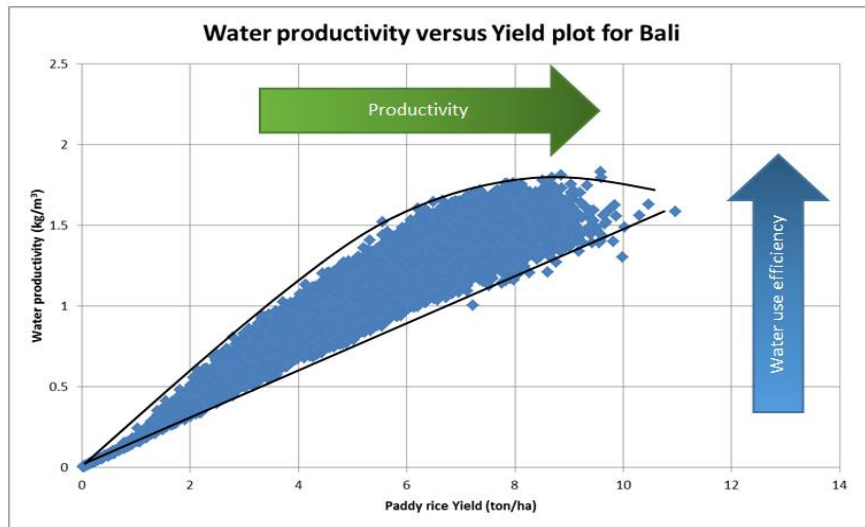


Figure 23 Water productivity versus Yield plot of Bali, 12Jun - 15Oct, 2016

Ideally, every farmer would improve both its yield and WP and move to the upper right corner of the plot. However, this is not possible for all farmers due to numerous factors such as water availability, soil quality, and social economic influences. Nevertheless, it is possible to identify areas where targeted investments could potentially make a difference. For example, a map can be created with rice pixels performing above and below average to obtain a quick overview of the areas of interest (Figure 25). It is also possible to identify the pixels with a high or low average WP (the average \pm 1 STD) as can be seen in Figure 24. The same maps can be made for both yield and ET to obtain more detailed areas of interest.

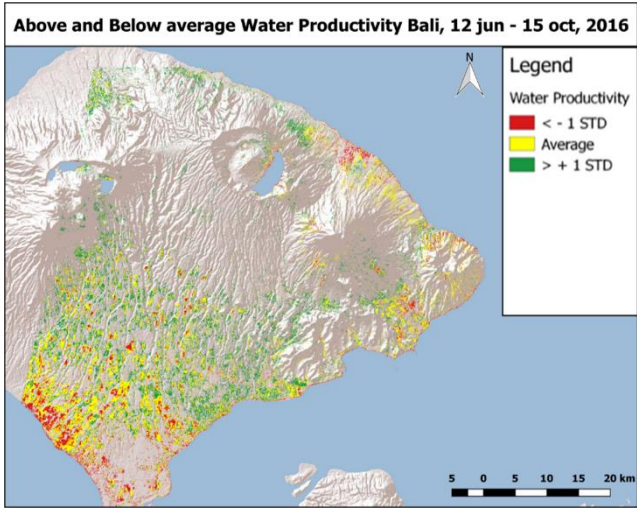


Figure 24 Map of one STD above and below average water productivity of Bali, 12Jun - 15Oct, 2016

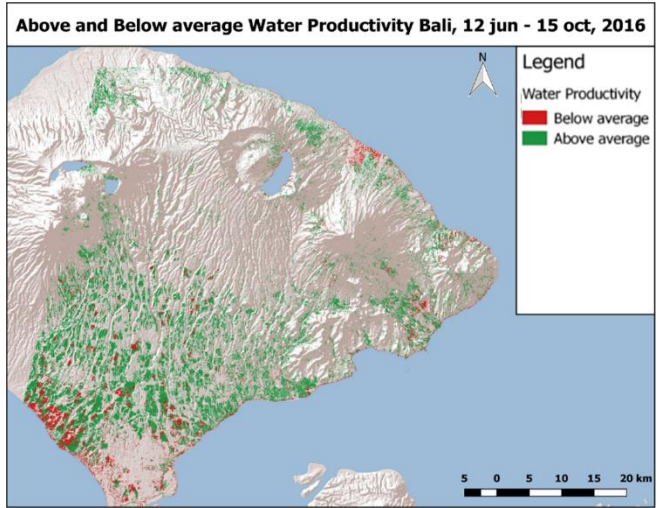


Figure 25 Map of above and below average water productivity of Bali, 12Jun - 15Oct, 2016

3.2. Java

Similar as for the Bali site, the months of one paddy season are identified based on outputs of SEBAL trial runs, Landsat images, and GT data. For the Java site the selected period is the 15th of June up to including the 15th of October.

3.2.1. SEBAL Results Java

Crop Classification

Like Bali, a crop classification for rice using GEE and GT data is conducted for Java too and will be used as paddy mask for all SEBAL outputs. The resulting rice classification for the Java site and the irrigation scheme which is used for these paddies is shown in Figure 26.

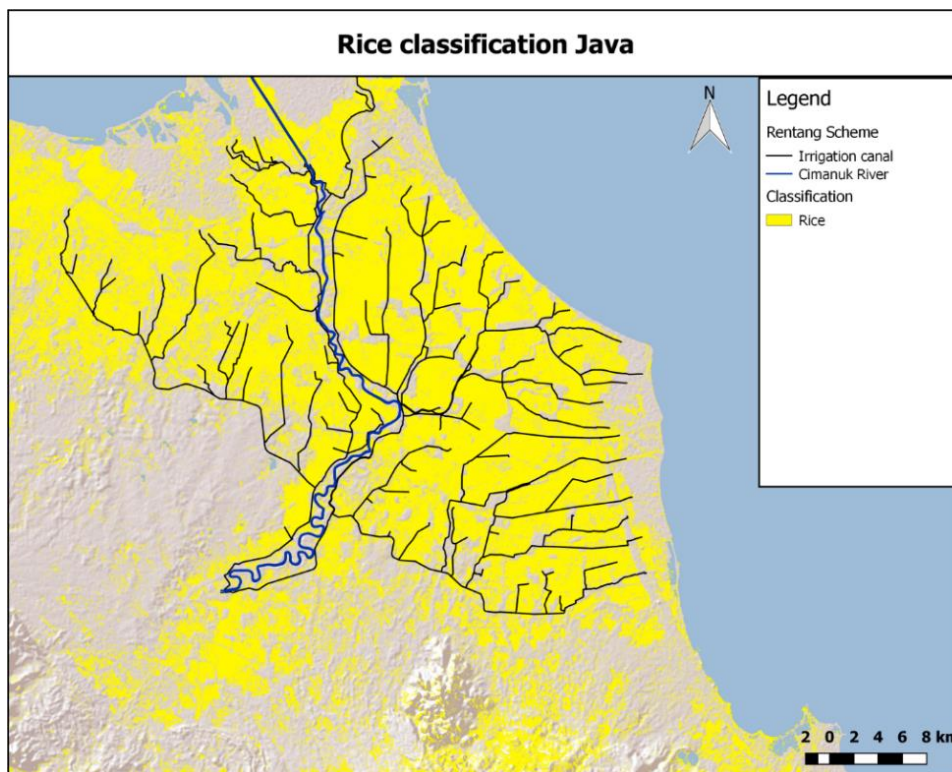


Figure 26: Rice classification Java

Evapotranspiration

The evapotranspiration (ET) map of Java is provided in Figure 27 and the corresponding histogram in Figure 28. The ET ranges from 38 to 685 mm and the average ET is 473 mm with a standard deviation of 85 mm. The ET map shows that near the coast the ET is higher than further inland.

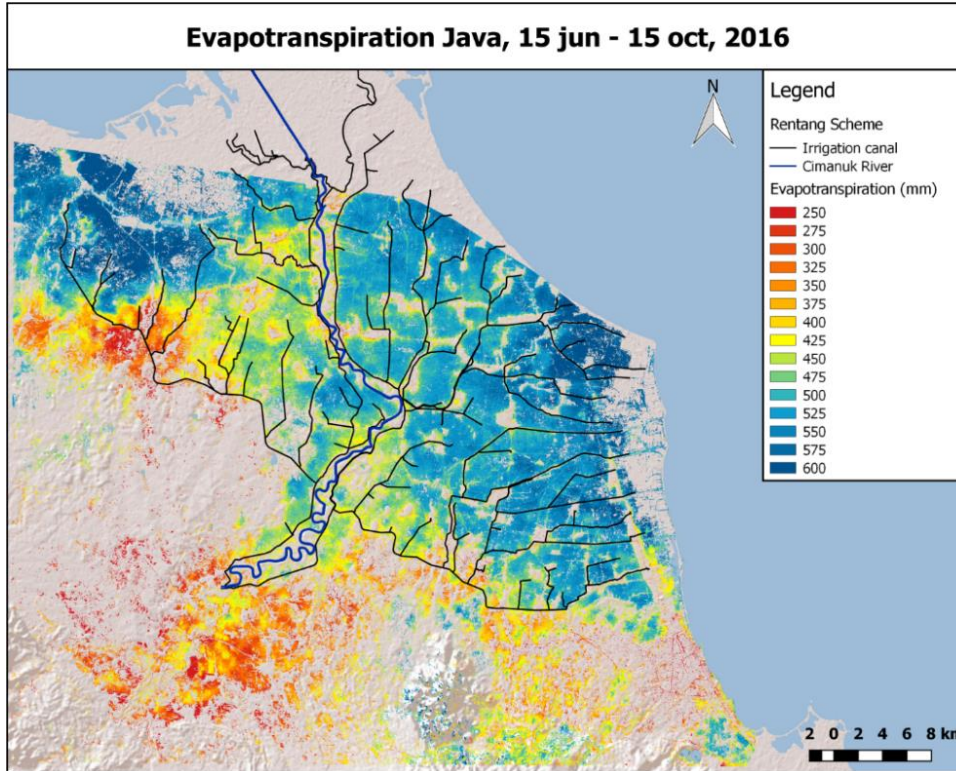


Figure 27: Map of Evapotranspiration (mm) for Java, 15Jun – 15Oct, 2016

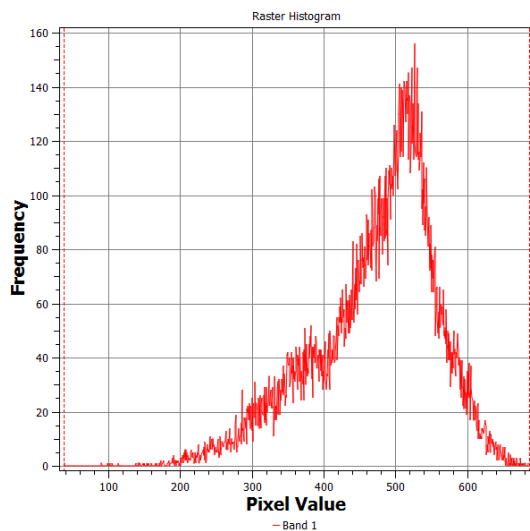


Figure 28: Histogram of the Evapotranspiration (mm) for the Rice paddy pixels Java, 15 Jun – 15Oct, 2016

Biomass production

The BP map of Java is shown in Figure 29 and the corresponding histogram in Figure 30. The BP ranges between 0 and 16 ton/ha. The average is 7.4 ton/ha with a standard deviation of 2.5 ton/ha. Similar as for Bali, the results of the BP map are used to determine the yield. The highest BP values are detected in the centre of the study area.

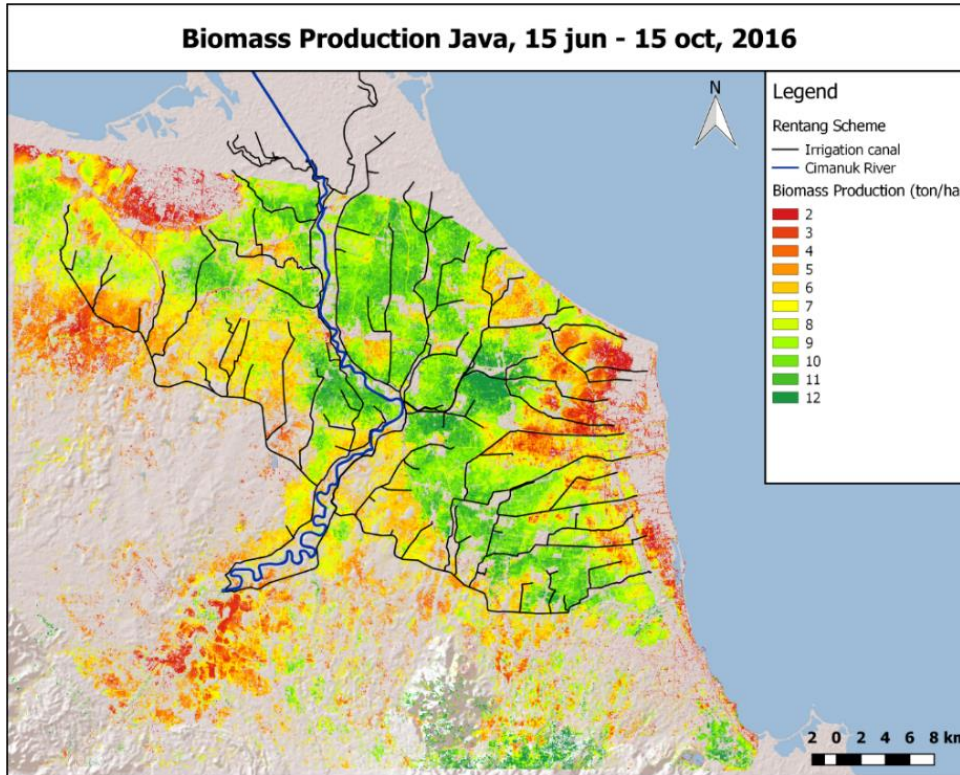


Figure 29: Map of Biomass Production (ton/ha) for Java, 15Jun – 15Oct, 2016

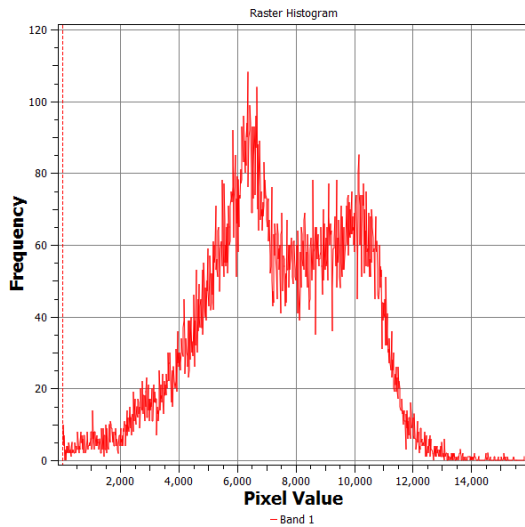


Figure 30: Histogram of the Biomass production (mm) for the Rice paddy pixels Java, 15 Jun – 15Oct, 2016

Yield

The yield is determined by multiplying the BP map with a yield factor. For this area the yield factor is equal to 0.48, determined by comparing the BP map with field data collected from interviews with farmers. The GT data points on which this yield factor is based are provided in Figure 114 of the appendix and the table of the yield factor calculation can be found in Table 3 of the appendix. In contrast to the Bali site, no yield data from institutes could be obtained for Java. This data did either not exist or the institutes were not willing to share it. The resulting yield map for Java can be found in Figure 31. The yield varies between 0 and 7.6 ton/ha. The average is 3.6 ton/ha with a standard deviation of 1.2 ton/ha.

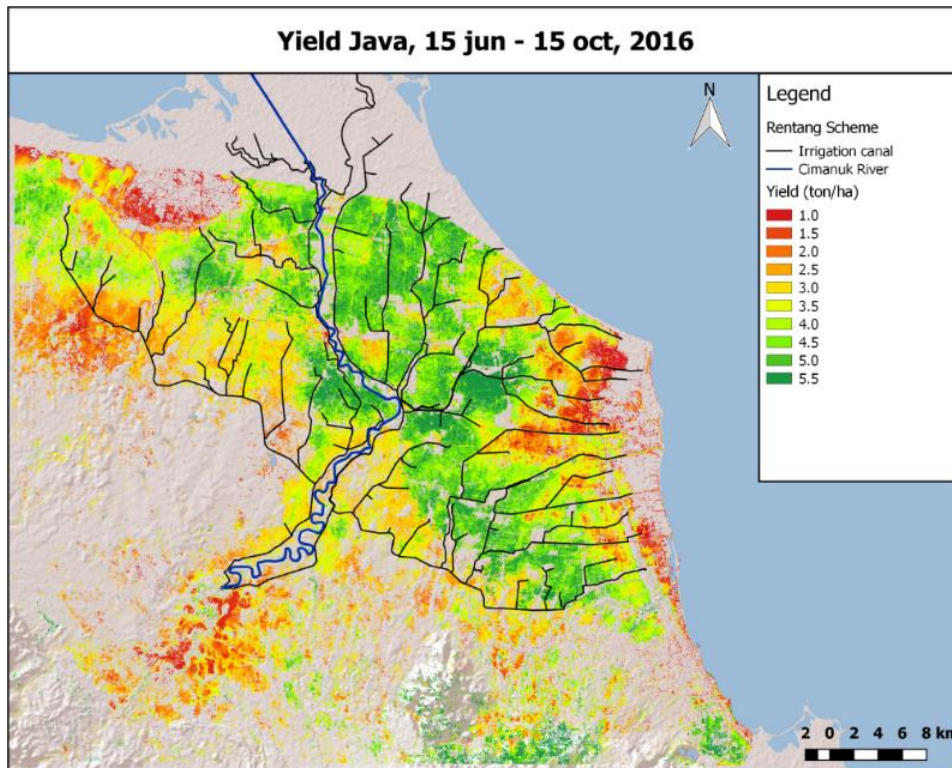


Figure 31: Map of Yield (ton/ha) for Java, 15Jun – 15Oct, 2016

Water Productivity

The WP (Figure 32) is created by dividing the yield map by the ET map. The WP ranges from 0 to 1.6 kg/m³. The average is 0.76 kg/m³ with a standard deviation of 0.24 kg/m³. The histogram can be found in Figure 33. The WP map shows very similar spatial patterns as the BP map.

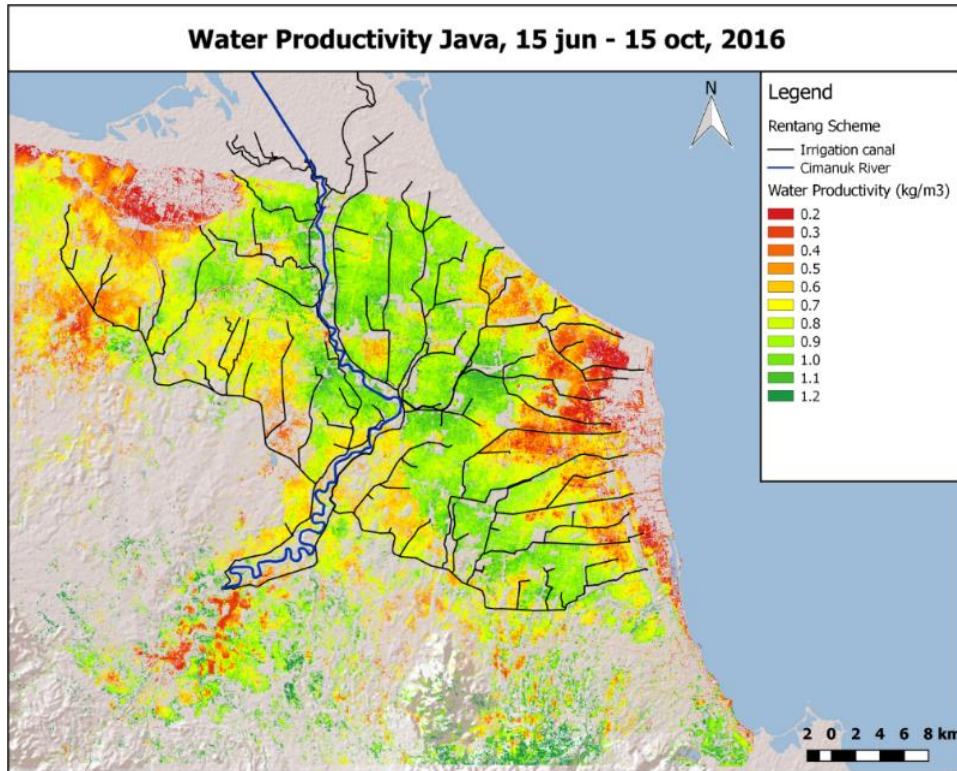


Figure 32: Map of Water Productivity (kg/m³) for Java, 15Jun – 15Oct, 2016

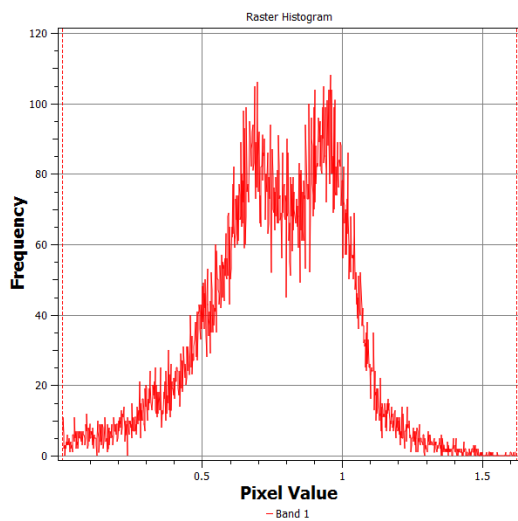


Figure 33: Histogram of the Water Productivity (mm) for the Rice paddy pixels Java, 15 Jun – 15Oct, 2016

ETdeficit

The ETdeficit can be found in Figure 34. The ETdeficit ranges between 0 and 180 mm. The average is 12 mm with a standard deviation of 15 mm.

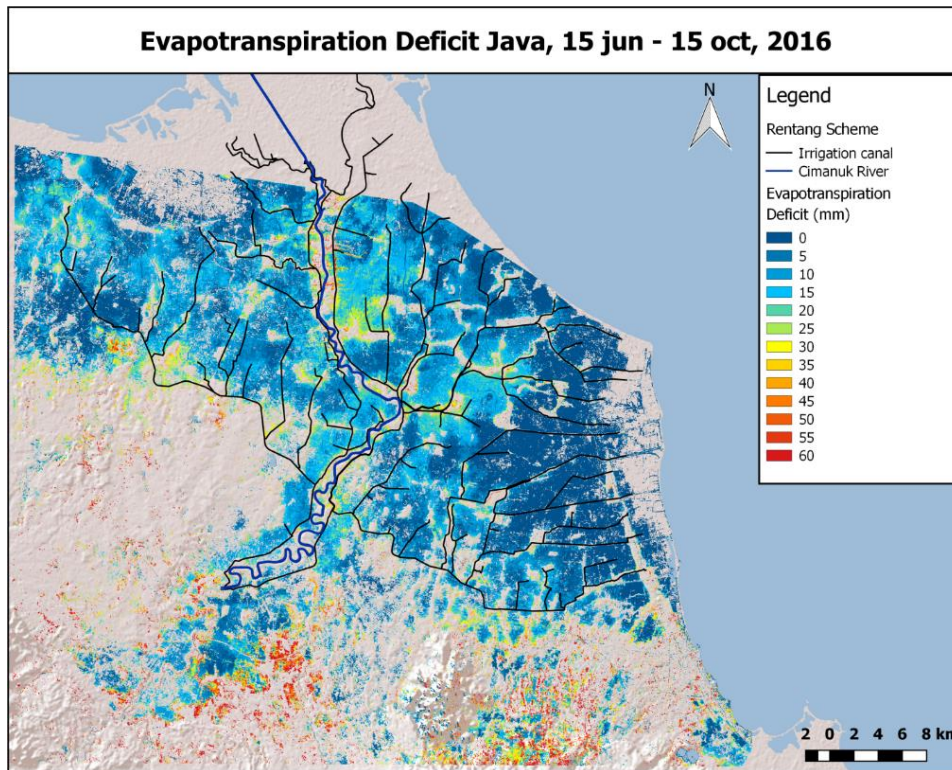


Figure 34: Map of the Evapotranspiration Deficit (mm) of Java, 15Jun - 15Oct, 2016

Transpiration

The transpiration of the rice plants is the beneficial evaporation which is used for the plant to grow. The map of the Transpiration can be found in Figure 35. The transpiration varies between 0 and 392 mm. The average is 173 mm with a standard deviation of 73 mm.

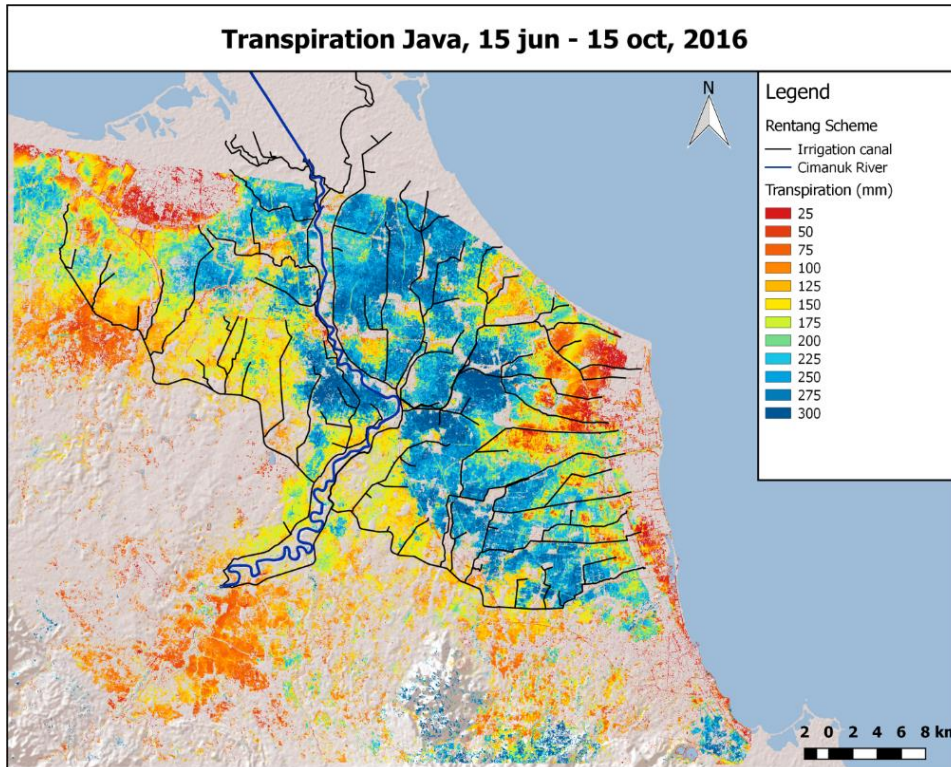


Figure 35: Map of the Transpiration (mm) of Java, 15Jun – 15Oct, 2016

Beneficial consumption

The beneficial consumption (BC) is the percentage of the water that is used for the plant to grow (transpiration) compared to the ET on the field. The BC can be calculated by dividing the transpiration by the ET. The map of the BC can be found in Figure 36. The BC varies between 0 and 90%. The average is 36% with a standard deviation of 13%. The BC is high in the centre of the fieldwork area where the BP is high too.

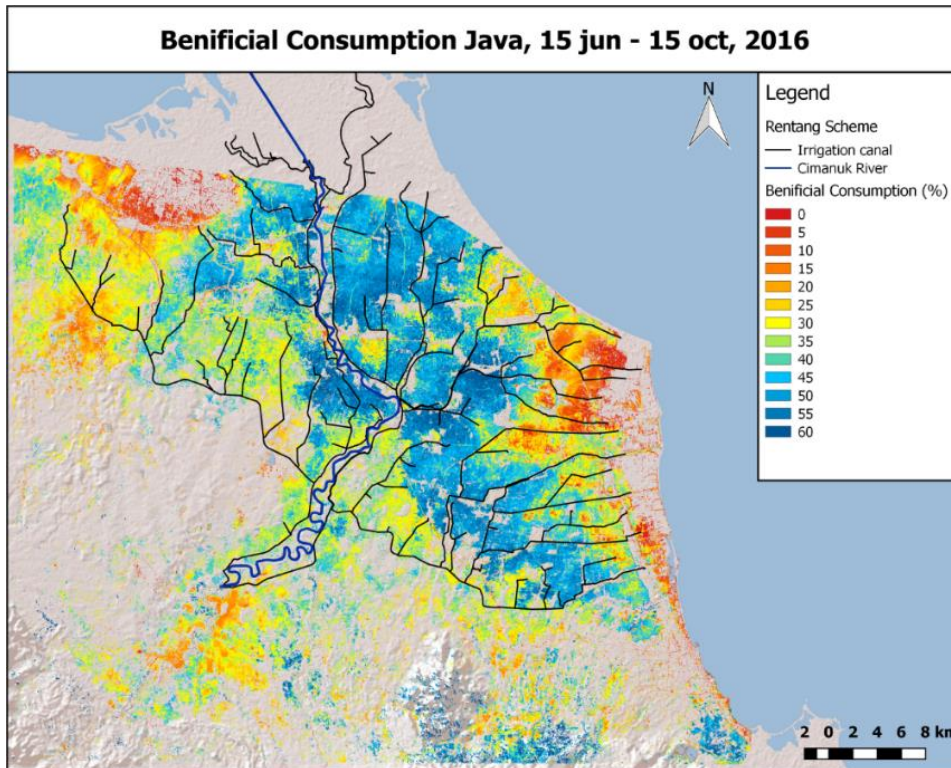


Figure 36: Map of Beneficial consumption (%) of Java, 15Jun – 15Oct, 2016

3.2.2. Statistical comparison of SEBAL

To analyse the SEBAL output maps of Java and define areas of interest the same approach as Bali has been used. Respectively, the WP versus yield plot, the above and below average WP map, and the +/- 1 STD WP map are provided in Figure 37, Figure 39, and Figure 38.

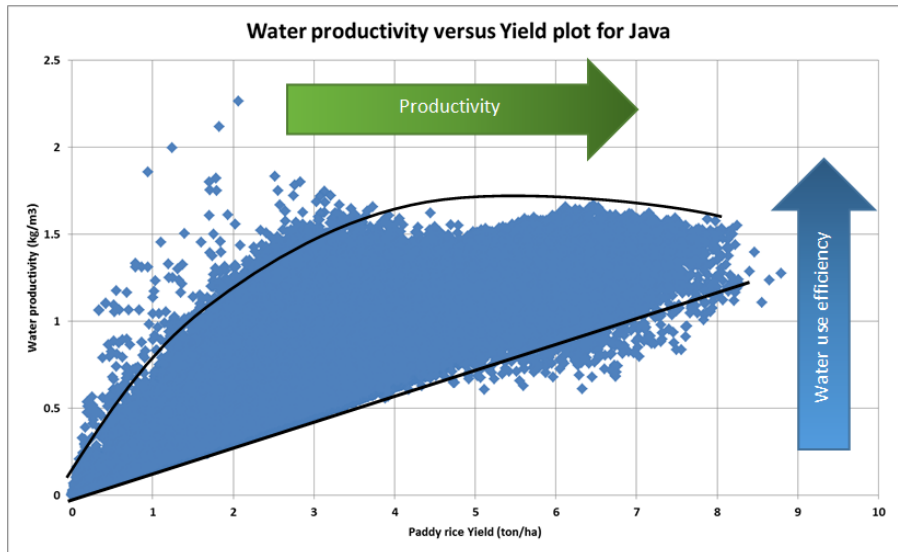


Figure 37: Water productivity versus Yield plot for Java, 15Jun - 15Oct, 2016

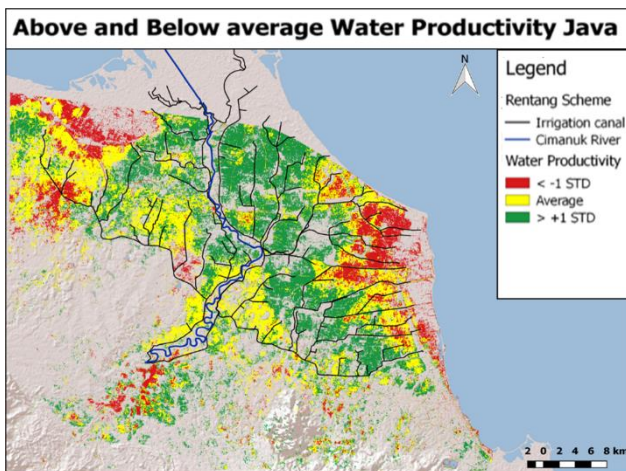


Figure 38 Map of one STD above and below average water productivity for Java, 15Jun - 15Oct, 2016

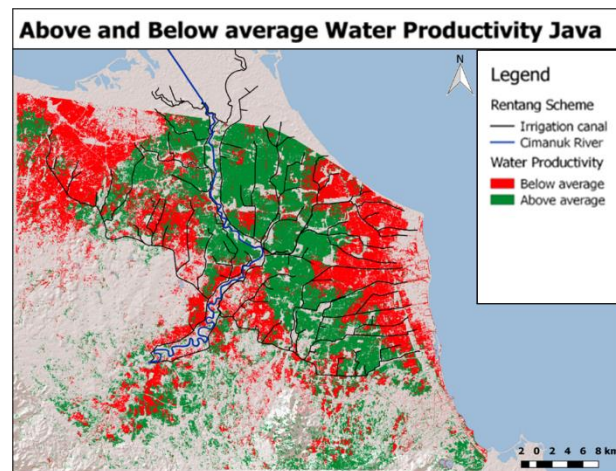


Figure 39 Map of above and below average water productivity for Java, 15Jun - 15Oct, 2016

3.3. Lombok

The SEBAL results of the Lombok can be used to find out how much of the outputs can be understood without visiting the area. The only information used is the open source data of the satellite images and open access weather data. The goal is to see if it is possible to get a first impression of the areas of interest without having to do extensive fieldwork first to gather GT points. For Lombok the same paddy season is used as for Bali, namely the 12th of June up to including the 15th of October.

3.3.1. SEBAL Results Lombok

Crop classification

For Lombok the same classification script is used as the one which is based on Bali. The classification of rice for Lombok can be found in Figure 40.

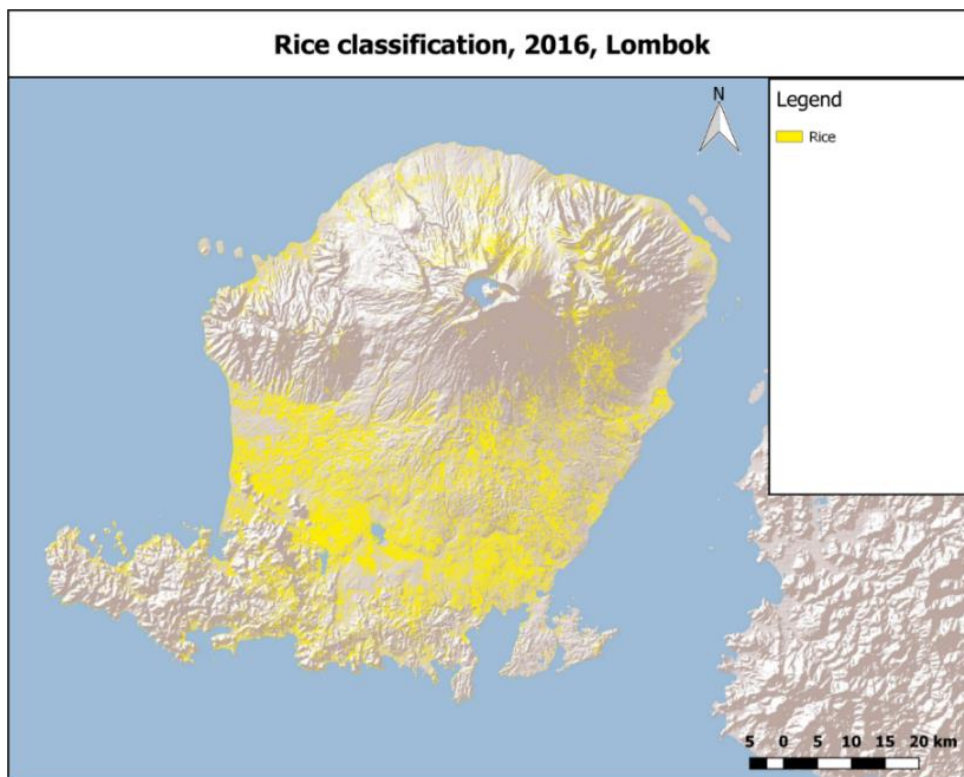


Figure 40 Rice classification map Lombok

Evapotranspiration

The map of the evapotranspiration (ET) for Lombok is provided in Figure 41. The ET ranges from 0 to 817mm and the average is 374mm with a standard deviation of 72mm. The histogram of the frequency of appearance can be found in Figure 42. The ET map shows that the evapotranspiration is high in the southwest of Lombok and low in the southeast.

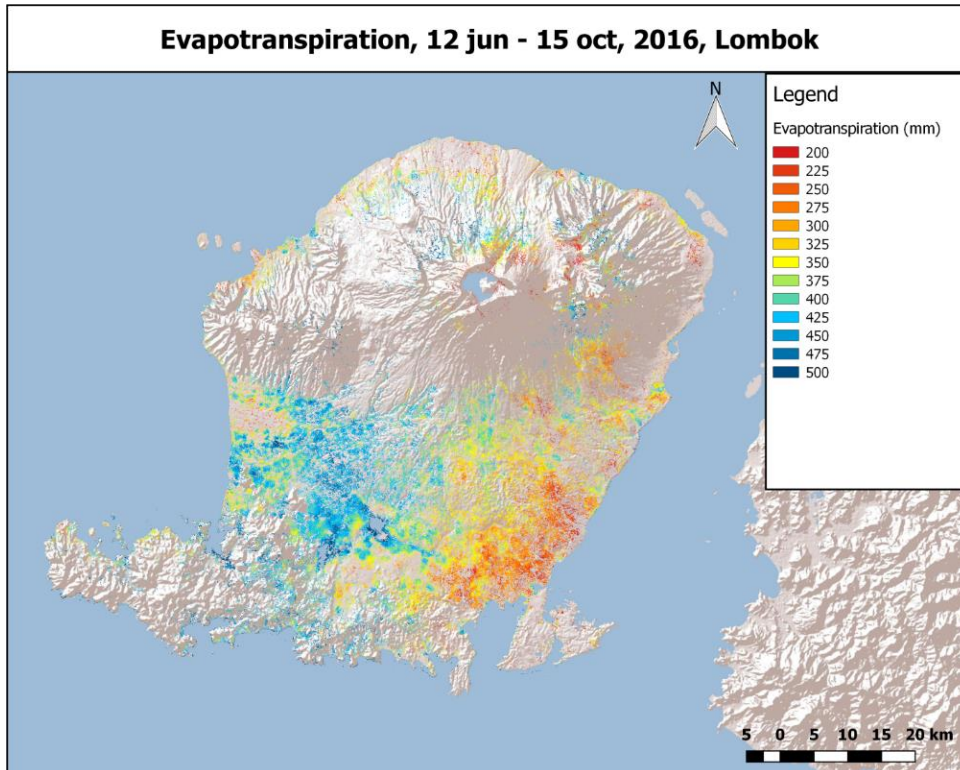


Figure 41: Map of Evapotranspiration (mm) for Lombok, 12Jun – 15Oct, 2016

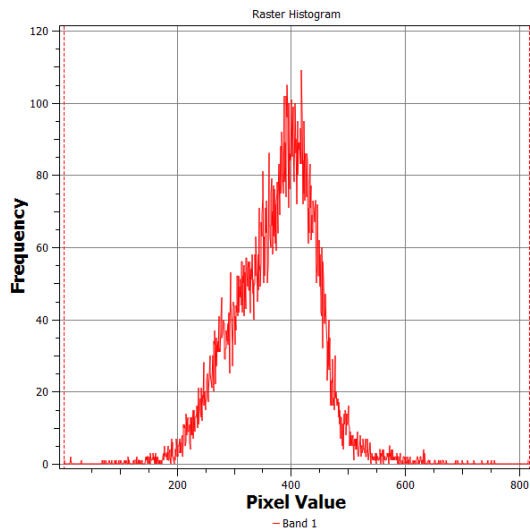


Figure 42: Histogram of the Evapotranspiration (mm) for the Rice paddy pixels Lombok, 12 Jun – 15Oct, 2016

Biomass production

The BP map is portrayed in Figure 43 and the corresponding histogram in Figure 44. The values range from 0 to 24.4 ton/ha. The average is 11.1 ton/ha with a standard deviation of 2.8 ton/ha. According to the map high BP is found in southwest Lombok and low BP in the southeast.

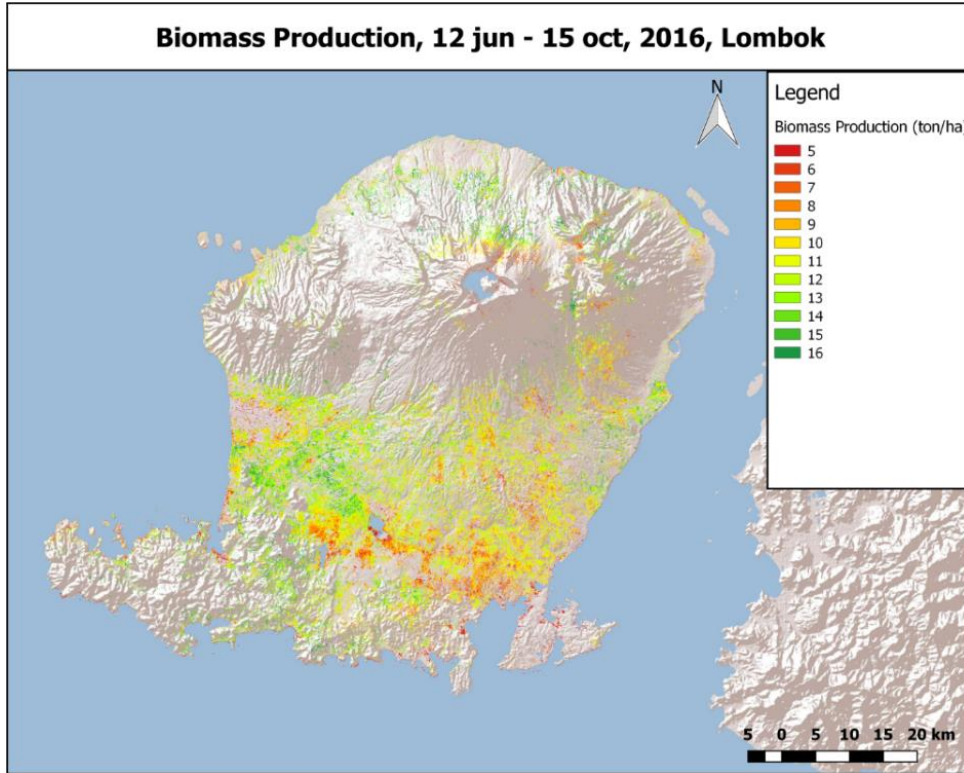


Figure 43: Map of the Biomass Production (ton/ha) for Lombok, 12Jun -15Oct, 2016

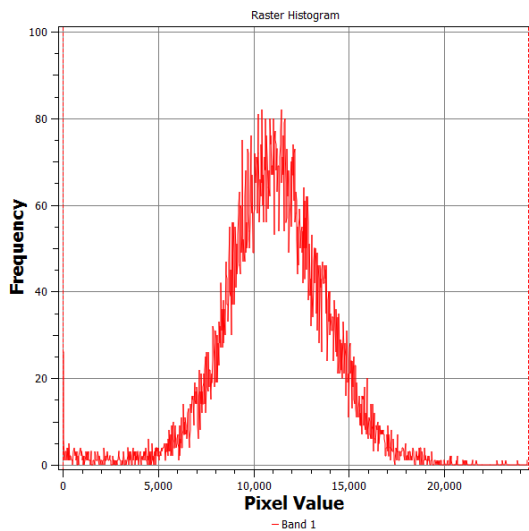


Figure 44: Histogram of the Biomass production (kg/ha) for the Rice paddy pixels Lombok, 12 Jun – 15Oct, 2016

Yield

For Lombok no field data has been collected so verifying the yield factor is not possible. Since Lombok is close to Bali the same yield factor as for Bali is used, this yield factor is 0.45. The map of the yield is shown Figure 45.

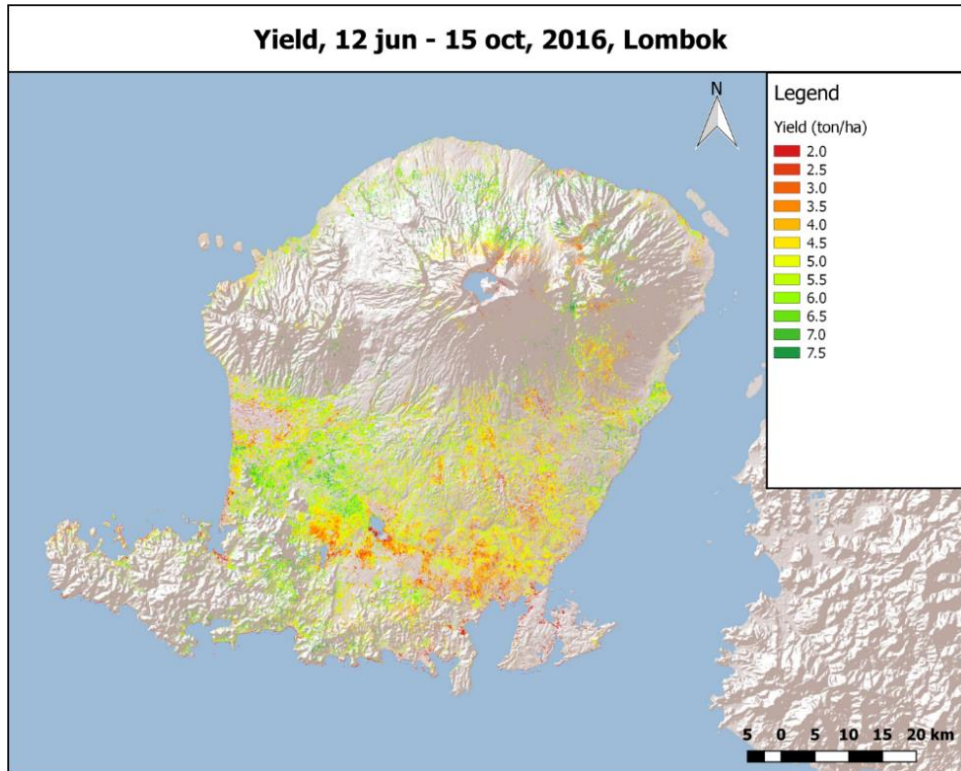


Figure 45: Map of the yield (ton/ha) for Lombok, 12Jun – 15Cct, 2016

Water Productivity

Figure 46 portrays the WP map of Lombok. The WP ranges from 0 to 3 kg/m³. The average WP is 1.4 kg/m³ with a standard deviation of 0.32 kg/m³. The histogram of the WP can be found in Figure 47.

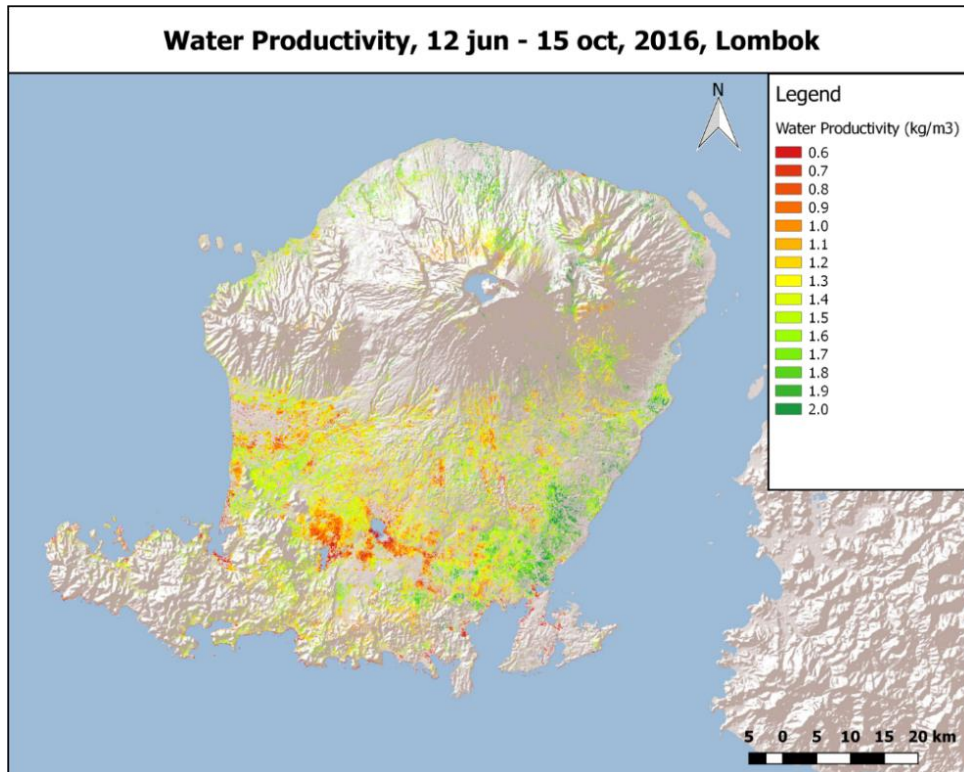


Figure 46: Map of the Water Productivity (kg/m³) for Lombok, 12Jun - 15Oct, 2016

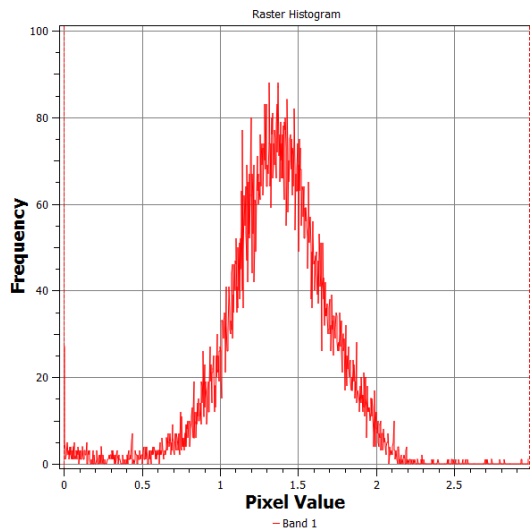


Figure 47: Histogram of the Water Productivity (kg/m³) for the Rice paddy pixels Lombok, 12Jun – 15Oct, 2016

ETdeficit

The map of the ETdeficit can be found in Figure 48. The ETdeficit ranges from 0 to 284 mm. The average is 23.5 mm with a standard deviation of 25.8 mm.

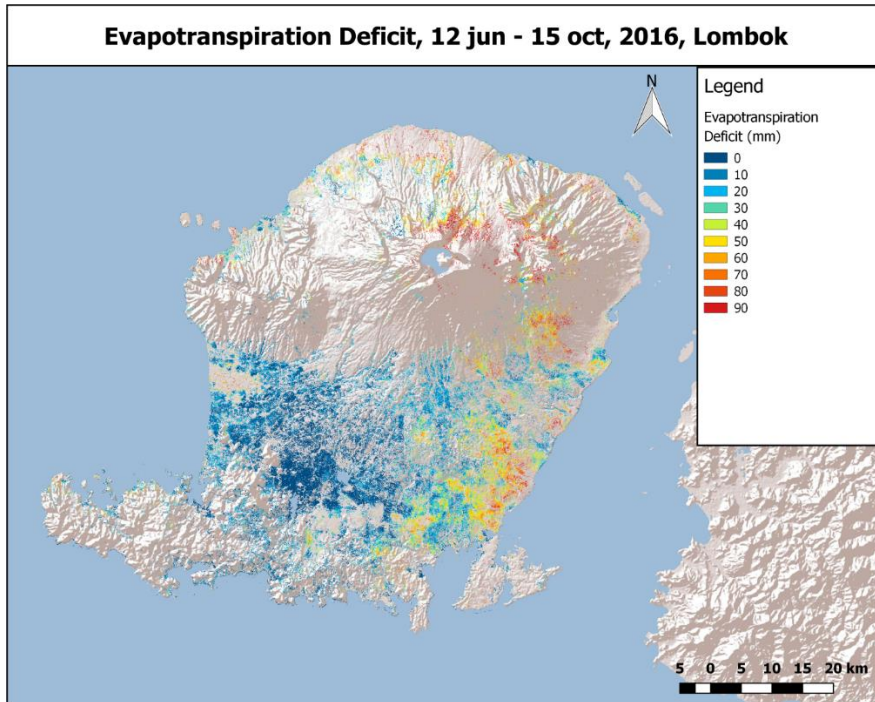


Figure 48: Map of the Evapotranspiration Deficit of Lombok, 12Jun - 15Oct, 2016

Transpiration

The map of the transpiration can be found in Figure 49. The transpiration varies between 0 and 636 mm. The average is 198 mm with a standard deviation of 71 mm.

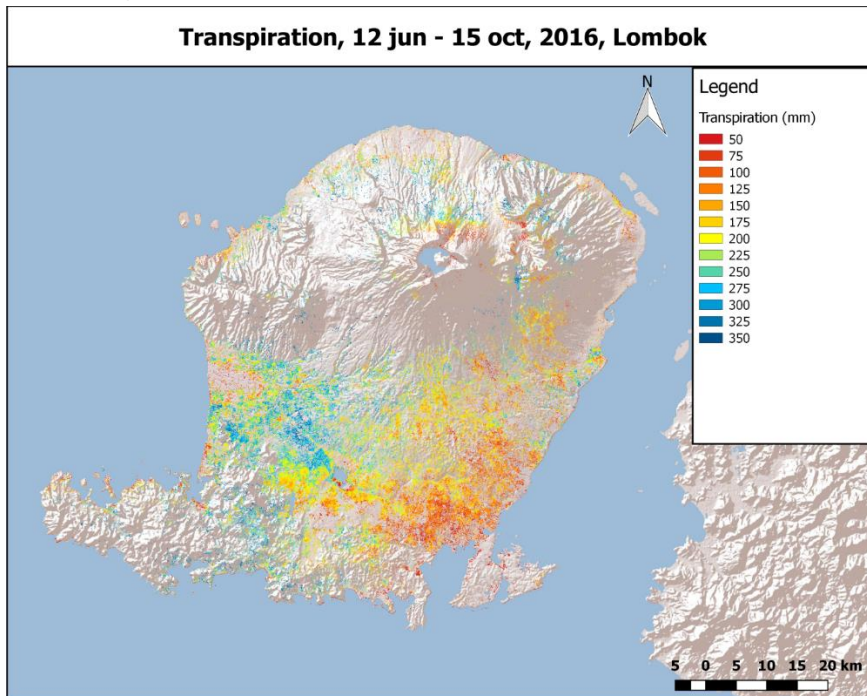


Figure 49: Map of the Transpiration (mm) of Lombok, 12Jun – 15Oct, 2016

Beneficial Evapotranspiration

The beneficial consumption (BC) is calculated by dividing the transpiration by the ET. The BC represents the percentage of water that is used for the plant to grow (transpiration) compared to ET. The map of the BC can be found in Figure 50. The BC varies between 0 and 90%. The average is 52.4% with a standard deviation of 13.7%.

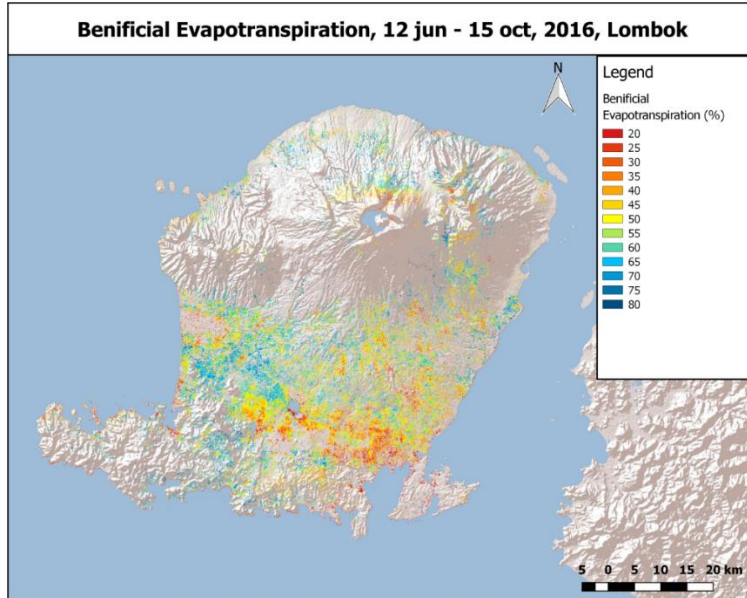


Figure 50: Map of the beneficial consumption (%) of Lombok, 12Jun - 15Oct, 2016

3.4. HANTS

For Java the HANTS algorithm is applied to VIIRS and PROBA-V data to create daily cloud-free data. The input and output data of HANTS are NDVI (PROBA-V), SAVI (PROBA-V), Albedo (PROBA-V) and temperature (VIIRS) maps. The cloud free maps (output of HANTS) are used in SEBAL to create daily maps of the BP and ET, which are the inputs for the final WP map. The PROBA-V data is in 100m grid cells and the VIIRS data is in approximately 440m grid cells. SEBAL makes the output maps in the same grid size as the PROBA-V data, which means all SEBAL output is in 100m grid cells. For the SEBAL runs with HANTS the same paddy season is used as for the java SEBAL run with Landsat data, namely 15 June up to including 15 October.

3.4.1. SEBAL Results Java by HANTS

Crop classification

For the SEBAL run for Java with HANTS, the same classification script is used as the one for the SEBAL run for Java with Landsat (Figure 26).

Evapotranspiration

The resulting ET map is shown in Figure 51. The ET ranges from 83 to 1022 mm. The mean value for the ET is 527 mm with a standard deviation of 83 mm. As can be seen in the histogram of the ET in Figure 52, the majority of the pixels values are between 450 and 650 mm of ET for the entire period.

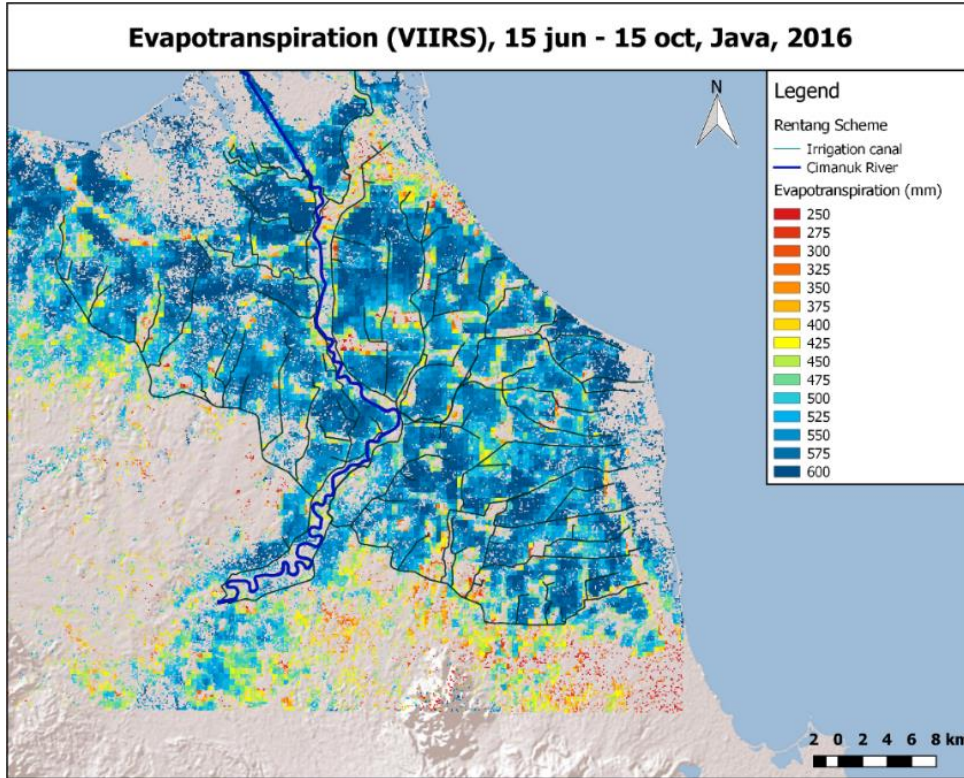


Figure 51 Map of Evapotranspiration VIIRS (mm) for java, 15Jun-15Oct, 2016

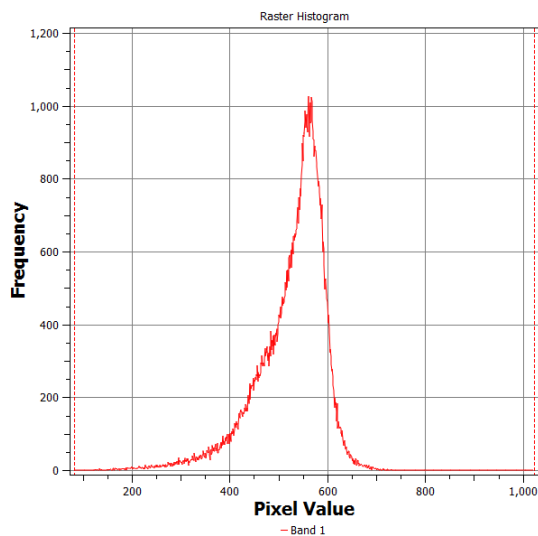


Figure 52 Histogram of the VIIRS Evapotranspiration (mm) for Rice, 15 Jun – 15Oct, 2016

Biomass production

The BP map shows higher values in the middle of the fieldwork compared to the coastal areas (Figure 53). The BP ranges between 9 and 17 ton/ha and is on average 7.4 ton/ha with a standard deviation of 2.5 ton/ha. The corresponding histogram shows that the majority of the pixels values are between 4 and 14 ton/ha of BP (Figure 54).

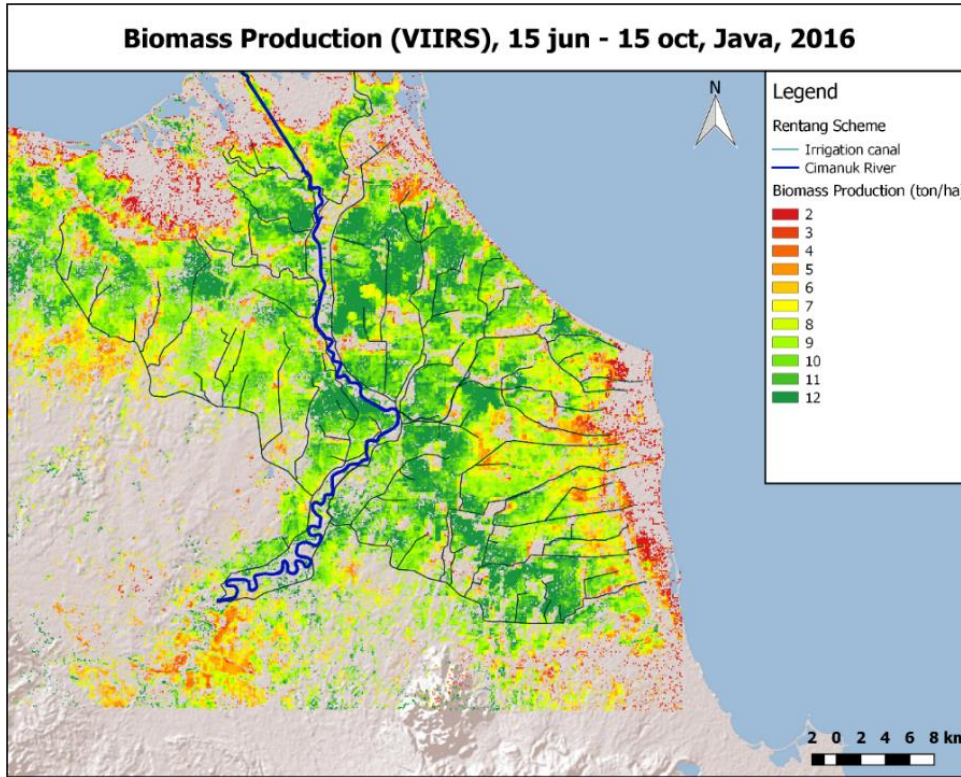


Figure 53 Map of biomass production VIIRS (ton/ha) for java, 15Jun-15Oct, 2016

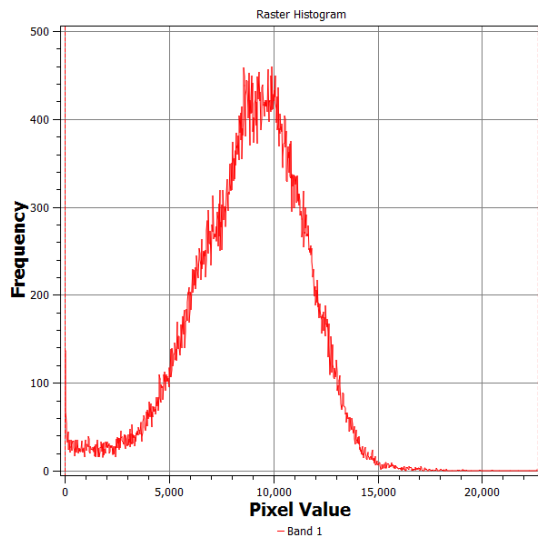


Figure 54 Histogram of the VIIRS Biomass production (ton/ha) for Rice, 15 Jun – 15Oct, 2016

Yield

For this area the yield factor is set to 0.48 as used for Java by using Landsat data in SEBAL. The resulting yield map shows a variation of 0 to 11 ton/ha (Figure 55). The average yield is 4.2 ton/ha with a standard deviation of 1.3 ton/ha.

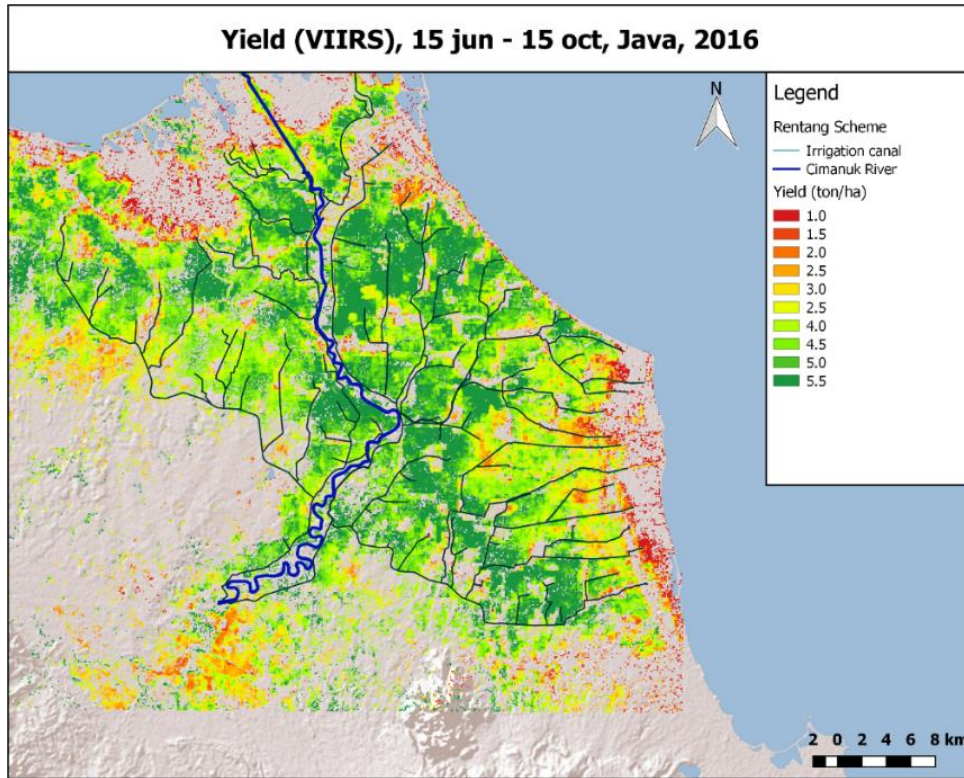


Figure 55 Map of yield VIIRS (ton/ha) for java, 15Jun-15Oct, 2016

Water productivity

In Figure 56 the WP map is portrayed and in Figure 57 the corresponding histogram. The WP varies from 0 to 1.71 kg/m³. The mean is 0.80 kg/m³ with a standard deviation of 0.22 kg/m³. The majority of the pixels values are between 0.4 and 1.2 kg/m³ for the entire period.

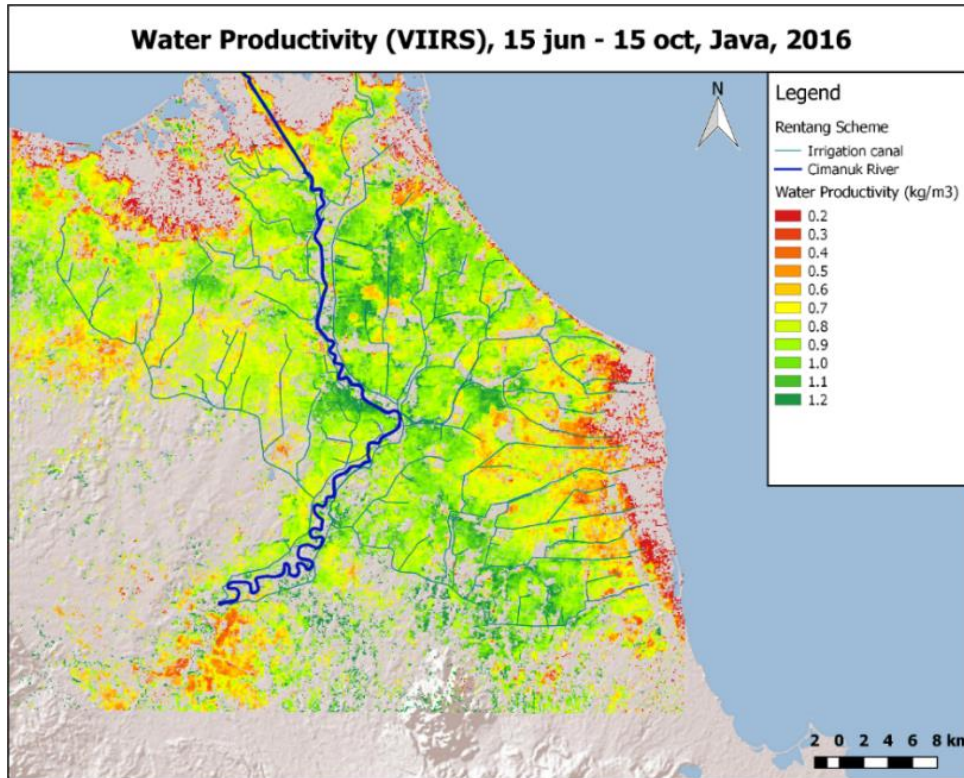


Figure 56 Map of the Water Productivity VIIRS (kg/m³) for Java, 15Jun - 15Oct, 2016

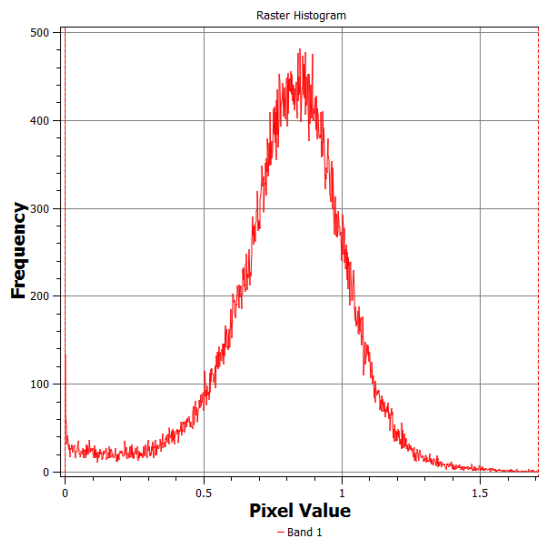


Figure 57 Histogram of the VIIRS Water productivity (kg/m³) for Rice, 15 Jun - 15Oct, 2016

ETdeficit

The result for the ET deficit map is shown in Figure 58. The ET deficit ranges from 0 to 565 mm. The mean is 25 mm with a standard deviation of 35 mm.

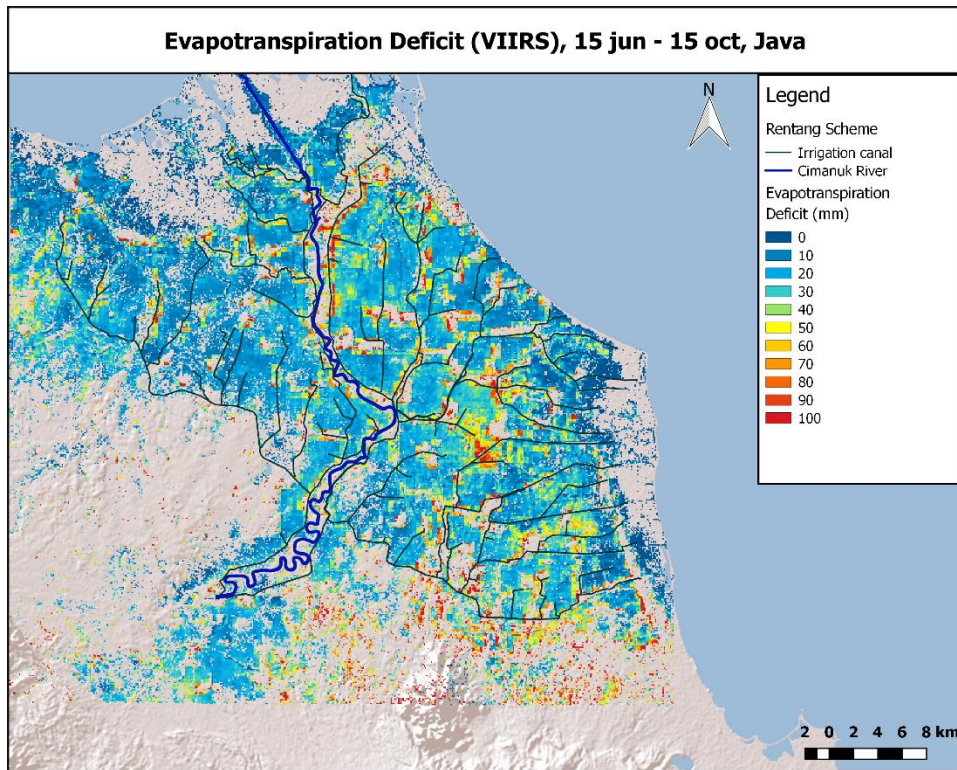


Figure 58 Map of the Evapotranspiration Deficit VIIRS (mm) for Java, 15Jun - 15Oct, 2016

Transpiration

The map of the transpiration can be found in Figure 59. The transpiration varies between 5.6 and 727.0 mm. The average is 191.6 mm with a standard deviation of 72.2 mm.

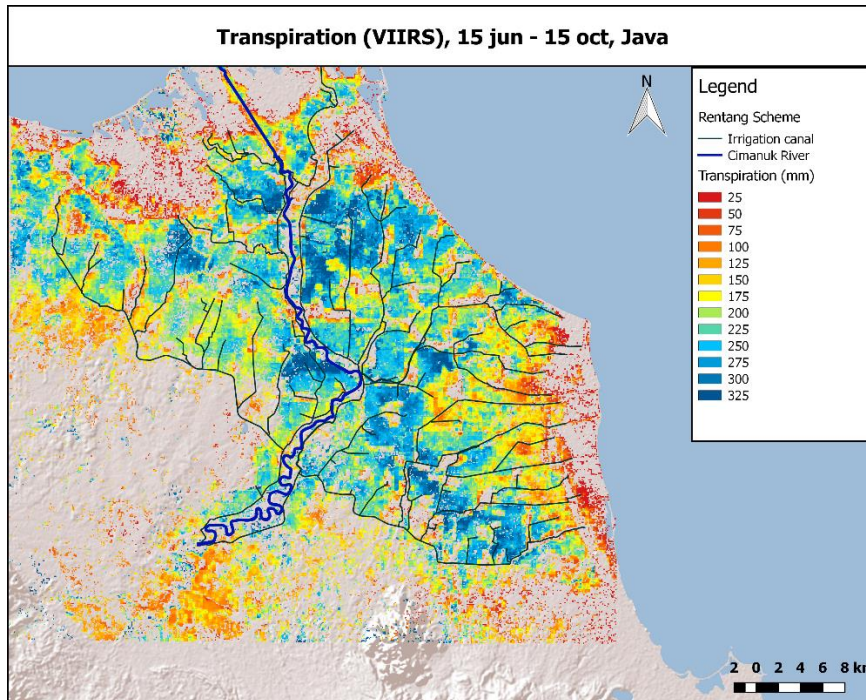


Figure 59 Map of the Transpiration (mm) for Java VIIRS, 15Jun – 15Oct, 2016

Beneficial Evapotranspiration

The beneficial consumption (BC) is calculated by dividing the transpiration by the ETact. The BC represents the percentage of water that is used for the plant to grow (transpiration) compared to the ETact. The map of the BC can be found in Figure 60. The BC varies between 0 and 86%. The average is 36.0% with a standard deviation of 11.9%.

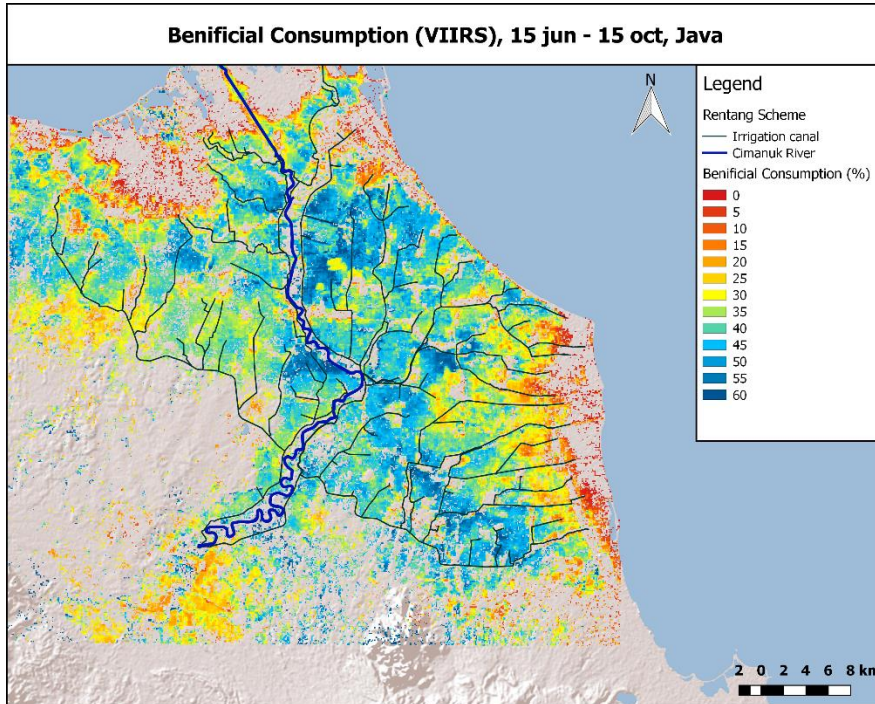


Figure 60 Map of Beneficial consumption (%) for Java VIIRS, 15Jun – 15Oct, 2016

4. Analyses

To understand the spatial distribution of the results from SEBAL, information from the ground is compared to the SEBAL maps. For the scope of this study, fieldwork was only conducted in Bali and Java. For these two sites different information was available. Therefore not all topics which are discussed in the Bali analysis will be discussed in the Java analysis and vice versa. The locations at which interviews with Subak leaders, Kelompok Tani leaders, and farmers were conducted, are shown in Figure 104 in the appendix.

4.1. Bali

For Bali, the WP, ET and Yield map values are compared to the following factors: season, sub-catchments, water quality, rainfall, erosion level, soil type, distance to the ocean, and pests. For pests, rainfall, and distance to the sea, no clear relation is found. Therefore, these sections are only presented in Appendix 7.2.1, and not further discussed in this chapter.

Season

Figure 61 shows the WP (using point sampling) of the locations where Subak leaders were interviewed sorted on production season which were indicated by the leaders. Each box represents one Subak. The blue boxes have the same season as the WP map. The green boxes started 1 month earlier (June) and the orange boxes started 3 to 4 months later (September-October). The orange boxes had another crop than rice for 3-4 months of the period on which the WP map calculation is based. The grey box represents a Subak which has 2 different seasons at the same time and which can thus not be included in the analysis. The middle line is the average WP for the blue boxes. The orange boxes have a higher WP than the average of the in-season boxes. The orange boxes have a lower ET than the in-season average ET (Figure 62). Additionally, the biomass of these locations is higher than the in-season average biomass (Figure 63).

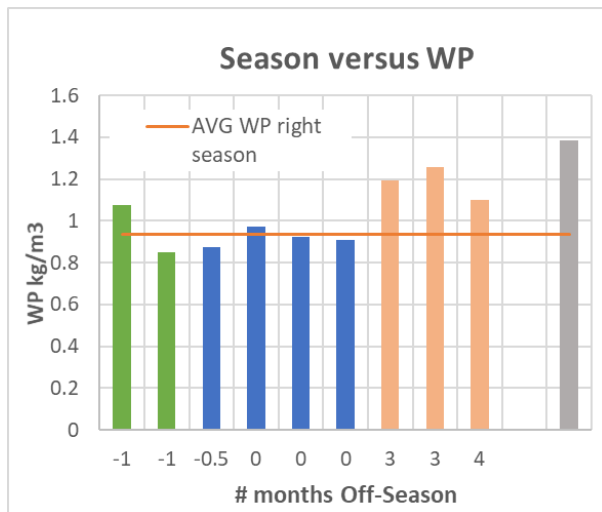


Figure 61 Season versus WP

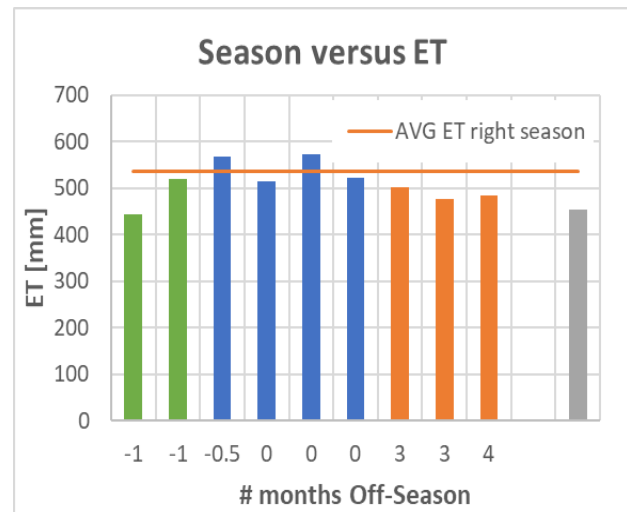


Figure 62 Season versus ET

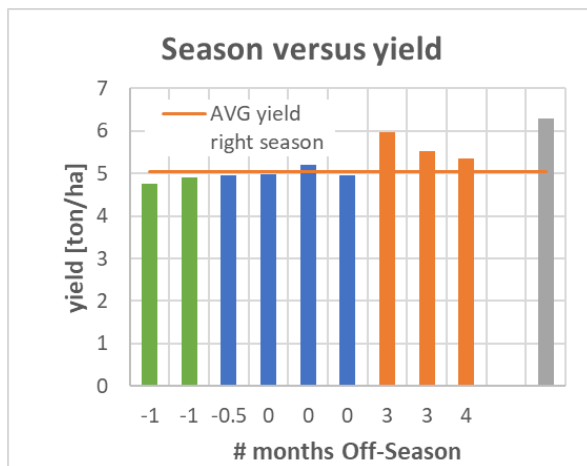


Figure 63 Season versus yield

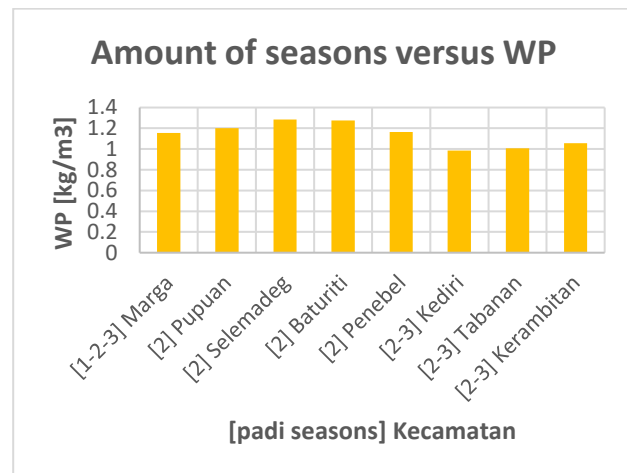


Figure 64 Amount of seasons versus WP

Another seasonal analysis is conducted which takes into account the amount of padi seasons per Kecamatan related to the WP (Figure 64). The WP for the Kecamatan where half the region has 2 seasons and the other half 3, is lower than for the Kecamatan where the majority has 2 seasons. The analysis has been performed for ET and yield too, but no potential relationship has been detected.

Sub-Catchment

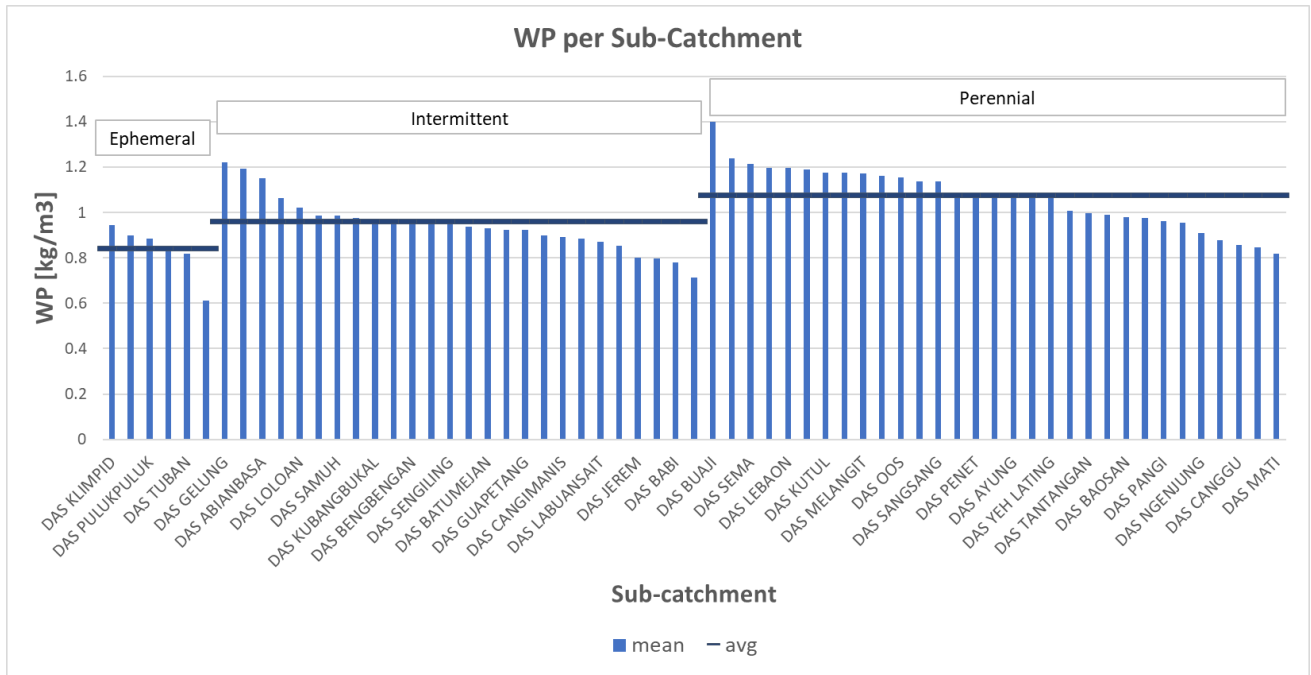


Figure 65 1WP per sub-catchment

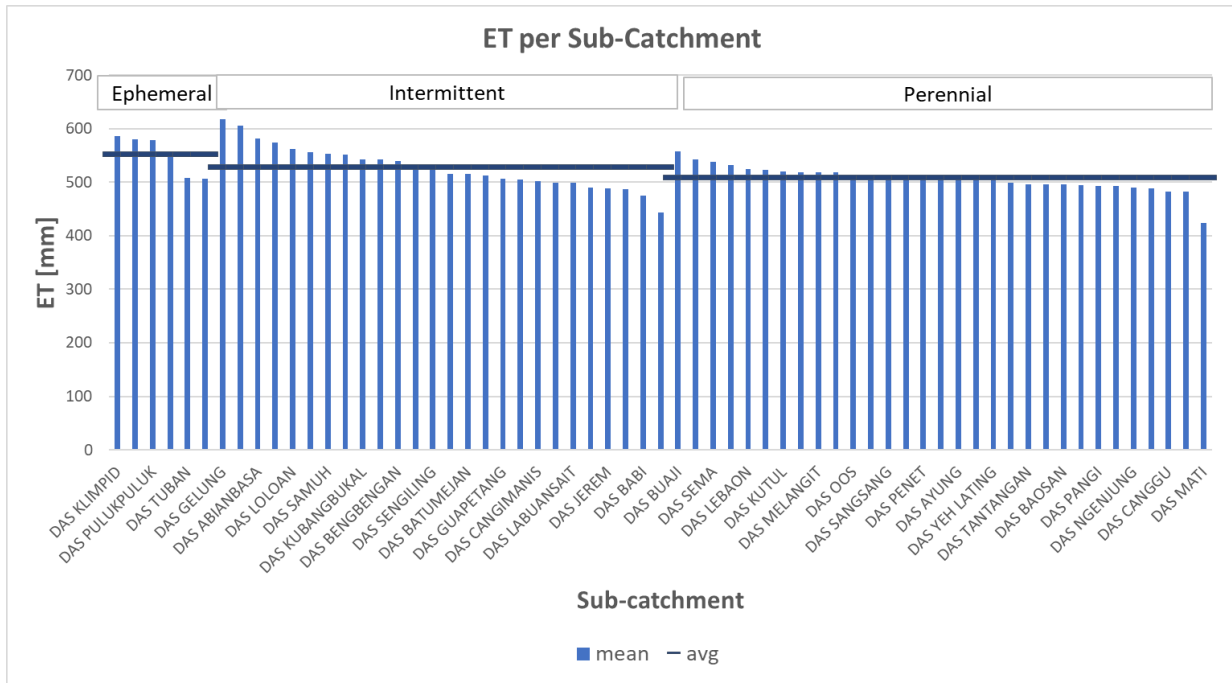


Figure 66 ET per sub-catchment

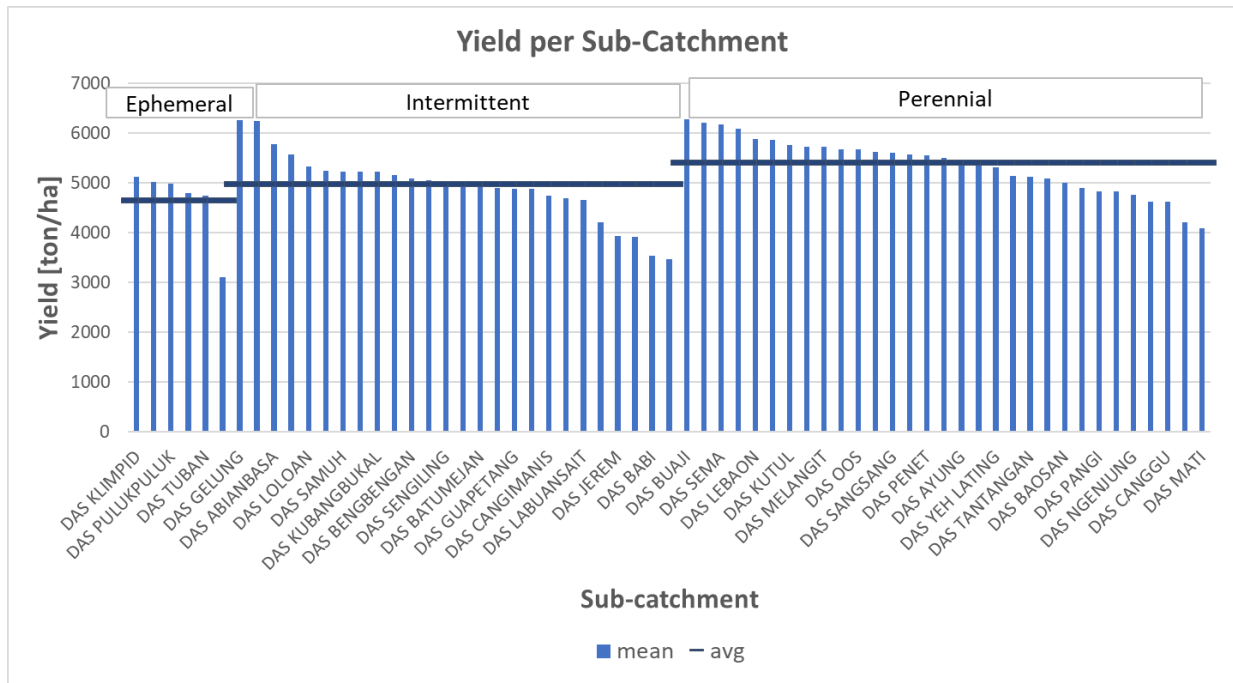


Figure 67 Yield per sub-catchment

The figures above (Figure 65, Figure 66, Figure 67) show the mean WP, ET and yield per sub-catchment, created using zonal statistics. The figures are sorted on factor from high to low and grouped per river type (ephemeral, intermittent, perennial). The average of the factor (WP, ET, yield) per river type are shown with a line. There seems to be a relationship between type of river and the WP. This is caused by a decreasing ET and an increasing yield.

Besides an analysis of the relationship between WP, ET, and yield versus river type, an analysis of WP, ET, and yield versus catchment size has been conducted too. However, no patterns which may suggest any relationship have been found.

Water quality analysis

Water quality parameters throughout the rivers and river basins of Bali are measured by the Balai BBWS (Balai Besar Wilayah Sungai). With this data a plot is made of BOD (biological oxygen demand), COD (chemical oxygen demand) and DO (dissolved oxygen) against Biomass production. The biomass values used are obtained by making a buffer of four kilometres around each water quality measurement station and calculating a mean biomass value for each buffer from the Biomass maps from SEBAL (using zonal statistics in QGIS). The plots shown in Figure 68 are the percentage of deviation from the average values of the measurement points. It shows that for a higher BOD and COD the DO and the biomass is lower than the average.

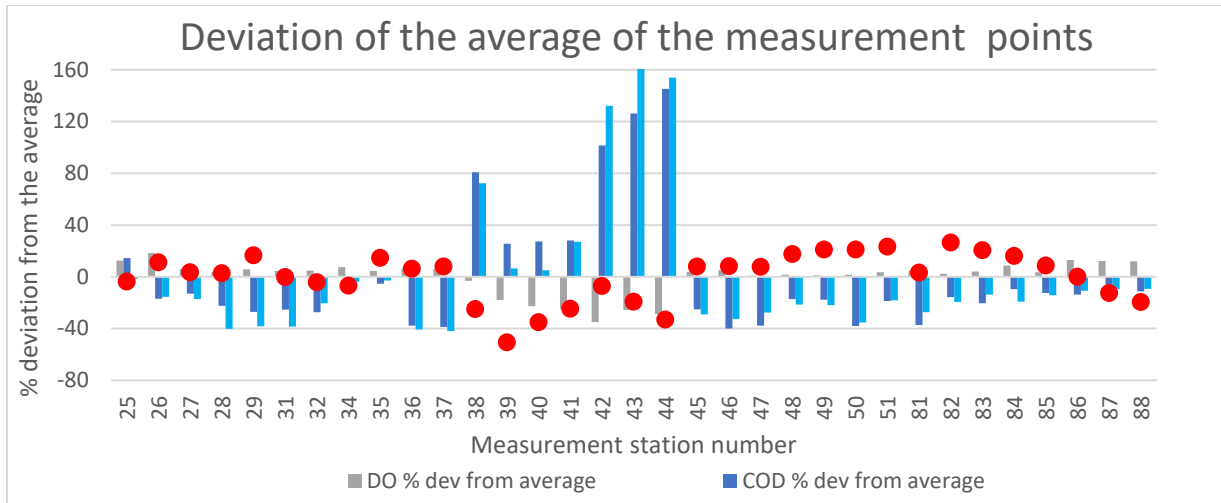


Figure 68 Water quality parameters compared to biomass production

As Figure 69 shows the area with high BOD and COD values, are in the low biomass area (the red areas) of Kuta and Denpasar in the south. These low values are measured in two rivers. The measurement station numbers with the river names can be found in Table 4 in the appendix. The two rivers are main rivers going through Kuta and Denpasar, named “Tk Bandung” and “Tk Mati”.

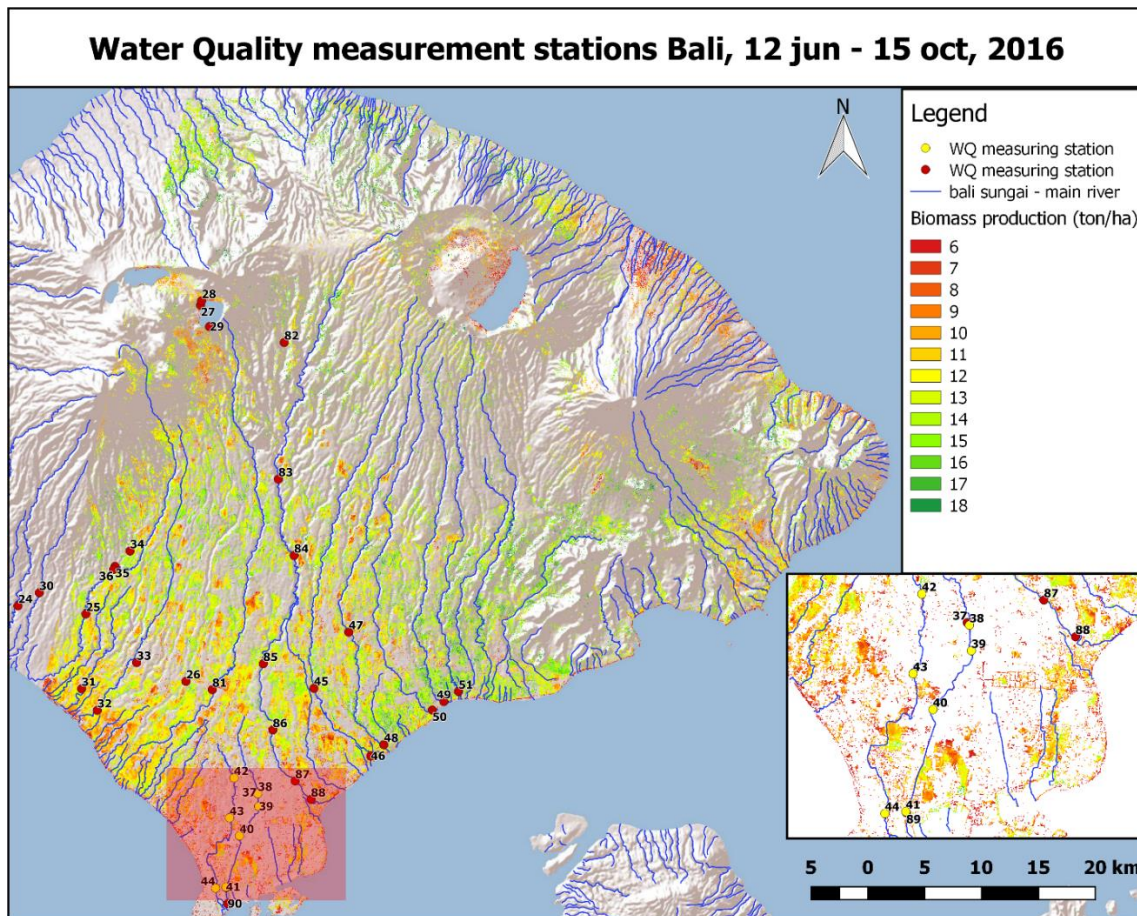


Figure 69 Measurement stations selected yellow in area with high COD values

Erosion

When comparing mean and median WP to erosion level of the area (using zonal statistics) (Figure 70), there seems to be a potential linear relationship. When analysing this further the figures suggest that the relationship originates from the ET (Figure 71) rather than the yield (Figure 72). The graphs suggest that the higher the erosion level is, the lower the ET becomes.

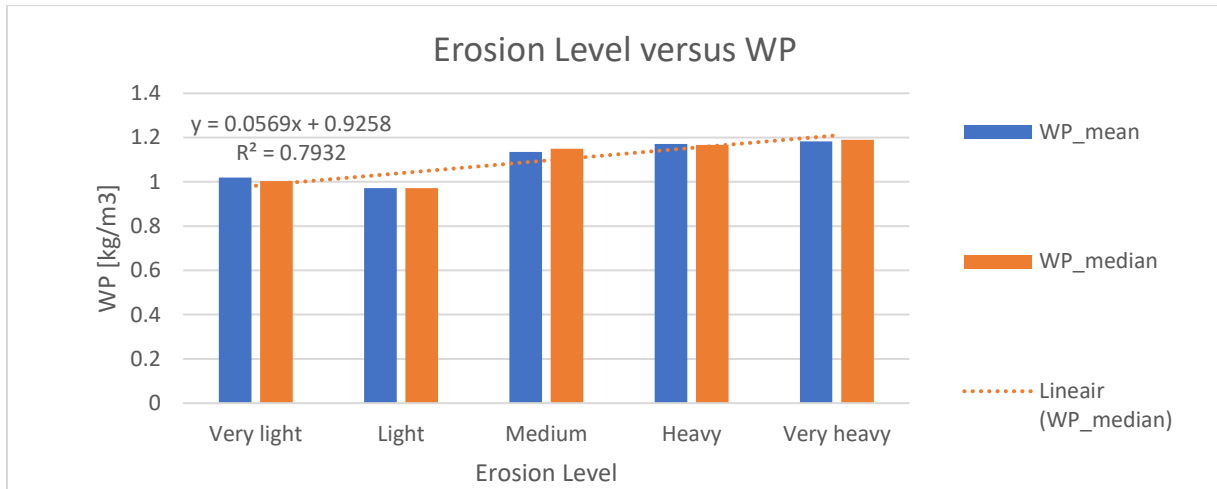


Figure 70 Erosion level versus WP

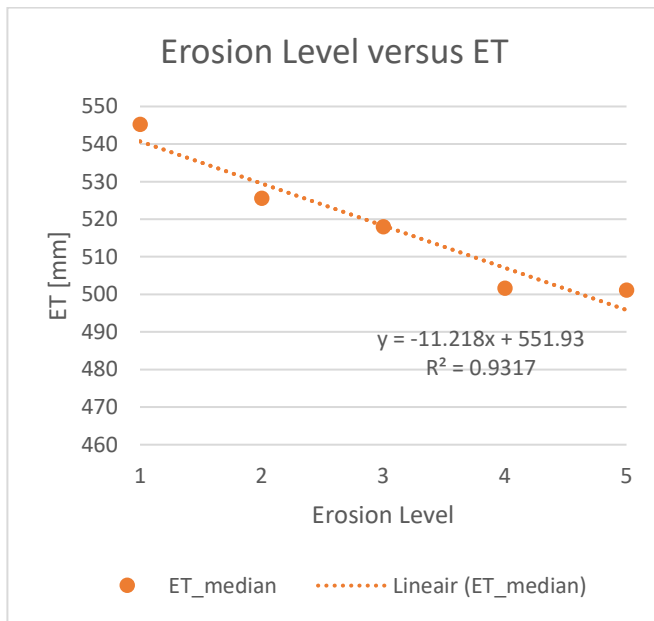


Figure 71 Erosion level versus ET

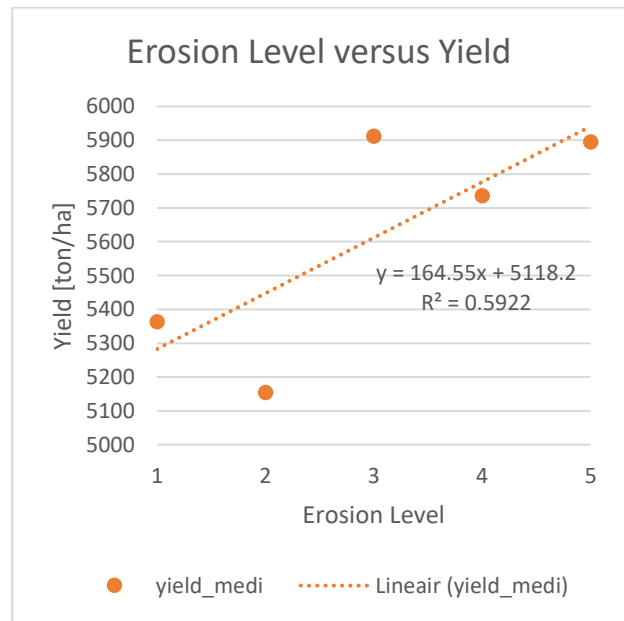


Figure 72 Erosion level versus yield

4.2. Java

For the study area in Java the results of SEBAL are compared with: seasons, flood zones, distance to canals, soil type, distance to salt bodies, and pests. For the comparison for season and pests no clear relation was found. The results of these comparisons can be found in Appendix 7.2.2. The rest of the comparisons will be explained briefly in the following section.

Floods

In the Rentang irrigation scheme, several regions cope with yearly floods (Nippon Koei Co., 2011). It is specified as flood when the region is inundated for more than 3 days and the water level is higher than 30 cm. The flood zones are shown in Figure 73. Per flood zone, the zonal average biomass production, evapotranspiration and water productivity are calculated. Next to that, buffers of 2km and 5km are created and the same statistics are calculated for these buffers. The relative difference between the original flood zone values and buffer values are shown in Figure 74.

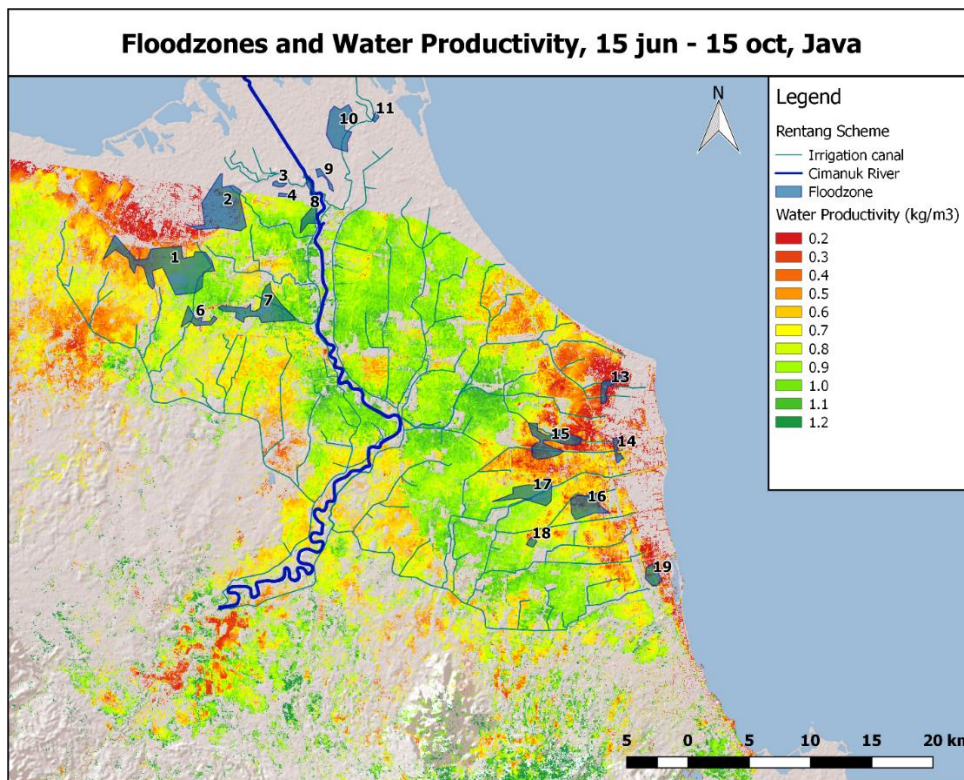


Figure 73: Flood zones and Water Productivity

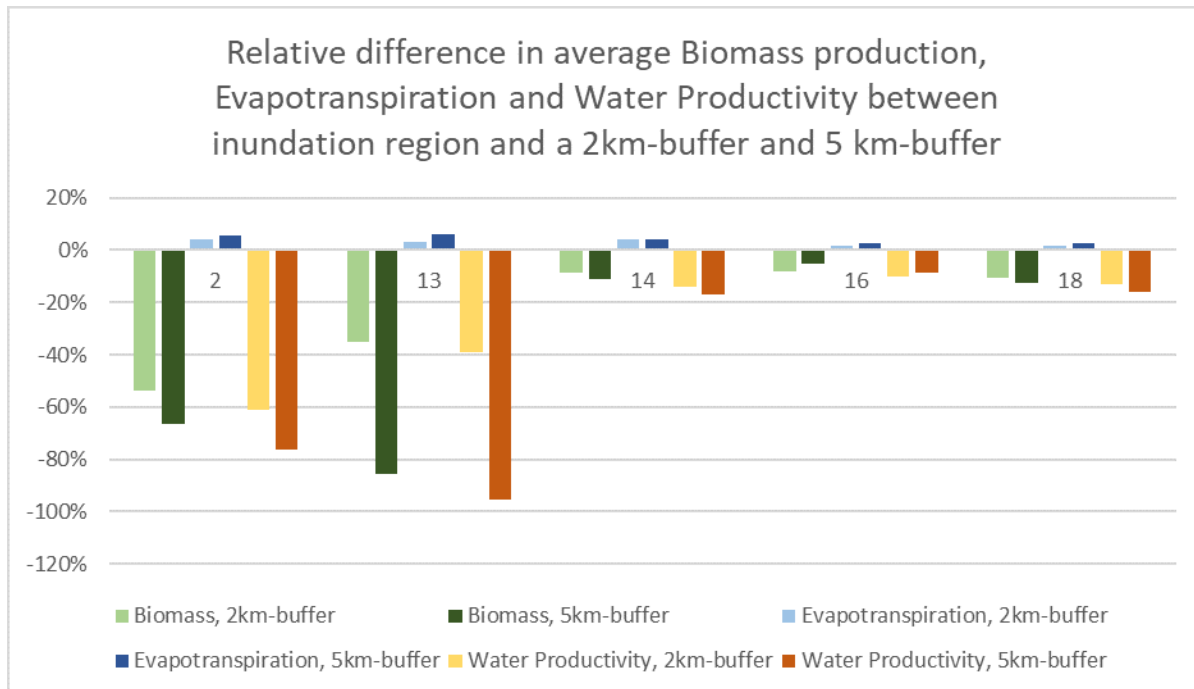


Figure 74: Relative difference in average Biomass Production, Evapotranspiration and Water Productivity between inundation region and 2km-buffer and 5km-buffer

The relative differences of the evapotranspiration values are smaller than 10% in all the flood zones, compared to the 2km as well as the 5km buffer. The relative difference of the biomass and water productivity values are significantly higher than the differences in evapotranspiration, especially in zone 2, 13, 14, 15, 16, 17 and 18.

Finally, zones 2, 13, 14, 16 and 18 show a pattern of a relatively higher ET and relatively low biomass production and water productivity within the flood zones. The statistics of these flood zones and corresponding buffers are shown in Table 1. Zone 2 and 13 have a 65% lower Biomass Production and a 76% lower Water Productivity compared to the surrounding 5 km buffers.

Table 1: Relative difference between average Biomass Production (BM) and Water Productivity (WP) per flood zone, compared to the average of a 2km-, and 5km-buffer

| Flood Zone | 2 km Buffer | | | | | | 5 km Buffer | | | | | |
|------------|-------------|---------|---------|------------------|---------|-------------------|-------------|------------------|---------|-------------------|--|--|
| | BM mean | WP mean | BM mean | BM difference[%] | WP mean | WP difference [%] | BM mean | BM difference[%] | WP mean | WP difference [%] | | |
| 2 | 4413.49 | 0.39 | 6787.82 | -54% | 0.63 | -61% | 7342.45 | -66% | 0.69 | -76% | | |
| 13 | 2587.60 | 0.21 | 3488.42 | -35% | 0.29 | -39% | 4795.43 | -85% | 0.41 | -95% | | |
| 14 | 4477.12 | 0.37 | 4871.19 | -9% | 0.42 | -14% | 4966.07 | -11% | 0.44 | -17% | | |
| 16 | 6420.58 | 0.56 | 6954.54 | -8% | 0.62 | -10% | 6741.87 | -5% | 0.61 | -9% | | |
| 18 | 7916.17 | 0.71 | 8749.66 | -11% | 0.81 | -13% | 8903.31 | -12% | 0.83 | -16% | | |

Distance to Canal

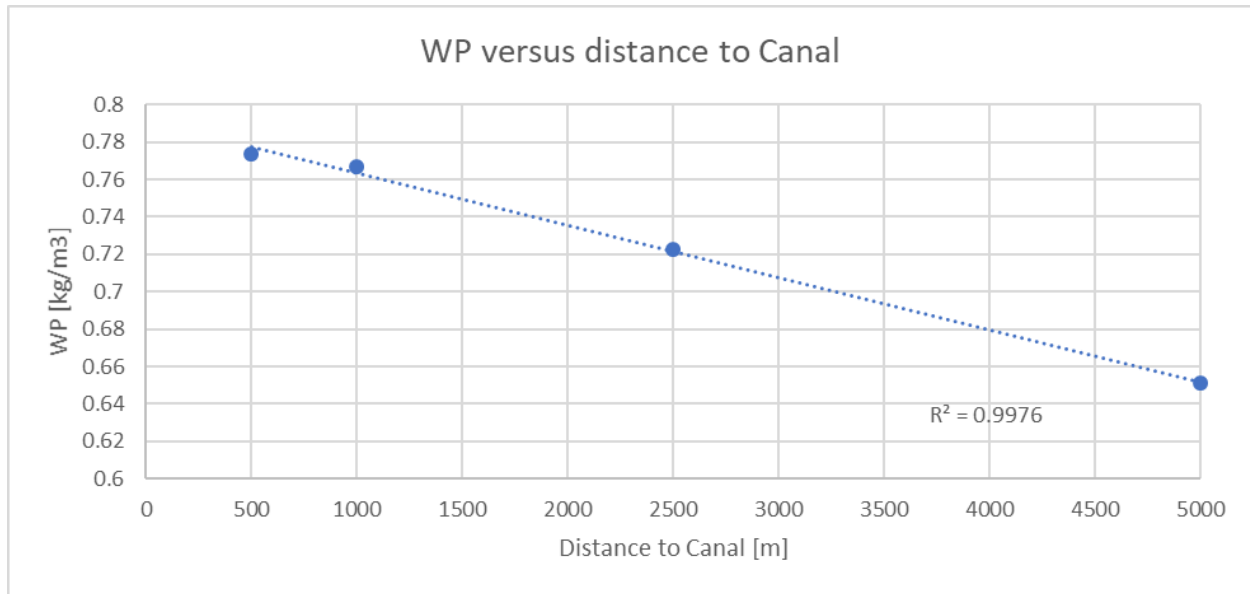


Figure 75 WP versus distance to canal

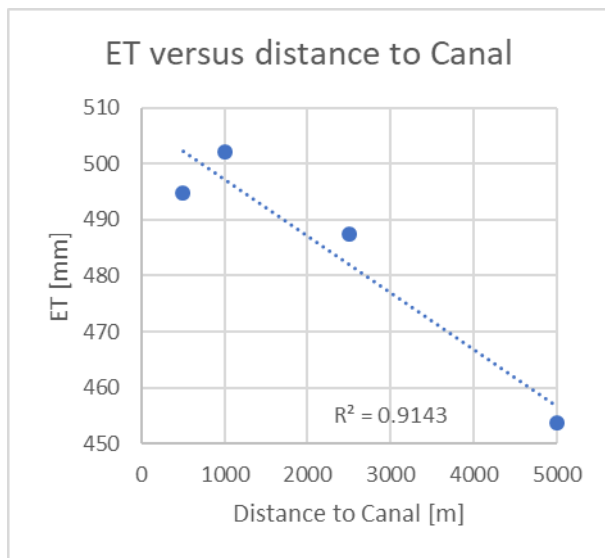


Figure 76 ET versus distance to canal

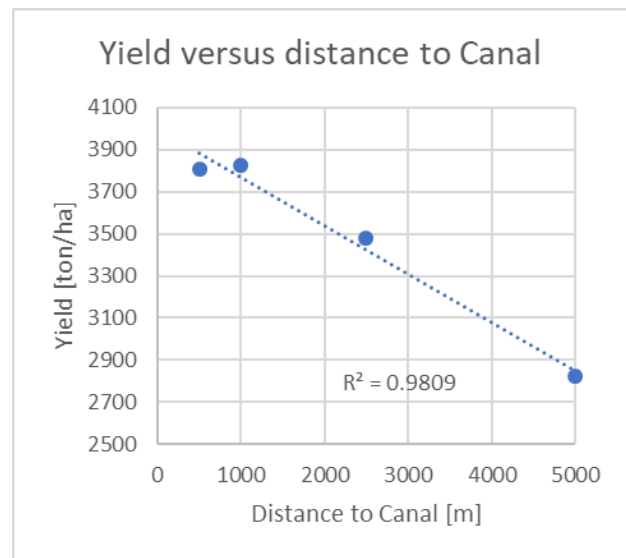


Figure 77 Yield versus distance to canal

Above, the relationship between the distance to the canals and the WP (Figure 75), ET (Figure 76) and Yield (Figure 77) is analysed. This analysis is performed using buffers of 500m, 1km, 2.5km, and 5km, around the primary canals, the secondary canals and the main river. Then, zonal statistics is used on each buffer to obtain the statistics for the WP, ET and yield. The WP seems to be linearly related to the distance to the canals and river. This relationship appears to be based mainly on the decreasing yield.

Distance to salt bodies

In the Rentang irrigation schemes salt intrusion is a problem at the coastal areas, influencing ground water (Nippon Koei Co., 2011). Next to the sea, salt farming performed in the northwest, as well as the East, contain high concentrations of salt. These salt farms are identified by the crop classification and shown in Figure 78. Two zones are selected to analyse the relation between water productivity and the distance to these salt bodies, sea, and salt farms. These two zones trigger the suspicion of salt intrusion because the water productivity appears to be lower close to the salt bodies. The zones are chosen as large as possible and as far away from each other as possible in order to see if this comparison is valid for both regions.

The results are plotted and shown in Figure 122 in the Appendix. The weighted average per 20 points is plotted in red. The results in Figure 122 for both zones look similar in the first 2000 meter, so they are shown more detailed in Figure 79. The evapotranspiration is relatively constant in both zones at approximately 600 mm until 1000 m in zone 1 and 2000 m in zone 2. In zone 1, the water productivity and biomass production increase with an increasing distance from the salt bodies until about 1000 m. Zone two shows this pattern until approximately 500m. Within these distances the average water productivity approximately triples from 0.2 kg/m³ to 0.6 kg/m³, for both zones. After the peak average water productivity of approximately 0.6 kg/m³ at respectively 1000 and 500 m, both zones show a decreasing average water productivity pattern until 1500 m until approximately 0.4 kg/m³. After this point both zones lose their similarity.

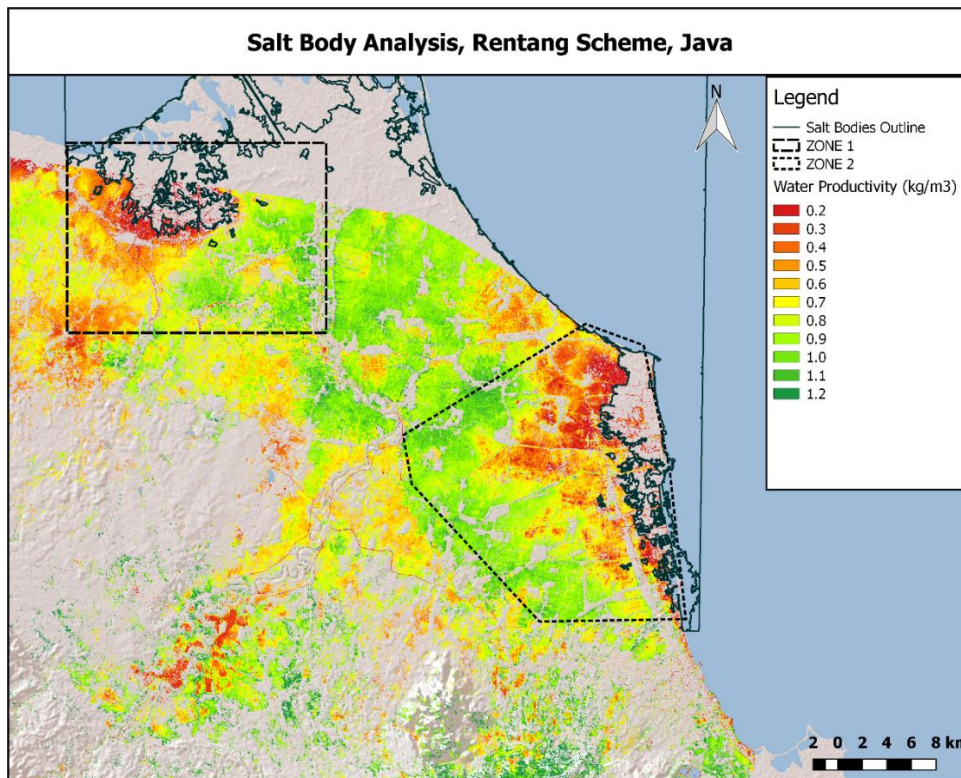


Figure 78: Salt bodies outline and Zones of interest for analysis.

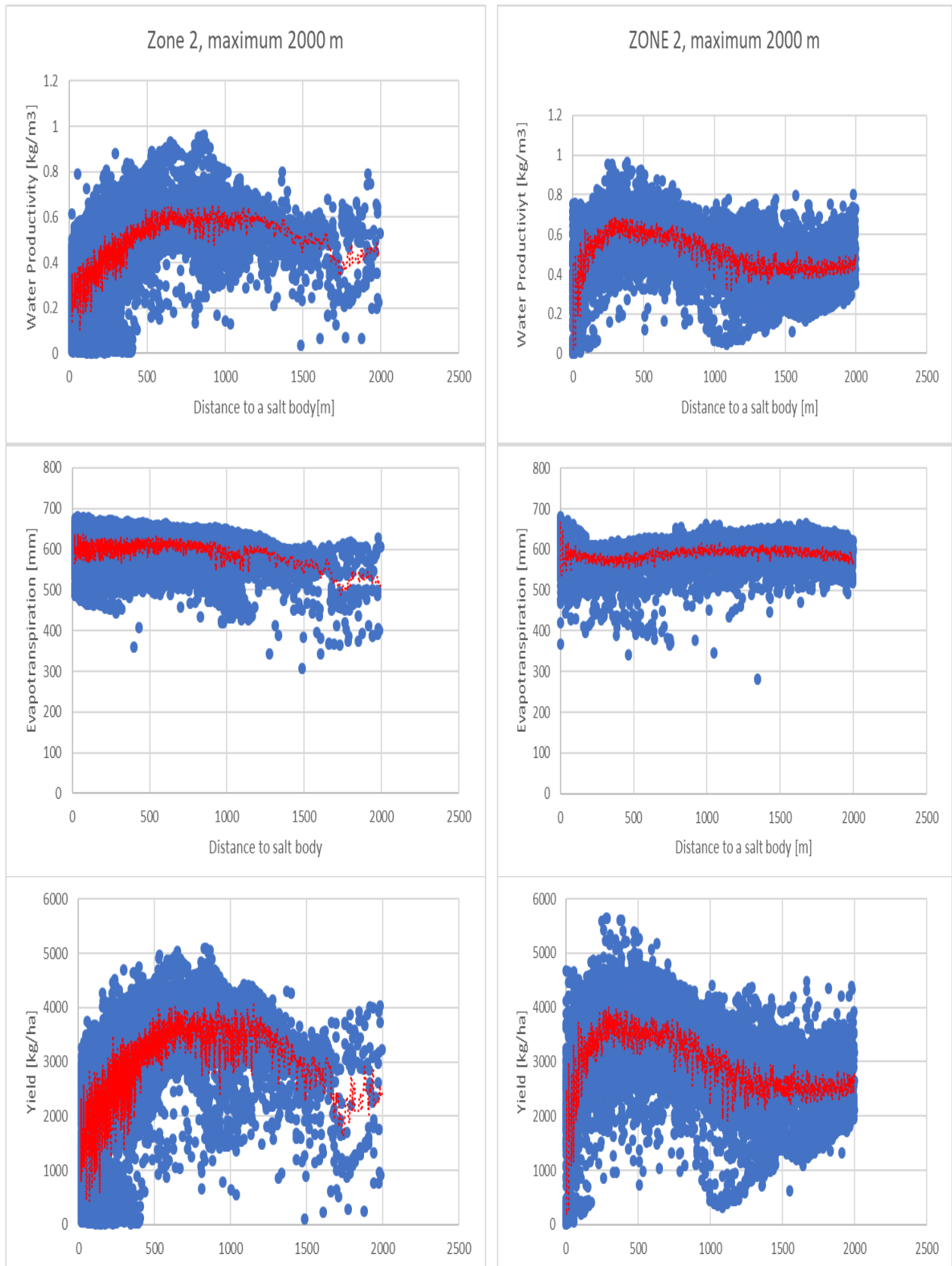


Figure 79: Water Productivity, Evapotranspiration and Biomass Production versus the distance to a salt body, with a maximum of 2000 m, in zone 1 and 2

4.3. HANTS

There are a few important differences between using LANDSAT data as input for SEBAL and using VIIRS and PROBA-V data that is processed by HANTS. One of the key differences is the amount of data. Where for HANTS daily data can be used as input for SEBAL, Landsat only has images every 16 days for Landsat 7 and Landsat 8. The images can be infested by clouds, resulting in even less usable images. When using Landsat in SEBAL, the output maps of SEBAL need to be interpolated to create maps for the whole period of interest. The second key difference is the resolution of the two different data sets. VIIRS and PROBA-V give a SEBAL output of 100m grid cells and Landsat give a SEBAL output 30m grid cells.

The differences between VIIRS and PROBA-V data in SEBAL in relation to Landsat data in SEBAL are presented in the following analysis of the evapotranspiration, biomass production and water productivity maps below. The maps which are created using HANTS are clipped to the same extent as the maps which are created without using HANTS.

Evapotranspiration

The differences between the evapotranspiration maps of the VIIRS and PROBA-V in SEBAL (ET of VIIRS) minus the evapotranspiration maps of Landsat in SEBAL (ET of Landsat) is presented in Figure 80. The positive values are shown as purple pixels and indicate a higher ET of VIIRS than the ET of Landsat. The negative values are shown as orange pixels and indicate a higher ET of Landsat. The green pixels (neutral values) indicated that there is no difference between the two data types. The most negative difference value is -693 mm and the most positive difference value is 496 mm. The mean of the difference is 45.6 mm and the standard deviation is 67.4 mm. The majority of the pixels near the Cimanuk River have a positive difference values, hence a higher ET of VIIRS compared to the ET of Landsat. Around the coast there are more negative and neutral difference values. The majority of the pixels are positive difference values, which means the majority of the pixels has a higher ET value for VIIRS.

Biomass production analyses

The differences between the biomass production maps of the VIIRS and PROBA-V in SEBAL (BP of VIIRS) minus the biomass production maps of Landsat in SEBAL (BP of Landsat) is presented in Figure 81. The positive values are shown again as purple pixels and indicate a higher BP of VIIRS than the BP of Landsat. The negative values are shown as orange pixels and indicate a higher BP of Landsat. The most negative difference value is -10.2 ton/ha and the most positive difference value is 16.1 ton/ha. The mean of the difference is 1.6 ton/ha and the standard deviation is 2.1 ton/ha. The majority of the pixels has a positive difference values and thus a higher BP of VIIRS compared to the BP of Landsat.

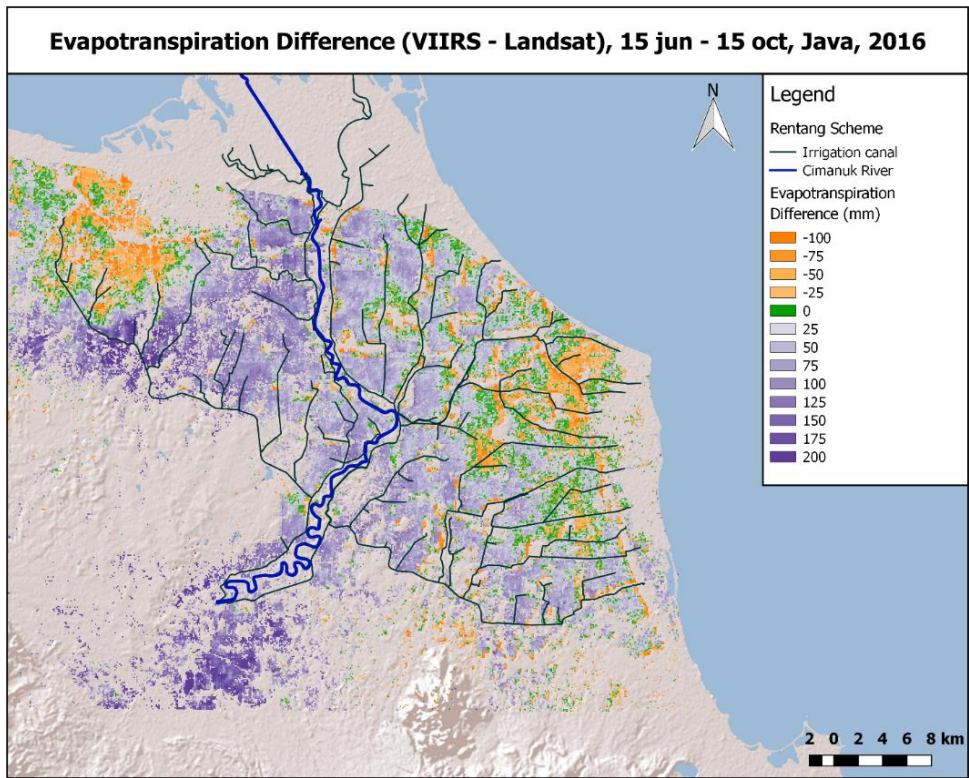


Figure 80 Evapotranspiration difference (VIIRS minus LANDSAT) (mm) for java, 15Jun-15Oct, 2016

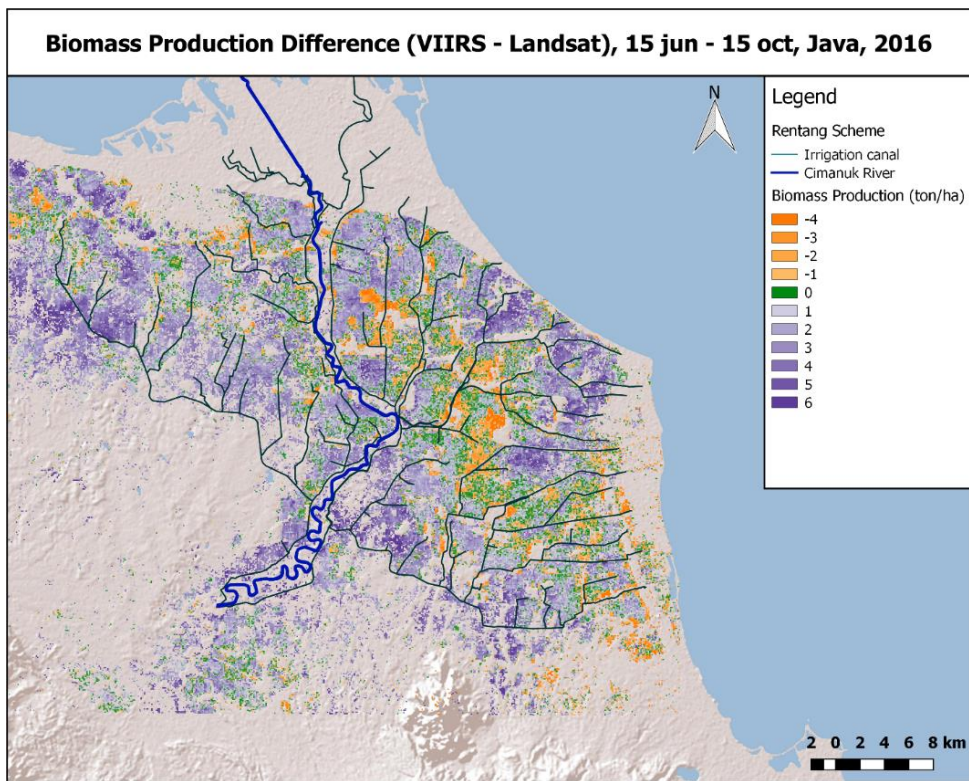


Figure 81 Biomass production difference (VIIRS minus LANDSAT) (ton/ha) for java, 15Jun-15Oct, 2016

Water productivity

The differences between the water productivity maps of the VIIRS and PROBA-V in SEBAL (WP of VIIRS) minus the water productivity maps of Landsat in SEBAL (WP of Landsat) is presented in Figure 82. The positive values are shown again as purple pixels and indicate a higher WP of VIIRS than the WP of Landsat. The negative values are shown as orange pixels and indicate a higher WP of Landsat. The most negative difference value is -0.9 kg/m^3 and the most positive difference value is 1.3 kg/m^3 . The mean of the difference is 0.08 kg/m^3 and the standard deviation is 0.2 kg/m^3 . There are significantly more green pixels in the water productivity difference map than in the evaporation and the Biomass production difference maps.

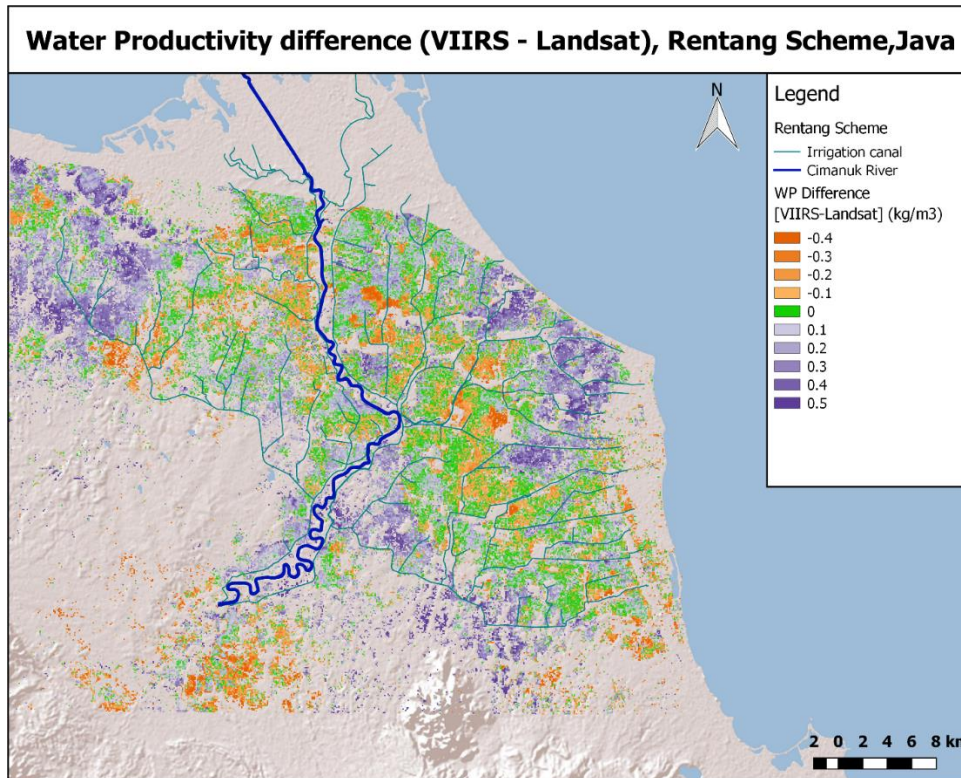


Figure 82 Water productivity difference (VIIRS minus LANDSAT) (kg/m³) for Java, 15Jun - 15Oct, 2016

5. Discussion

5.1. Case studies

5.1.1. Bali

General influences

Based on the conducted fieldwork, the overall impression in Bali regarding its rice production system is very positive. Farmers and institutes mentioned only a few obvious problems which they have in specific areas. In general, the irrigation systems are well organized and well-maintained. In addition, water shortage is not a predominant problem.

The WP map Figure 18 shows a scattered distribution. The WP variations on a small scale can be explained by the following findings. First, the rice production in Bali is managed on Subak level. Factors such as crop seasons and crop management can vary per Subak. Since each Subak covers a quite small area (less than 50ha on average) this can introduce WP variations on a small scale. The analysis on crop seasons in chapter Bali, Season) shows that the variety in used cropping calendar is huge. In the ten conducted interviews, six different cropping calendars were discovered. It should be noted that the number of interviews for this analysis is very low. Therefore no conclusions can be drawn with certainty. However, this dataset suggests a relation between the yield and the cropping pattern. Figure 65 namely indicates a slightly higher yield for the regions that have followed a cropping season later than the 12 June- 15 October period used for SEBAL. Therefore, if a WP map is created of an area with highly fluctuating seasons such as in Bali, the WP values may be influenced by the choice of the season for SEBAL. It may be valuable to conduct further research on this topic.

Secondly, small plots can suffer significantly from pests and/or weeds causing lower biomass growth, while simultaneously, adjacent plots do not. From interviews with both institutes and Subak it became clear that in 2016 the majority of rice paddies, 7.2.1 -Pests, did not suffer from pest attacks. However, a few farmers mentioned that locally biomass growth had decreased because of pests and weeds, which could therefore influence the WP. Once a harvest is considered to have failed, farmers often leave their paddy untouched for the rest of the season and therefore SEBAL will continue in monitoring Biomass growth. Thus, the question arises to what extent SEBAL can detect these pests? The available data on pests was however too few and unspecific to conclude proper statements.

Thirdly, several institutes (e.g. the Agricultural offices of Kabupaten Tabanan and Badung) mentioned a high difference in cloud coverage and sunshine hours between the inland northern regions compared to the southern coastal regions. The institutes claimed that higher sunshine hours and less cloud coverage were important factors causing more suitable conditions for rice production in Southern Tabanan and Badung compared to the Northern parts of the districts. However, this pattern is not recognized in Figure 15. Unfortunately, this meteorological knowledge was not available in a spatial dataset and therefore this influence is hard to specify, but interesting for further research.

Zones of interest

To examine particular regions with relatively high WP or relatively low WP, three zones have been selected. This can be seen in Figure 83, in which zone 1 and 3 are areas with WP values below average, and zone 2 is an area above average. Possible hypotheses for the WP values in these areas will be discussed below.

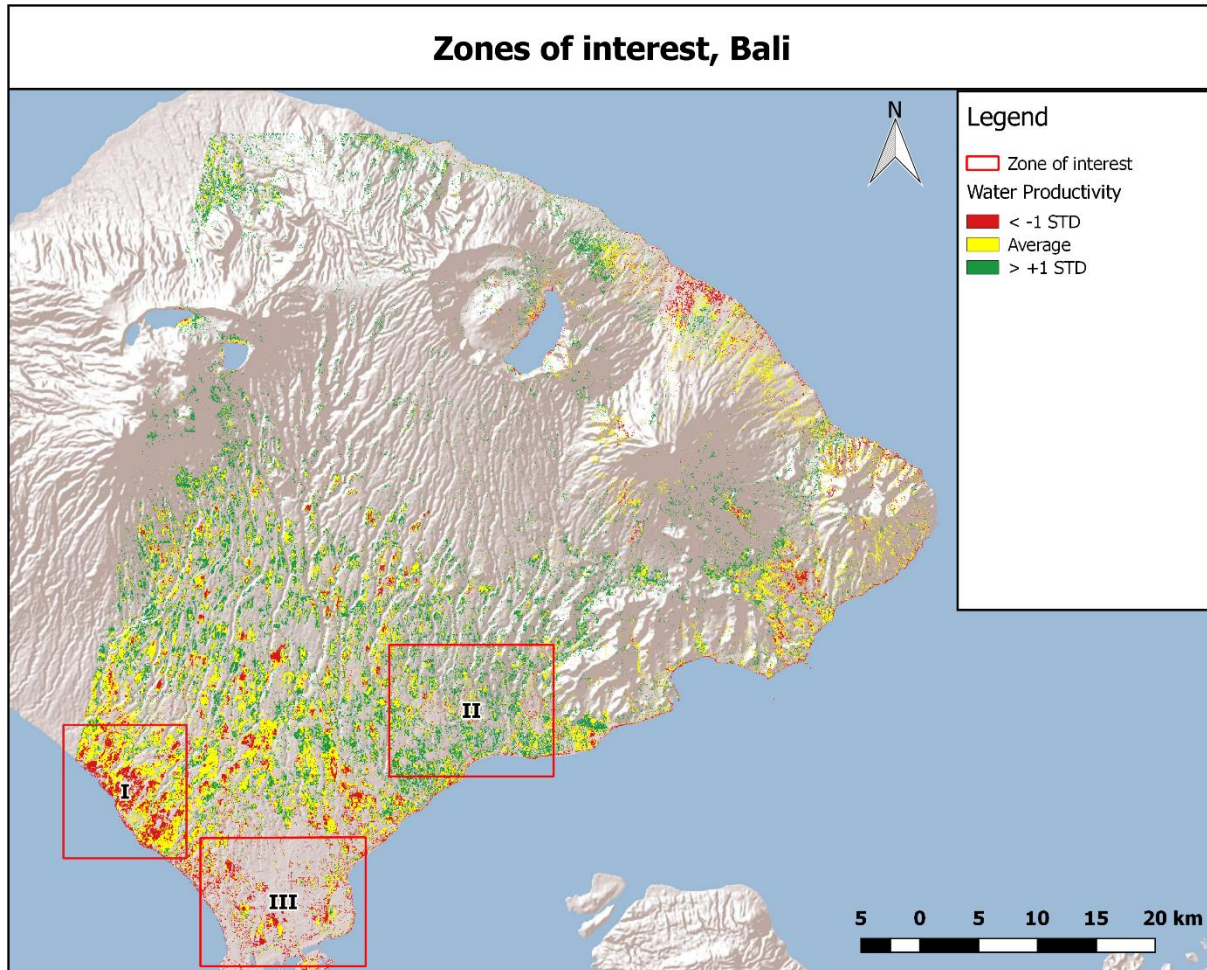


Figure 83:Zones of interests in Bali

Zone 1

Zone 1 (see Figure 83), is situated in the southern part of district Tabanan and Badung (Kecamatans (sub-districts): Kerambitan, Tabanan, Mengwi and Kediri). When comparing the yield (Figure 84) and the ET (Figure 85) to the WP map, it becomes evident that the low WP values in zone 1 mainly originate from the high ET values in these areas, since the yield values are moderate to low and the ET values are very high.

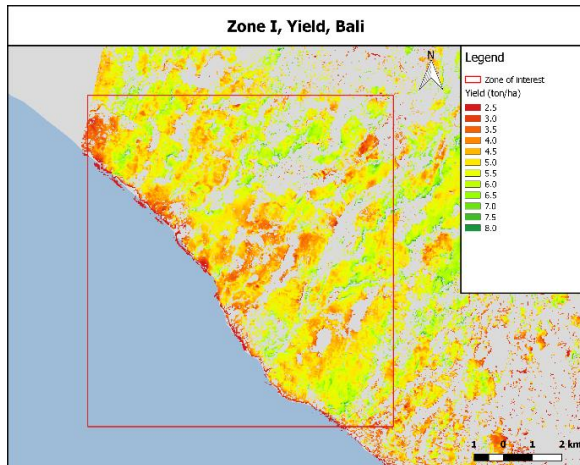


Figure 84: Yield in Zone 1, Bali

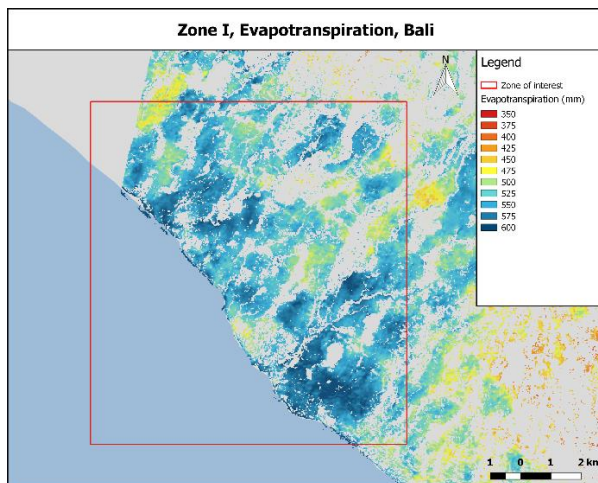


Figure 85: ET in Zone 1, Bali

Farmers and institutes commonly acknowledge that in the southern parts of Kabupaten, Tabanan and Badung, more water is available for agriculture than in the north. This area is relatively flat compared to the sloped northern areas. In line with this, drainage appears to be problematic in zone 1, according to several farmers. This very likely implies the higher values for evapotranspiration in this area compared to the lower ET values in the north.

This suggests that there could be a relation between ET, BP and WP and the distance to the sea. However, this relation is not strongly supported by 7.1.1- Distance to sea, where only the Das Celukapuh catchment catchments, shows a correlation, particularly on ET.

The soil and its erosion levels also differ spatially. Zone 1 is generally covered in the erosion class ‘Light’ and as shown in 4.1- Erosion this erosion class seems to have lower water productivity values than the regions classified as ‘medium’, ‘heavy’ or ‘very heavy’.

The three sub-districts that cover the whole coast of Tabanan are, from north to south, Kerambitan, Tabanan and Kediri. In these regions respectively 60, 40 and 50 percent of the farmers grow three cycles paddy per year, which is significantly higher than the other areas. 4.1 -Seasons shows that regions which have the highest percentage of 3 cycles, have a lower Water Productivity, Figure 64. The fact that downstream sub-districts feel confident enough to run three cycles per year supports the theory that they have a surplus of water.

Zone 2

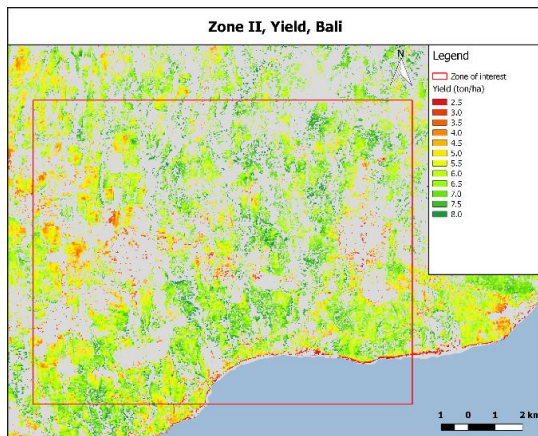


Figure 86: Yield in Zone 2, Bali

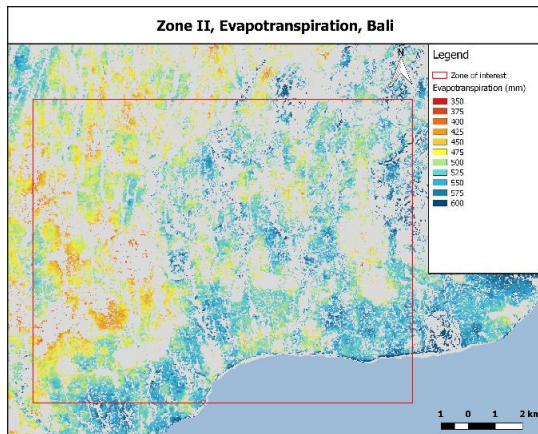


Figure 87: ET in zone 2, Bali

Zone 2 is situated in the southern part of District Gianyar (Kecamatans: Tampaksiring, Gianyar and Blahbatuh), see Figure 83. This area appears to have a relatively high water productivity, caused by low ET values as well as high yield values (Figure 86 and Figure 87). Conducted interviews with farmers and

institutes concerning zone 2, did not imply that conditions were ‘better than average’. Neither were any specific reasons or factors causing higher yield and lower evapotranspiration given. In addition, no access could be achieved to datasets on rice paddies for Gianyar.

However, based on our analyses, erosion could be influential in causing the WP to be higher in zone 2 compared to zone 1, given that zone 2 has the highest erosion class. As shown Figure 71, the higher the erosion levels, the lower the ET. No clear explanation has been found of why the ET is lower for areas with high erosion. It is therefore uncertain whether erosion is a significant factor for the high WP in this area. Further examination should be done, for which datasets of rice paddies in Gianyar could be useful.

Zone 2 is generally covered by soil type called ‘Regosol Gray Chocolat’. In comparison, zone 1 is generally covered by ‘Latosol Red Yellow’. The fact that the soil type coverage pattern seems similar to the erosion class distribution does not seem a coincidence, because erosion is often influenced by soil type. Even though no clear relationship between these two soil types and WP has been found, it may be worth exploring in further research.

Zone 3

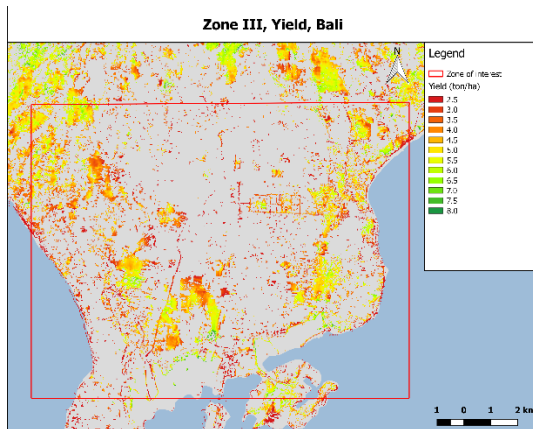


Figure 88: Yield in Zone 3, Bali

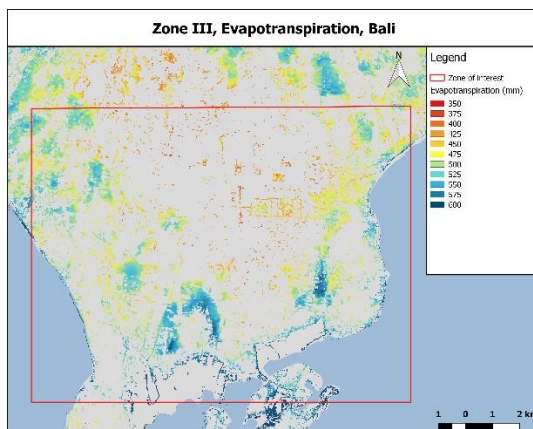


Figure 89: ET in Zone 3, Bali

Zone 3 is located in a highly dense urban area in southern Badung and Denpasar (Kecamatans: Kuta Utara, Kuta, Denpasar Selatan, Denpasar Timur and Denpasar Barat). Figure 83 shows that the WP in zone 3 is

generally below average. Yield values, as well as ET values are generally scattered (Figure 88 and Figure 89). Per location it differs whether low BP or high ET causes a low WP. With growing tourism, agricultural land is increasingly being replaced by urban land types. Given this and the negative effects that tourism often involves, such as water pollution and degradation of agricultural land quality, the rice production in this area is under pressure. In several interviews on district level, this area was frequently specified as the problematic area of the districts regarding rice production. The yield in this area is claimed to be far below average, which is also clear from the received datasets on yield. In line with this, the yield estimated with SEBAL is predominantly low in this area. The water quality analysis confirms this too (4.1 -Water Quality), which indicates that it is very likely that areas with high BOD and COD values and low DO values, have lower BP. Given that the water in Kuta has very high BOD and COD values, a low DO value (Figure 68), and a low average BP this hypothesis is very likely for Kuta.

It must be noted that possible unexplained phenomena in WP, BM or ET can be caused by inaccuracies of SEBAL. These inaccuracies, or limitations, are discussed in 5.3.

5.1.2. Java

General influences

Currently, the biggest acknowledged problem by institutes and farmers in the Rentang irrigation scheme is water availability. In interviews with farmers and institutes, as well as field observations, it was strongly noted that tertiary, and sometimes even secondary, canals in the Rentang irrigation scheme were often dry and in bad condition, coping with high pollution. Shortage of water is obviously a major influence on rice production and water productivity. Attempts from institutes to evenly distribute the water, mostly via policy measures, throughout the whole area often failed because farmers close to irrigation channels took more water (using pumps) than they were officially allowed to extract. To illustrate the matter of importance of this problem institutes used terms as 'water stealing' and 'water maffia'. Pumps were often noticed in the field observations, however officially there is just one legally registered pump in the whole Rentang irrigation scheme. Upstream farmers taking too much water leads to droughts for the downstream located farmers. It is assumed, based on field observations and interviews, that canal drought is a problem that mostly occurs in tertiary channels and therefore the distance to secondary and primary canals is relevant. 4.2 -Distance to Canal identifies this problem clearly and shows a linear relation between the WP and distance to the primary or secondary channels. Closest to the canals, the highest WP is noticed, however also the highest ET, see Figure 75. This high ET indicates a surplus of water and therefore supports the suspicion of 'water stealing' close to the main canals. It should be noted that pumps are not only used in water abundant areas, but also by farmers in areas where the canals are malfunctioning. These pumps are only used by farmers who can afford to hire one and are used to pump water from a functioning canal to a field which is connected to a malfunctioning canal.

With 14 different soil classifications in the Cirebon and Indramayu district, the variation is higher than in Bali. This high variation could be influential in the WP distribution, because Figure 119 suggests that there is a relationship between soil type and WP. Regions covered with the coastal soil type 'Regosal Kelabu' have an average WP of almost three times as low as regions covered with 'Latosol Clkt Kemerahn'. The relationship in ET and Yield however does not follow the same pattern as the WP, see Figure 120 and Figure 121.

In 7.2.2- Seasons, it becomes clear that farmers in the Rentang irrigation scheme follow a more homogeneous cropping calendar compared to Bali. In 15 interviews, only four different scenarios were

found. Farmers used either a cropping pattern that started 1.5 or 0.5 months before the used season in SEBAL, they used a cropping pattern within the used SEBAL period or they used a pattern of 0.5 months later. Therefore difference in used cropping pattern is a less realistic explanation for possible scattering, compared to Bali. Figure 116, shows a slight pattern of farmers that started before the used SEBAL period. Particularly the ones which started 1.5 months before the SEBAL period have a lower average WP. The Java results seem to inversely support the theory derived from Bali on that farmers who apply later cropping seasons have a higher WP. However, similar as for 4.1- Seasons, the datasets are small and observed relations are minimal, but the constancy triggers the curiosity after this relation.

Zones of interest

To examine particular regions with relative high WP or relative low WP, three zones have been selected. This can be seen in Figure 90, in which zone 1 and 2 are areas with WP values below average, and zone 2 an area above average. Possible hypotheses for the WP values per zone will be elaborated below.

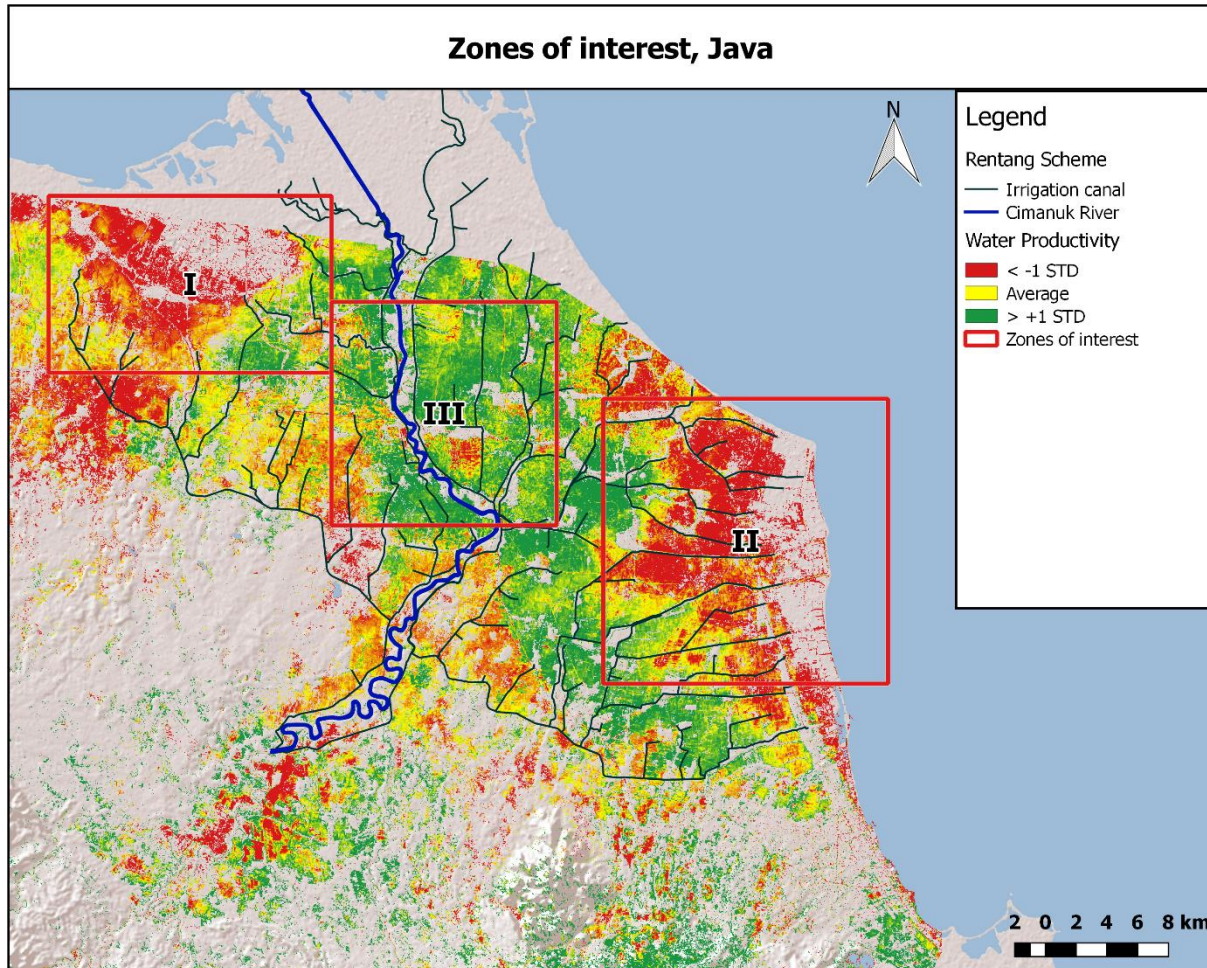


Figure 90: Zones of interest in the Rentang irrigation scheme

Zone1

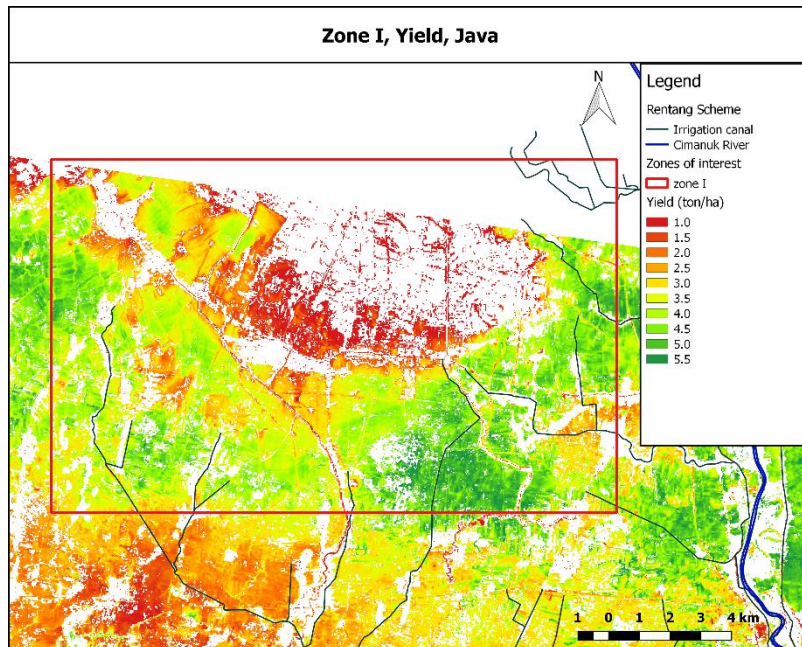


Figure 91: Yield in Zone 1, Java

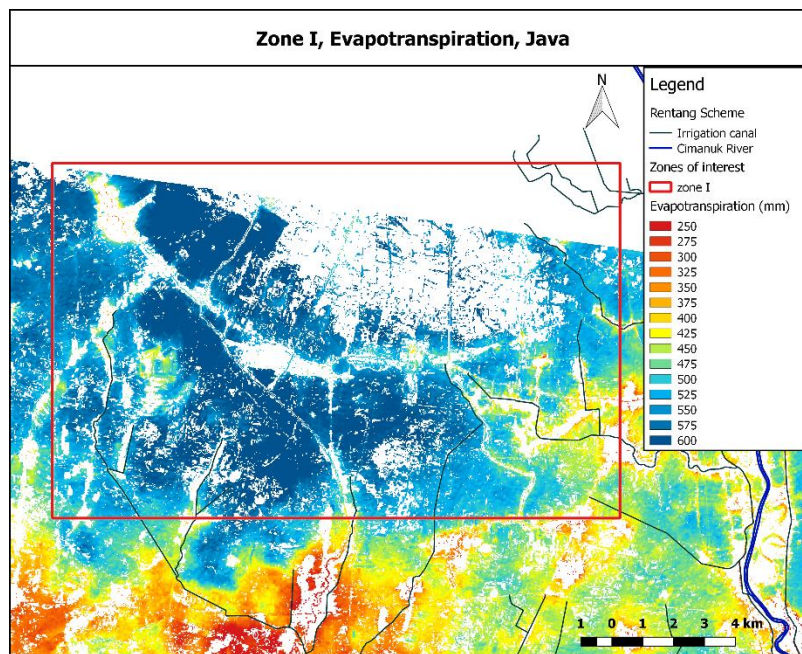


Figure 92: ET in Zone 1, Java

As can be seen in Figure 90, WP in zone 1 is generally below average. Figure 91 shows low yields close to the sea, but high ET values (see Figure 92) occur throughout almost the entire zone and therefore influence the WP.

The identified salt farms in zone 1 are located in the region where BP is low, 4.2- Distance to Salt Bodies. Rice paddies that are located within or closer than 500 m to these salt bodies have a low average BP (Figure 79). This is reasonable, as the salt bodies are likely to increase adjacent soils' salinity, which in turn negatively affects the BP of rice (Erfandi and Rachman, 2013; Ghosh et al., 2016). In-field, several paddies have been observed in between salt farms, which are also identified by the crop classification.

Flood zone 2 is located in this low BP region. Flood zone 2 shows a very low BP and WP (Figure 73). As explained by institutes, this could relate to salt intrusion as well. Regions that face the yearly problem of flooding often choose to switch their cultivation to salt. Sometimes they even switch within a year between salt and rice cultivation.

Besides the proximity to salt intrusion and flood zones, the distance to the closest primary or secondary canal is far (Figure 90). As discussed, this is very likely related to low BP and WP as well. This large distance also applies for regions outside the salted area. Next to that farmers close to the canals are located in the high ET regions, see Figure 92 **Fout! Verwijzingsbron niet gevonden.** and show a slightly higher WP in Figure 90. Farmers close to the primary irrigation channel are not bounded by water availability and it is likely that they therefore use even more water than minimum required, causing higher yields, but also higher ET.

Zone2

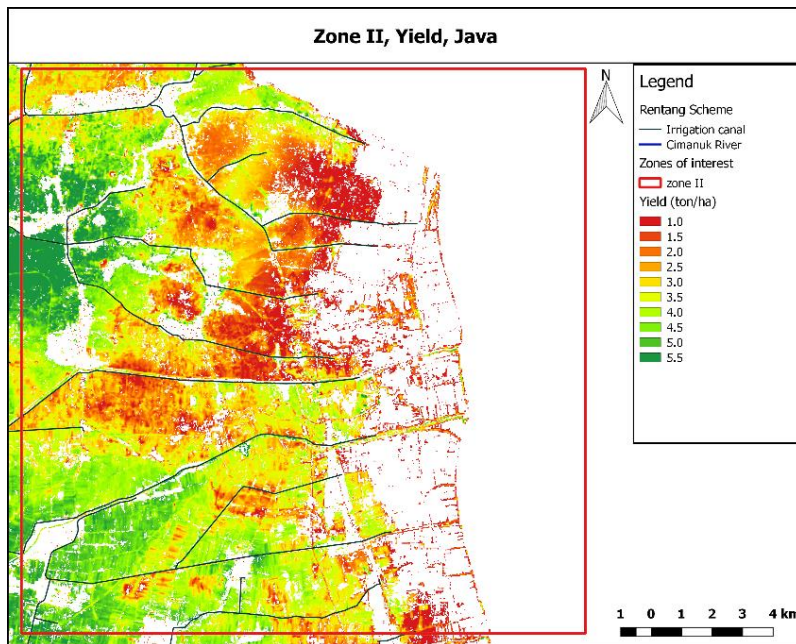


Figure 93: Yield in Zone 2, Java

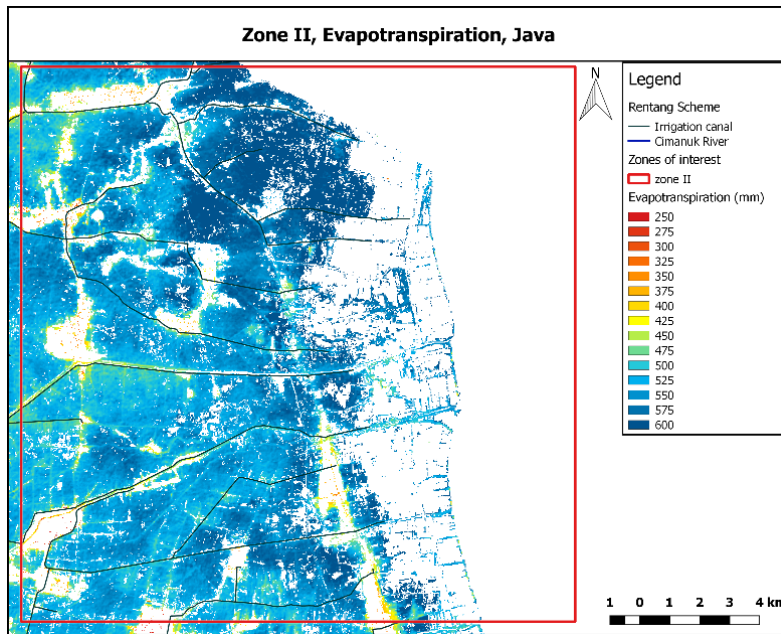


Figure 94: ET in zone 2, Java

The WP distribution in zone 2 looks pretty similar to zone 1. The average WP is generally low (Figure 90), low biomass regions are concentrated in the north east(Figure 93) and ET values are generally high throughout the whole zone(Figure 94).

Just like zone 1, salt cultivation occurs in zone 2 and additionally flood zones 13, 14, 16 and 18 are located in zone 2. Compared to their surroundings, all these flood zones show a pattern of high ET and a much lower BP, as can be seen in Figure 74. Undesired floods cause depletion of oxygen in the soil, which reduces the presence of nutrients and therefore the fertility of the soil (Patrick and Mahapatra, 1968), with lower BP as result. In addition, as stated before, regions that face yearly floods, often cultivate more salt which could also affect the soil's fertility.

The distance to primary and secondary canals seems less far in zone 2 compared to zone 1. However, as noted before, sometimes even secondary canals were observed to be dry in the field. These observations were noticed in this specific zone. A farmer in the region confirmed the observations and claimed the secondary canal near his plot has not been working properly for several years due to very high sedimentation. Since 2015 he has not had any yield for this paddy season (the SEBAL season) due to water shortages. Therefor water scarcity, although not identified in 4.2-Distance to Canal, is expected to be an involving factor in this region.

Zone 3

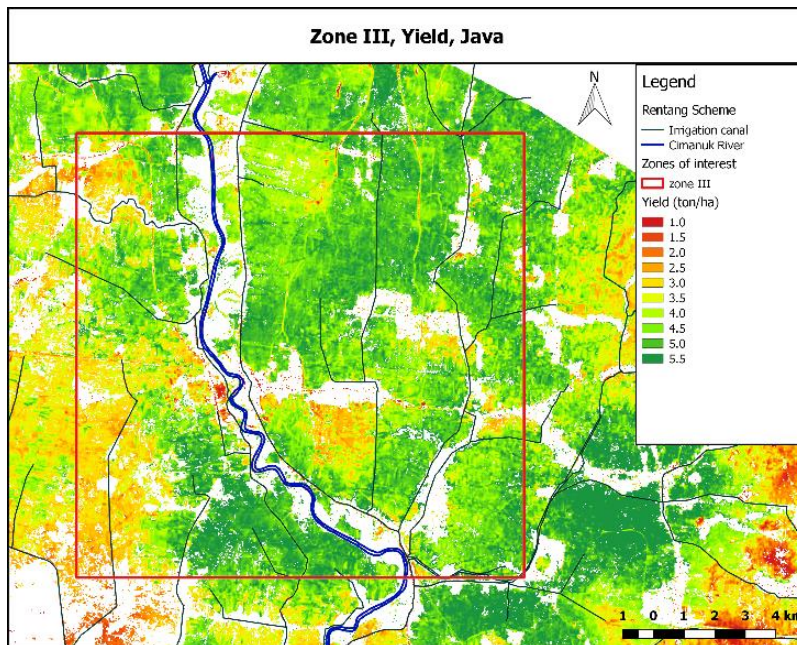


Figure 95: Yield in zone 3, Java

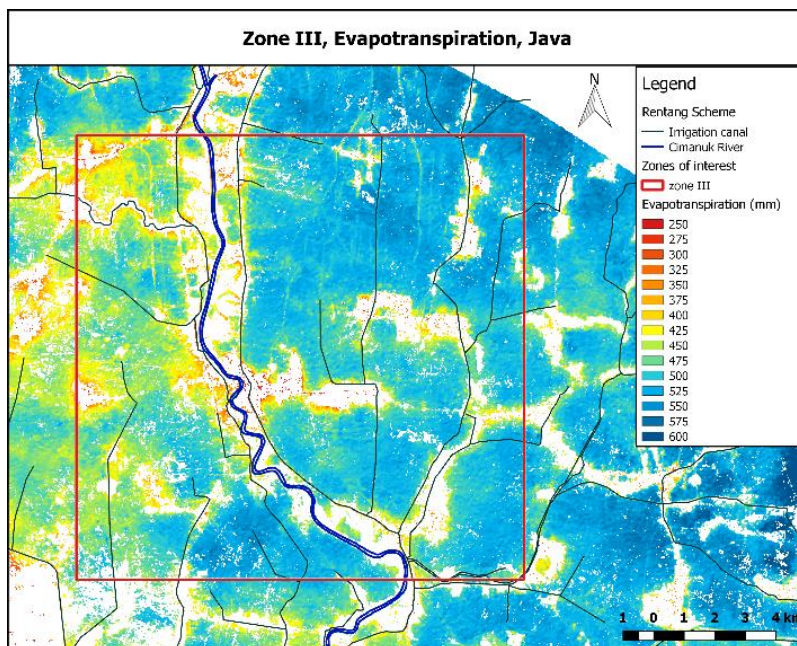


Figure 96: ET in zone 3, Java

The WP in zone 3 is mainly above the average WP for the study area, in contrast to the WP of zone 1 and 2 (see Figure 90). Two regions of low WP are identified, the first red area is located south of the center of zone 3, close to the city Jatibarang, and the second red area is located southwest. Figure 95 and Figure 96 point out that this difference in WP is particularly induced by a low yield.

The relatively high WP of zone 3 in comparison to zone 1 and 2 could firstly be explained by the absence of salt bodies and flood zones. Next to that zone 3 is crossed by the Cimanuk river, a steady source of water.

The fact that the biomass production maps show lower values near the city of Jatibarang, feeds the suspicion of a relationship between pollution, and therefore water quality, as was discovered in Bali 4.1- Water Quality. Data on water quality was not available, and this relation could therefore not be further examined. However, as stated before, high levels of pollution of irrigation canals was observed frequently in the field.

The red region in the southwest of zone 3 is clearly surrounding a secondary canal. It is suspected that the state of this secondary canal is insufficient and the supply of water forms a problem in this region.

Similar as for Bali, it must be noted that possible unexplained phenomena in WP, BP or ET can always be caused by inaccuracies of SEBAL. These inaccuracies, or limitations, are discussed in 5.3.1..

5.1.3. Lombok

In 3.3 -Lombok, the SEBAL outcome is presented for Lombok. Whereas fieldwork has been conducted for Java and Bali, no ground truth research has been done in Lombok. This section attempts to examine the WP distribution for Lombok on the basis of SEBAL outputs and analyses outcomes of Bali and Java. Figure 27, Figure 29 and Figure 32 are examined and some regions show notable results. Just like Bali and Java, three zones have been selected (Figure 97).

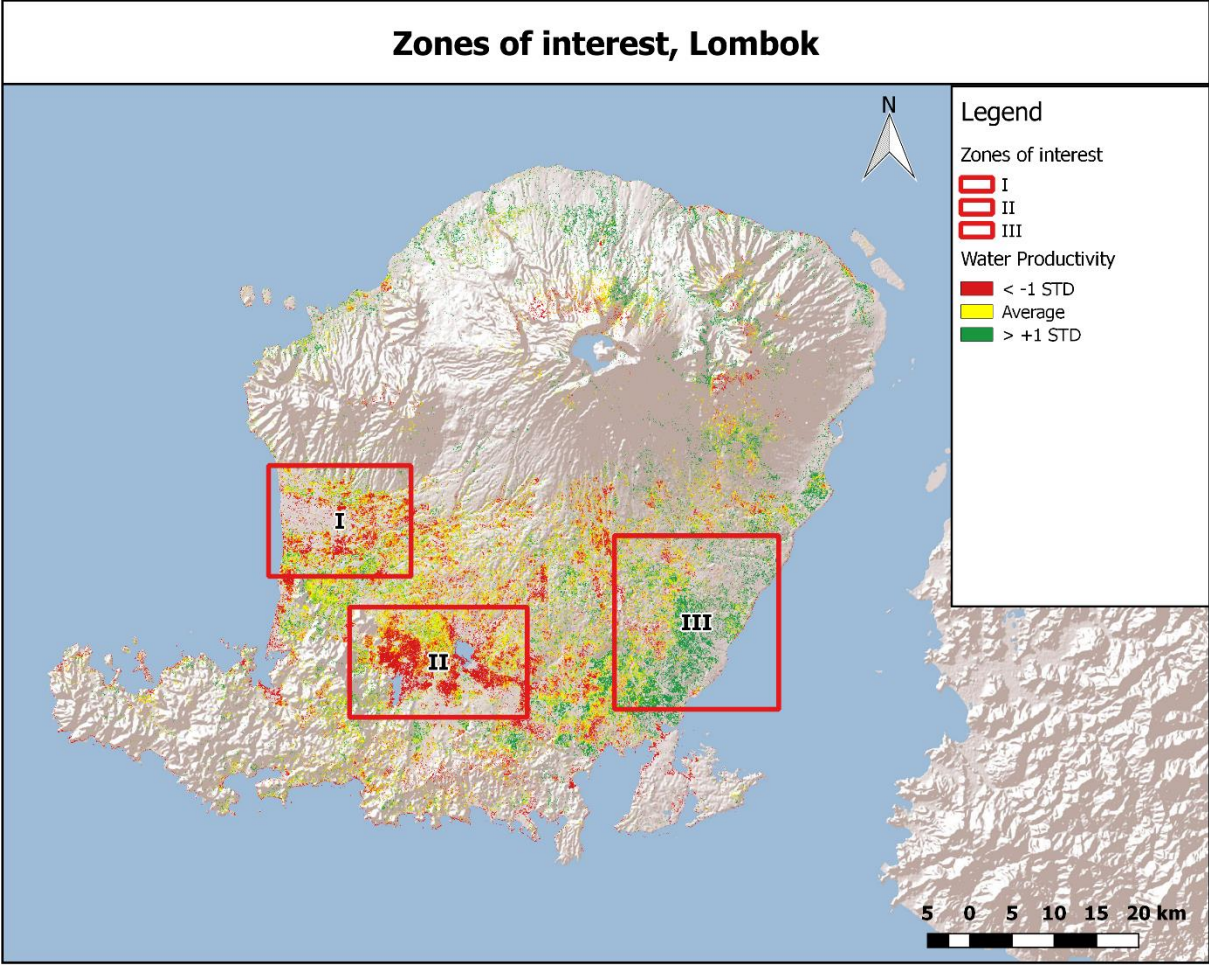


Figure 97: Zones of interest in Lombok

Zone 1

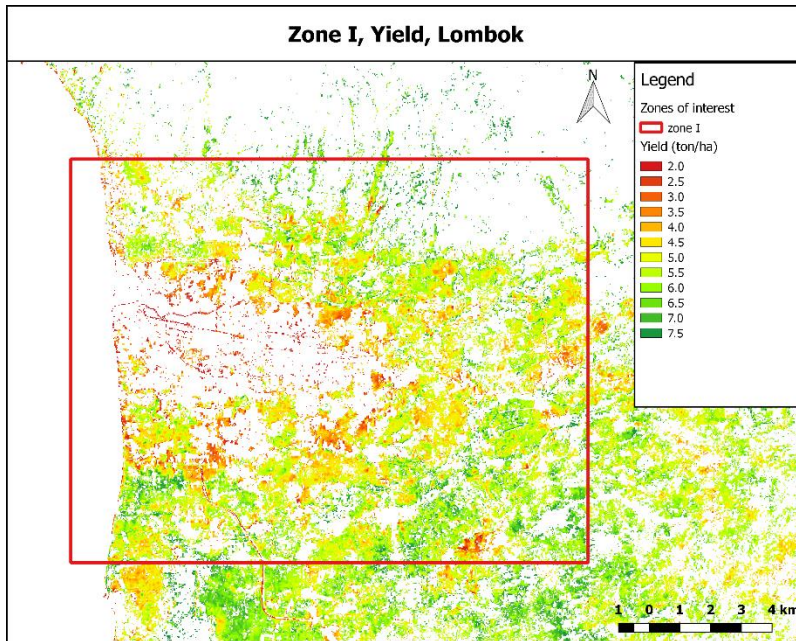


Figure 98: Yield in zone 1, Lombok

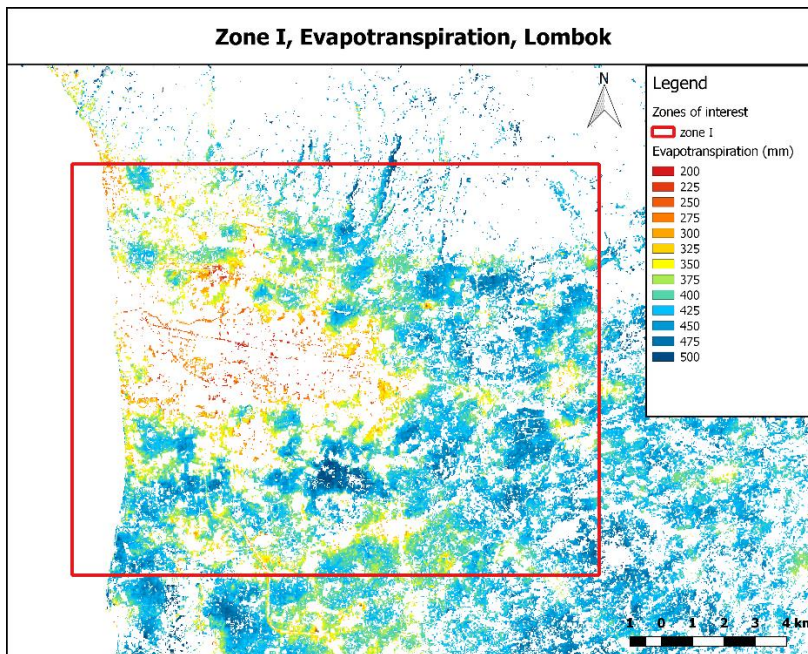


Figure 99: ET in zone 1, Lombok

Zone 1 has a generally low WP and as can be seen in Figure 98 and Figure 99 it does not become clear whether high ET's or low BP is more significant in causing this low WP. Zone 1 is located close to the city Mataram. Considering the relation found in Bali zone 3, between bad water quality in urban areas and low WP, this could be an influential factor in this region too. Next to that zone 1 is close to the sea and therefore salt intrusion may occur, like the Rentang scheme. However, since Lombok's climate and geology is more comparable to Bali, where salt intrusion was not a problem, this argument is not valued as strong.

Zone 2

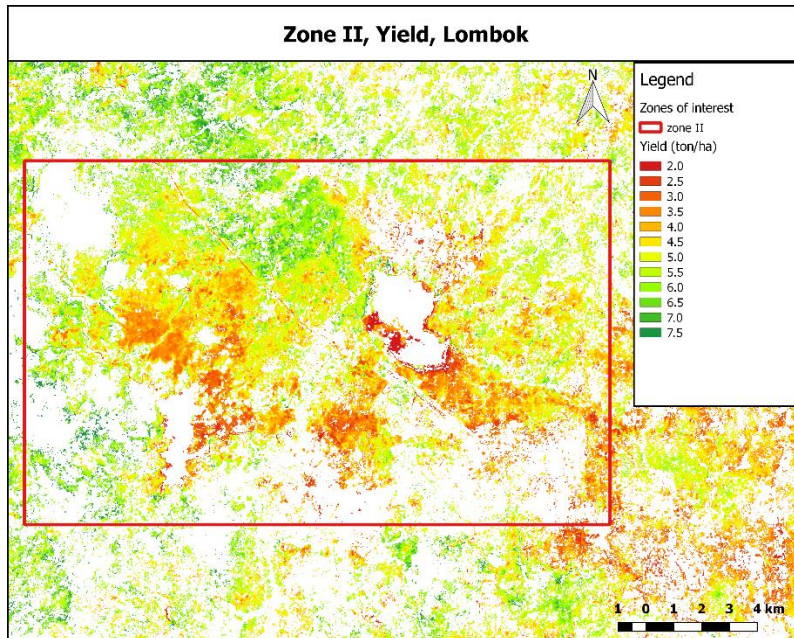


Figure 100: Yield zone 2, Lombok

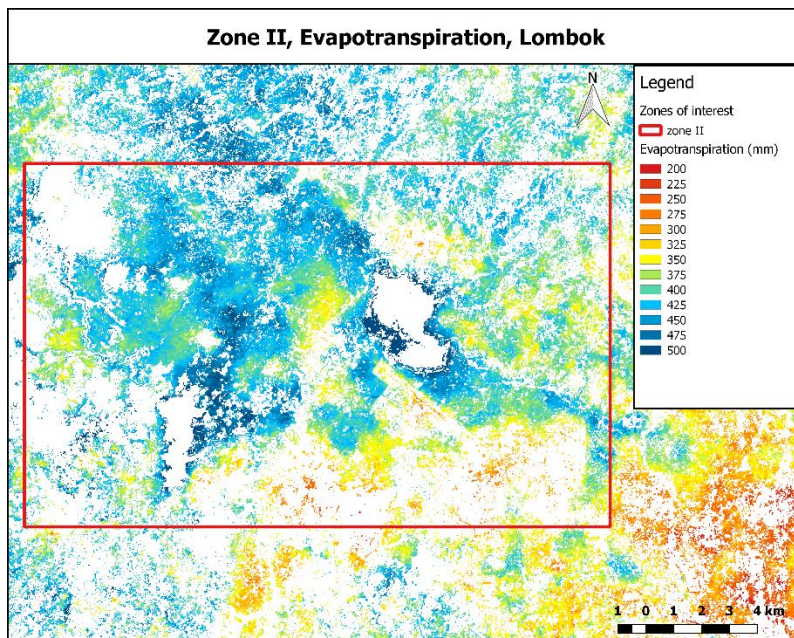


Figure 101: ET zone 2, Lombok

In Figure 97, it can be seen that zone 2 faces the lowest WP in the island and that makes it a zone of interest. Zone 2 knows regions of both low BP (Figure 100), and high ET, (Figure 101). The white body in the center of the Eastern region of this zone is lake Waduk Batujai. The high ET and low yields surrounding this lake can be perhaps be explained by flooding that occurs, or a mistake in crop classification. Since a large water body is present in this region, water scarcity is not likely to be a problem. This suggest that farmers can use as much water as they want and this could explain the high ET in the Western region of zone 2. To the South of this lake, the airport Bandar Udara is located. Planes, people and infrastructure could be a source of pollution that again influences BP, this is supported by Figure 99 and Figure 100 that show low ET values near to the airport, but more importantly very low BP values which influence the WP.

Zone 3

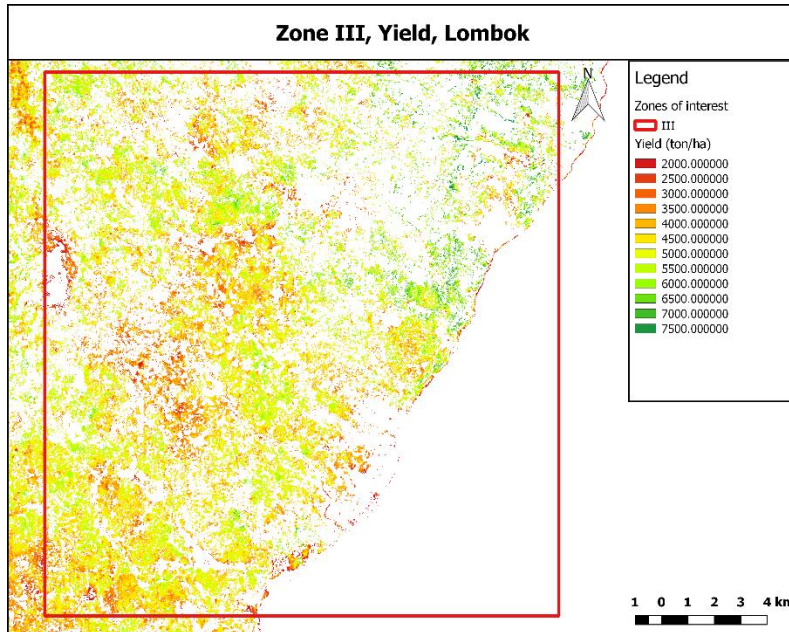


Figure 102: Yield zone 3, Lombok

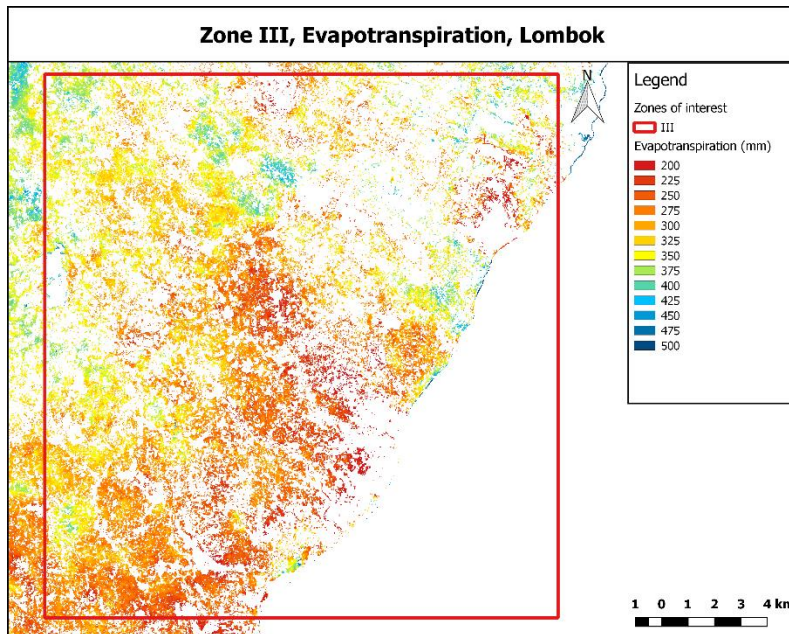


Figure 103: ET zone 3, Lombok

Zone 3 shows the region with the highest WP of Lombok, Figure 97. In Figure 103 it becomes clear that this is particularly caused by low ET-values and some high yield regions in the North-East, Figure 102. It is likely that the apparent absence of factors which have caused low WP values in other areas, namely big cities, salt intrusion, or a water surplus, could be the influential factor for a very high WP in this region.

5.2. HANTS

This chapter discusses the differences between SEBAL based on Landsat images and SEBAL based on VIIRS and PROBA-V data after being processed with HANTS-software.

Using VIIRS and PROBA-V gives a more reliable dataset set in terms of usable images. This is simply because there will be more cloud free images if there is a satellite overpass every day instead of once every sixteen days for Landsat. Per image, the chance that an image is infested with clouds is equal for Landsat, VIIRS and PROBA-V. For Landsat however, the consequences are higher due to the low amount of initial images. The SEBAL results with Landsat as input already have to be interpolated for the missing days, if images are not useful this interpolation-period will only increase.

The difference in resolution makes the VIIRS and PROBA-V data less detailed which gives the preference to the more detailed Landsat images. The next development will be combining the frequent overpasses of VIIRS and PROBA-V with higher resolution of Landsat.

When comparing the VIIRS and the Landsat output maps of SEBAL it is visible that the ETact of VIIRS is higher than ETact of Landsat around the Cimanuk River and the ETact of Landsat is higher near the coast. The last several Landsat images of the period are infested with too many clouds and therefore unusable.

For this reason, the latest usable image of the period is interpolated for a larger number of days. This last unusable Landsat image represent the period where areas around the coast are still in growing phase with much water on the field, while more land inwards the period is already further in the phase where no water is on the field anymore. This image is interpolated for the remaining 50-days, creating a distorted impression of the situation. In contrast, the daily images of VIIRS and PROBA-V interpolate these cloud pixels using cloud free pixels of the other days of the year. Therefore, the final period of the paddy season is considered more accurately using VIIRS and PROBA-V data through HANTS, than using Landsat images in SEBAL directly. The ETact of the VIIRS map in Figure 51 shows that there is no particular area with higher or lower evapotranspiration pixels. In contrast, the ETact of the Landsat-based map in Figure 80 for the same pixels range, shows higher evapotranspiration around the coast. This difference supports the hypothesis of the distorted effect caused by the interpolation of the last usable Landsat image.

The values for biomass production of VIIRS are in general higher than the values for biomass production of Landsat (Figure 81) The reason for this could be that all steps of the rice process are taken into account due to the daily data of VIIRS. This is the same case for the yield map of VIIRS, which is the biomass production map with a yield factor over it.

The water productivity difference map of Figure 82 shows that the majority of the pixels are green, which indicates that there is no difference between the WP of VIIRS and the WP of Landsat. This stands out especially compared to the evapotranspiration and the biomass production difference maps. WP is the ratio between yield and ET. The yield and ET are both larger for VIIRS-based maps than for the Landsat-based maps. As the average WP of the map remains fairly constant when comparing the two methods, the factor of yield increase and ET increase for VIIRS compared to Landsat is thus similar for Java.

5.3. Limitations of Research

5.3.1. SEBAL

The SEBAL model depends on satellite images and meteorological data as input. The best results will come from cloud free satellite images and meteorological data from a weather station which represents the conditions in the study area. However, in reality this is not always the case. In case of clouds, the SEBAL model will erase cloud infested pixels from the output maps. The resulting gaps will be filled by a gap filling algorithm. This is a good solution when there are small clouds within the study area. However, if there are too many clouds this is not possible and the satellite image has to be disregarded. Within a growing season there will always be a couple of images that cannot be used because there are too many clouds. This is not a problem when the majority of the images are useful, but it can get problematic when more images (especially images in succession) are infested with a lot of clouds. The current works on the HANTS algorithm in combination with the VIIRS and PROBAV satellites are very promising when it comes to dealing with clouds.

The meteorological data is dependent on the weather stations closest to or in the area of interest. Since SEBAL requires several parameters in order to function, a station needs to be present which records all of this data. If this is not the case, data needs to be gathered from different stations, which might not represent the conditions in the area perfectly. The geography around the weather station compared to the study area is important when choosing a station for this data. A weather station near the mountains can

for example have different sunshine hours compared to a weather station in a flat plain. All these issues with the availability and quality of the meteorological data can have an influence on the SEBAL results.

The Biomass production maps from SEBAL are multiplied with a yield factor, or harvest index, to get the yield maps. This yield factor typically varies between 0.2 – 0.55 but the exact value needs to be verified with yield data from the field. Accurate yield data is however not always accessible or noted down which makes it difficult to determine the exact yield factor. For this study an average yield factor is determined, which influences the transition between Biomass production maps and Yield maps linearly and can therefore alter the outcome of the WP maps. Next to that, this yield factor can vary spatially through the area in case of for example different rice types or harvest conditions. During fieldwork, data on rice types was attempted to be obtained, but unfortunately no useful data was acquired.

The SEBAL output maps must be combined with a crop classification in order to compare the ET, biomass and WP for a single crop. The crop classification map is not perfect which results in miss-classification of pixels. This is especially relevant for areas with very heterogeneous landscapes, like the study area in Bali. Here rice is grown in the mountainous areas as well as in coastal areas. Rice paddies in both these areas can have very different characteristics, making classification more difficult. Errors in the classification process causes errors in the resulting maps. For example, the WP map shows relatively low water productivity values for the entire shoreline of Bali. The shore is sometimes misclassified as rice paddies while in fact these areas are beaches. This is caused by very similar signal patterns for both land type classes, on which the applied crop classification is based. Improving this classification would yield more accurate results for the WP analysis.

Another important input for the SEBAL model is the start and the end date that is chosen. This period of time has to be chosen with care. For this research one growing cycles of rice was chosen. However, it is important that the right start and end date is chosen to ensure exactly one growing cycle is captured. If the start and end date are chosen wrongly, there is a possibility that only part of the cycles is captured. It is also possible that part of the previous or next cycles is included. Discovering the right period turned out to be more difficult than expected as not every region follows the rice planting guidelines, and different regions (or even farmers only a few plots apart), follow a different season. Choosing an incorrect period can result in incorrect values for the ET and biomass production, and thus the WP.

Within an irrigation scheme the SEBAL model can be used to locate and compare areas of interest to, for example, locate areas where the irrigation system could be improved. As stated, local insecurities such as yield factor, meteorological data and cropping pattern influence the water productivity. However, if these insecurities are constant for one region, the SEBAL-outcome still has a high value for local comparison. Nevertheless, comparing completely different regions based on just the WP (and ET and biomass production), is difficult. This is the case as the WP on itself is very hard to compare without local context. Farmers in completely different regions might be producing at the top of their ability (given local conditions), but can have a completely different WP. Therefore, local context should always be kept in mind.

5.3.2. VIIRS, PROBA-V and HANTS

By using VIIRS and PROBA-V data, and therefore having the ability to use HANTS to remove clouds on the data, is a very promising new method. However, at this point finding the best cloud removal fit by HANTS

can be difficult. The parameters for the cloud removal are chosen by visual inspection. This makes it person dependent what is chosen as the best fit. The parameters chosen can affect the algorithm and thus its results. Trying different parameters and assessing them is a time-consuming task. In order to get the VIIRS and PROBA-V data working in SEBAL, a different model calibration is needed. This calibration should be carefully examined for different regions as it can differ from the Landsat calibration.

The amount of data and linking this data in the SEBAL excel sheet is something to take into consideration. For NDVI, SAVI, Albedo, and VIIRS temperature, daily images are available, which need to be linked to all the locations which are connected to the meteorological data of the corresponding days of data. For Landsat there is only one complete image that needs to be linked and this image is every 16 days. This means less work for Landsat to prepare the Excel sheet for SEBAL.

5.3.3. Fieldwork

Fieldwork and its results are an important part of this report. Collecting the data needed for the analysis can be difficult. Data might not always be available. There are several institutes responsible for the irrigation system and the agricultural areas (Balai, Ministry of Agriculture and PSDA), who all have records of different aspects of the system (for example yield and pest data). The complexity of this institutional system makes it more difficult to get access to the required data.

Additionally, data is often not open-source and is not accessible via internet. The only way data for this research could be accessed at institutes was by visiting the offices and providing a letter from the Indonesian partners at the ministry of Public Works, while accompanied by a local guide. Request for digital data, instead of hardcopy, was often rejected. However, after these procedures a lot of required data could be obtained.

For this study the language barrier created some difficulties in the fieldwork. This was visible in both the interviews with farmers and in conversations with the many different institutes. The language barrier created some miscommunications and made it harder to exchange ideas and information.

Finally, data acquired via interviews with farmers may contain some inaccuracies. Of course, farmers will know their own fields, but their quantification of, for example yields and water usage, can still contain errors. Next to that farmers were often met in groups, so exaggeration of for example yield must be kept in mind.

6. Conclusion

In this research the Water Productivity of paddy rice is mapped for sites in Bali, West-Java, and Lombok using SEBAL. The resulting maps show a high variety in ET, Yield and WP for all study areas. In Bali the distribution is more dispersed in comparison to the distribution in West Java and Lombok, where the maps show a more clustered pattern.

Promising relationships have been found between the WP and several factors, namely the distance of a paddy to the irrigation canal, salt farms, water quality, and erosion levels.

Analyses of water quality in Bali show a clear relation between water quality and the biomass production that is estimated with SEBAL. It strongly suggests that BOD and COD values above average indicate lower biomass production values, and BOD and COD values below average in general indicate higher biomass production values. In Bali, high BOD- and COD-values were discovered in the urban area around Denpasar, where also yield is discovered to be under-average. Observations in the field as well as interviews with institutes point out that pollution in this urban area is a likely cause of lower yields.

In addition, the results in Bali demonstrate a relation between the level of erosion and the ET. A higher level of erosion implies lower ET values. For biomass this relation between the level of erosion and the extent of biomass is less clear.

The WP map produced in West Java, clearly shows that the WP of rice paddies is lower with increasing distance from the irrigation canals. Ground truth confirms this relation, as institutes and farmers often indicated water shortages at locations further away from the canals and main river.

Moreover, WP adjacent to salt farms appears to be relatively low according to the maps produced with SEBAL. This is in agreement with earlier researches conducted on salt intrusion in Northern Indramayu, in which is stated that existing salt intrusion has negative effects on rice paddies (Erfandi and Rachman, 2013).

This research suggests to further examine the relation between WP and water quality, erosion, distance to canals, and salt intrusion for the considered areas, as these can be interesting for further investment purposes. To illustrate, if it turns out that water quality is a significant (limiting) factor in the WP, effective investments in improving this quality can be made. Further research is also suggested in the practice of flooding the rice field with irrigation water in intermittent time-intervals, compared to continuous flooding. Farmers have indicated that they believe intermittent farming results into higher plant populations (number of stems per rice plant). Though this topic is outside the scope of this research it may have an impact on the WP and thus is worth conducting further research on.

Besides the suggested topics for further research, this pilot study has several other recommendations. Firstly, a more detailed understanding of the ET of rice paddies can be obtained by comparing the ET of the SEBAL output (the actual ET) to the reference ET, which is the environmental demand of ET of the reference crop (grass). Secondly, to obtain an accurate reference ET and to improve the SEBAL inputs, more weather stations should be present close to, or inside of, the study area. Currently the spatial distribution of weather stations is low, and several stations are lacking data. Finally, it is recommended that further attention is paid to the definition of rice yield. Farmers, institutes, and literature use various definitions. These definitions mainly differ on whether the rice is husked or unhusked and on the amount of moisture which the rice contains. When converting the biomass maps into the yield maps this definition is of great importance.

This pilot project has introduced this new remote sensing approach of mapping WP using SEBAL in Indonesia to discover its challenges and opportunities. It has succeeded to map and assess the WP for three different study areas with varying landscapes and contexts. All three sites have their own specific criteria and needs to be assessed individually. For example, the growing seasons that needs to be chosen for SEBAL and the crop classification algorithm, are site specific and may vary within one site too. Moreover, it is important that the context of each area is considered when analyzing the results.

Although the resulting maps seem to provide a good indication of the WP in the concerned areas, the accuracy and further understanding of the results could be even further improved when the method is applied by local experts. When being more familiar with the local context, concerning agriculture practices, institutional framework and local customs, data enquiries become easier. For example, using accurate yield data at farmer scale, would further improve the conversion from biomass to yield. In addition, having both extensive knowledge on local conditions and access to comprehensive data sets, allows for an even better understanding of the WP distribution. This in turn improves the applicability of the WP outputs for policy-making.

In addition, assessing the WP with SEBAL can even further be improved by expanding the assessment using the software HANTS. Through HANTS more satellite data is used, which makes a more extensive interpolation possible, leading to higher quality inputs for SEBAL. Within this research the first outputs of SEBAL using HANTS have been established for West Java. Using this method could lead to a great improvement in accuracy of the SEBAL results. Further analysis on the results are beyond the scope of this pilot study.

Overall, from this research it can be concluded that the resulting WP maps are a reasonable indication for the WP distribution in study sites in West Java, Bali and Lombok. Given the objectives of the government to rehabilitate the irrigation system, in order to assure the staple food of the country in a sustainable way, further expansion of the WP method throughout Indonesia seems very promising.

7. Appendices

7.1. SEBAL

7.1.1. Appendix material Bali:

Yield factor

Table 2 Yield factor calculation data for Bali

| Kecamatan | yield (ton/ha) | Biomass (ton/ha) | yieldfactor |
|----------------|-------------------|---------------------|-------------|
| Mengwi | 6.24 | 11.75 | 0.53 |
| Petang | 5.91 | 13.76 | 0.43 |
| Kuta | 4.07 | 10.22 | 0.40 |
| Abiansemal | 6.51 | 12.53 | 0.52 |
| Kediri | 6.20 | 11.44 | 0.54 |
| Pupuan | 5.46 | 12.64 | 0.43 |
| Tabanan | 6.13 | 11.76 | 0.52 |
| Selemadeg | 4.38 | 13.31 | 0.33 |
| Baturiti | 5.60 | 12.51 | 0.45 |
| Marga | 4.00 | 13.26 | 0.30 |
| Kerambitan | 5.86 | 12.12 | 0.48 |
| Penebel | 6.13 | 12.78 | 0.48 |
| Average | 5.54 | 12.34 | 0.45 |

7.1.2. Appendix material Java:

Yield factor

Table 3 Yield factor calculation data for Java

| Fieldpoint | Yield (ton/ha) | Biomass production (ton/ha) | Yieldfactor |
|------------|----------------|-----------------------------|-------------|
| E003 | 3.0 | 4.9 | 0.61 |
| E006 | 3.2 | 10.2 | 0.31 |
| E008 | 3.0 | 10.2 | 0.29 |
| E010 | 3.8 | 8.0 | 0.48 |
| E011 | 5.5 | 10.5 | 0.52 |
| E012 | 5.0 | 7.4 | 0.68 |
| E014 | 0.3 | 8.0 | 0.04 |
| E015 | 3.5 | 7.8 | 0.45 |
| E016 | 6.0 | 7.9 | 0.76 |
| E017 | 5.0 | 7.6 | 0.66 |
| E018 | 4.0 | 9.9 | 0.40 |
| E019 | 3.5 | 10.6 | 0.33 |
| I004 | 6.0 | 9.0 | 0.67 |
| average: | 4.0 | 8.6 | 0.48 |

7.2. Analyses

7.2.1. Bali

Interview locations Bali

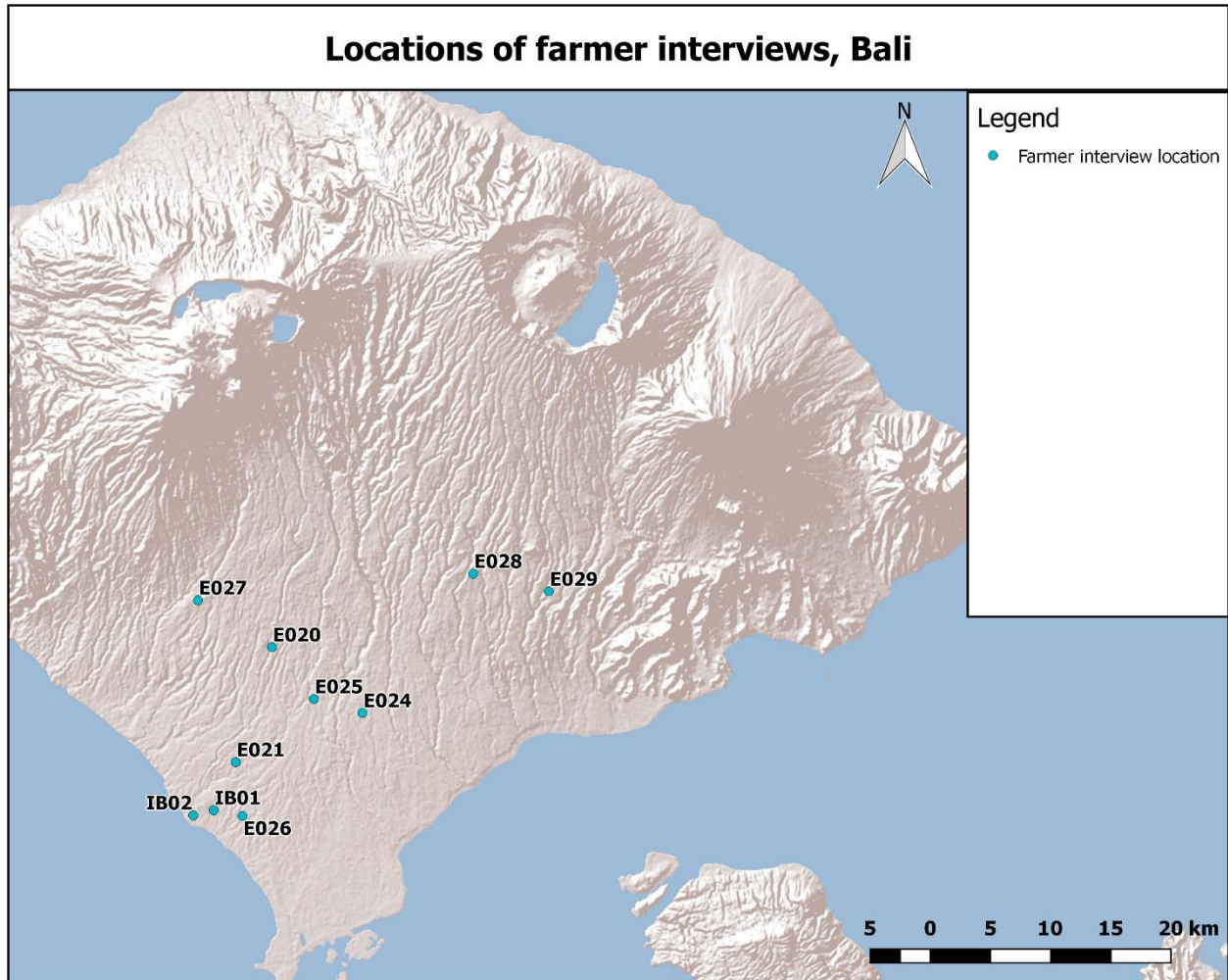


Figure 104 Interview locations Bali and the corresponding field note numbers

Water Quality

Table 4 Measurement numbers and stations, high BOD and COD values marked red

| Measurement station number | River |
|----------------------------|--------------|
| 25 | Tk. Yeh Hoo |
| 26 | Tk. Sungai |
| 27 | D. Beratan |
| 28 | D. Beratan 2 |
| 29 | D. Beratan 3 |

- 31 Tk. Yeh Aba
- 32 Tk. Yeh Empas
- 34 Tk. Yeh Mawa
- 35 Bendungan Telaga
Tunjung
- 36 Bendungan Telaga
Tunjung 2
- 37 Tk. Badung
- 38 Tk. Badung 2
- 39 Tk. Badung 3
- 40 Tk. Badung 4
- 41 Tk. Badung 5
- 42 Tk. Mati
- 43 Tk. Mati 2
- 44 Tk. Mati 3
- 45 Tk. Oos
- 46 Tk. Oos 2
- 47 Tk. Petanu
- 48 Tk. Petanu 2
- 49 Tk. Sangsang
- 50 Tk. Pakerisan
- 51 Tk. Melangit
- 81 Tk. Penet
- 82 Tk. Ayung
- 83 Tk. Ayung 2
- 84 Tk. Ayung 3
- 85 Tk. Ayung 4
- 86 Tk. Ayung 5
- 87 Tk. Ayung 6

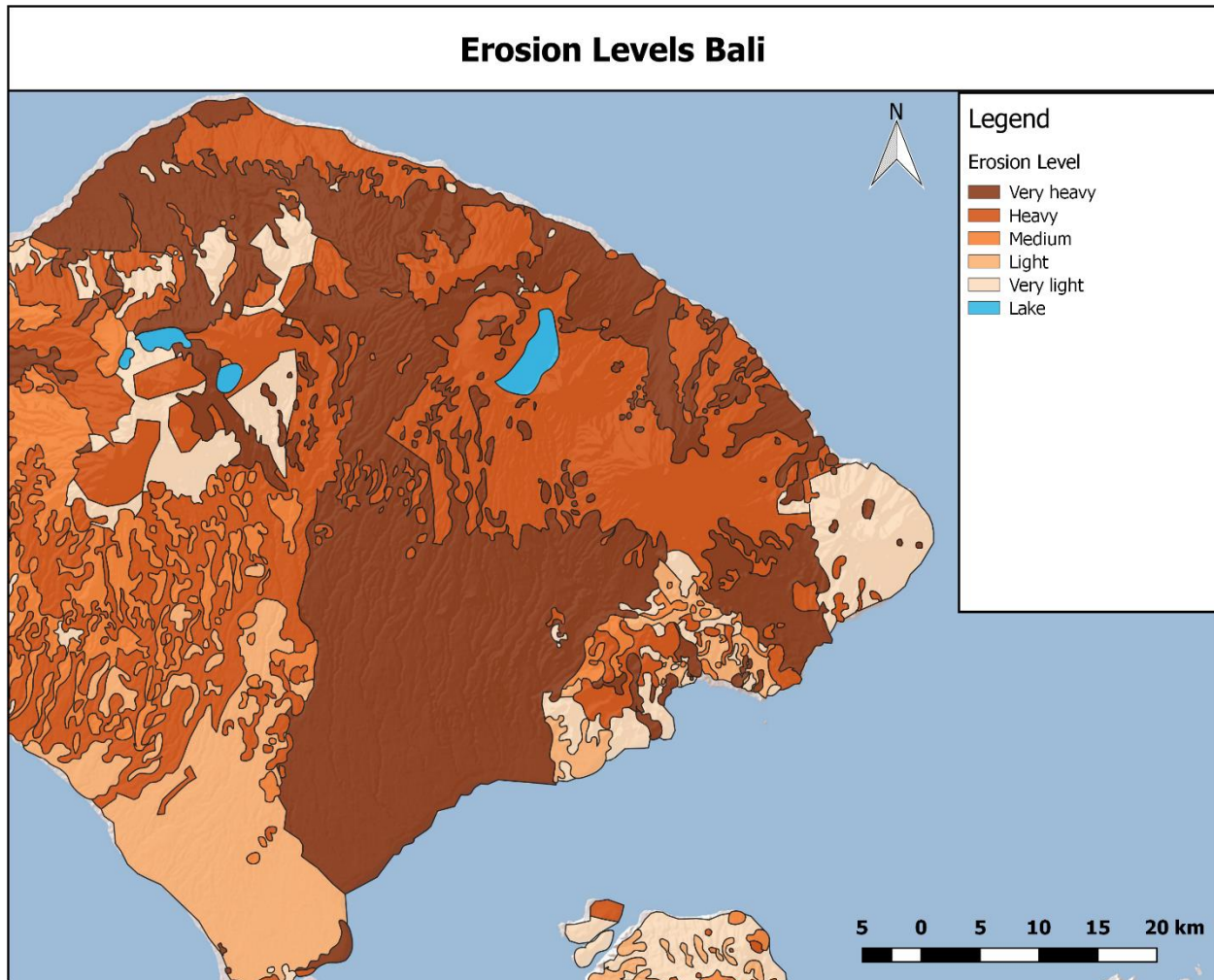
Erosion Level

Figure 105 The erosion level classification for Bali

Pests

The only data about pests on Bali was acquired in the Badung district and shown in Table 5. The areas shown are total area influenced by a pest, so not only failed harvests. In the last column, the percentages compared to the total area of rice production per district is shown. The highest areal percentage influenced by a pest in the investigation period, halfway June until halfway October 2016, occurred in the Mengwi subdistrict and was less than 4 %.

Table 5: Area influenced by a pest from June to October 2016 in the Badung district

| Kecamatan | Rats[ha] | Tungro[ha] | Wr Coklat[ha] | Stemborer[ha] | Peny Kresek[ha] | Blas[ha] | Total [ha] | Total [%] |
|--------------|----------|------------|---------------|---------------|-----------------|----------|------------|-----------|
| Kuta Selatan | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0% |
| Kuta | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0% |
| Kuta Utara | 2 | 0 | 0 | 8 | 0 | 0 | 10 | 1.4% |
| Mengwi | 9 | 1 | 7.75 | 33 | 4 | 0 | 54.75 | 3.9% |
| Abiansemal | 10 | 0 | 0 | 3 | 0 | 1 | 14 | 0.8% |
| Petang | 12 | 0 | 0 | 0 | 0 | 5 | 17 | 2.1% |

Rainfall

Bali has several weather stations located in the investigated fieldwork area of Bali. In Figure 106 and Figure 107 respectively, the rainfall vs water productivity (WP) and the rainfall vs ETual (ET) can be found. The WP and ET data are mean values of a buffer of 4km around the weather stations (using zonal statistics in QGIS). The rainfall data are from the weather stations given in millimetres of rain for the period of half June until half October.

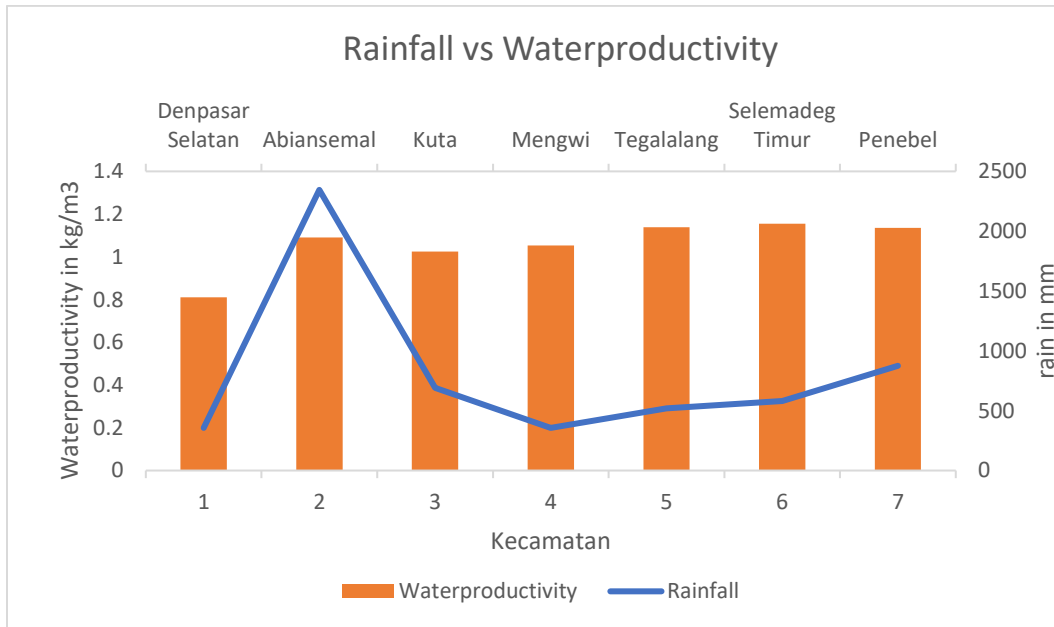


Figure 106 Rainfall vs Water Productivity in 4km buffers around the weather stations

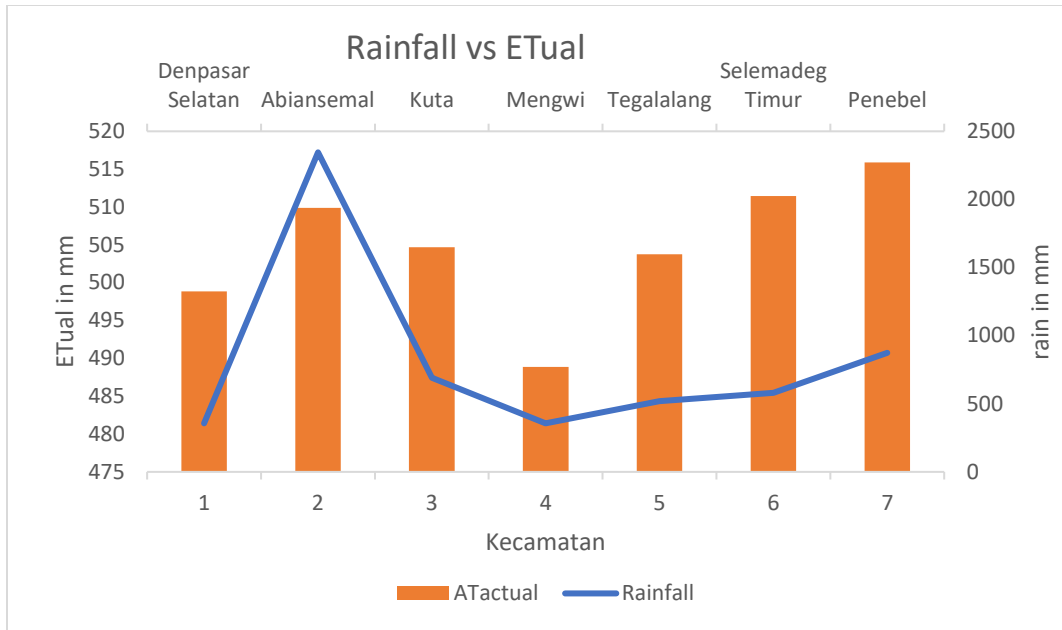


Figure 107 Rainfall vs ETual in 4km buffers around the weather stations

When analysing the rainfall data with the water productivity (WP) and ETual (ET) maps no clear relation is found between rainfall and the WP and ET in a 4km buffer around the weather stations.

Distance to sea

The values for water productivity-, evapotranspiration- and biomass production of the SEBAL maps are plotted against the distance to the sea. For this analysis, a site has been selected at the west coast of Bali where a lot of rice is produced and where red water productivity areas are identified near the coast. Next to that, the distance-to-sea analysis is performed on three catchments within this site, namely the Das Yeh Abe catchment, Das Yeh Empas catchment, and Das Celukapuh catchment. All the rivers on Bali approximate a perpendicular position compared to the coast line, this means that the distance to the sea is approximately inversely related to the downstream distance per river. The graphs are shown in Figure 109 of the Appendix.

Trend lines are inserted to fit the scatterplots, but all the graphs except the Das Celukapuh catchment have R squared values less than 0.1. The Das Celukapuh plot however shows higher R squared values, with a maximum of 0.7025 for the linear relation between the evapotranspiration and the distance to the sea. This seems to suggest that, closer to the sea results in a higher evapotranspiration in this catchment. However, as this relationship cannot be detected for the other catchments it may simply be coincidence.

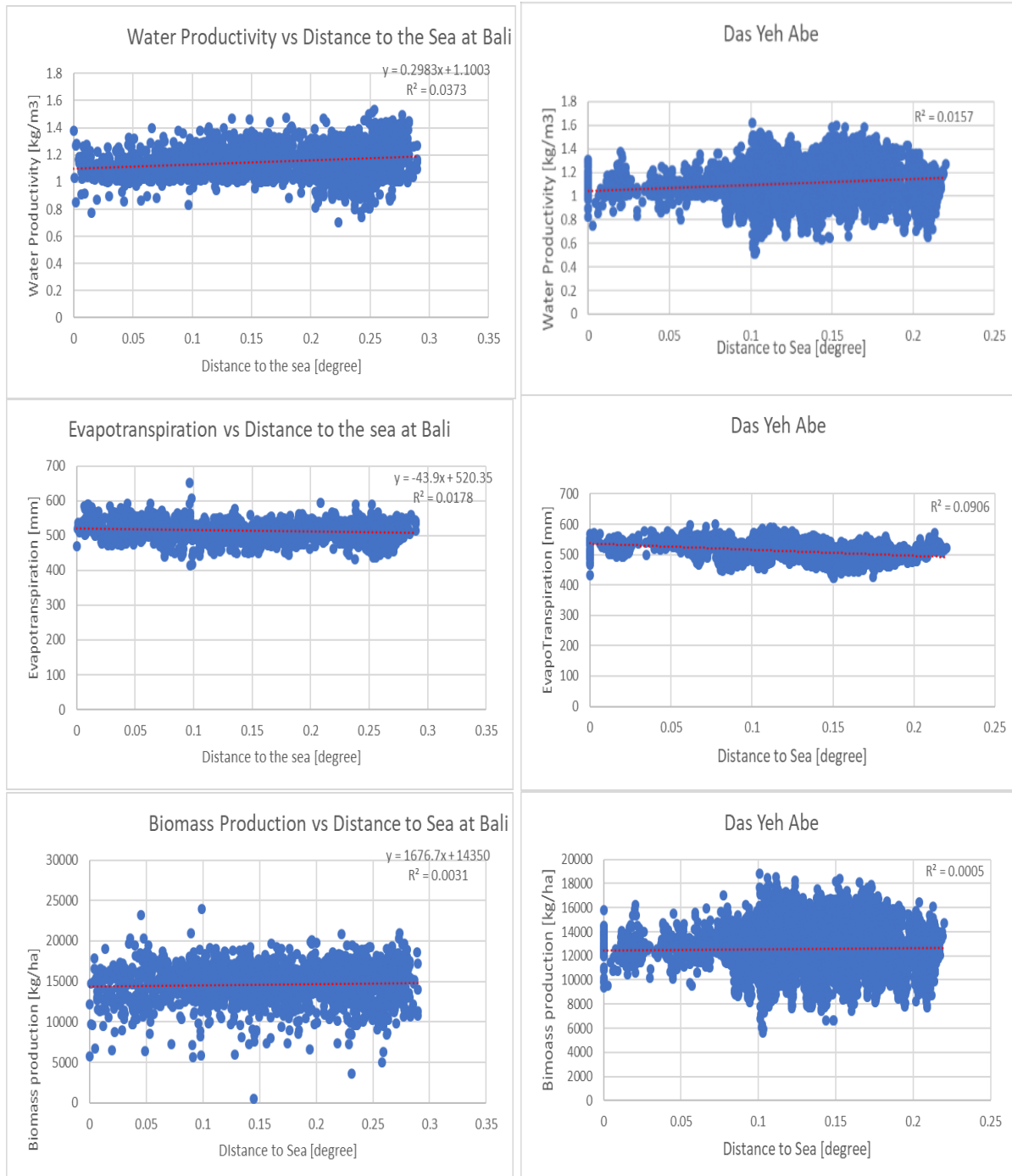


Figure 108: Scatterplots of Water productivity, evapotranspiration and biomass production versus the distance to the sea at the general investigation site in Bali and in the Das Yeh Abe catchment

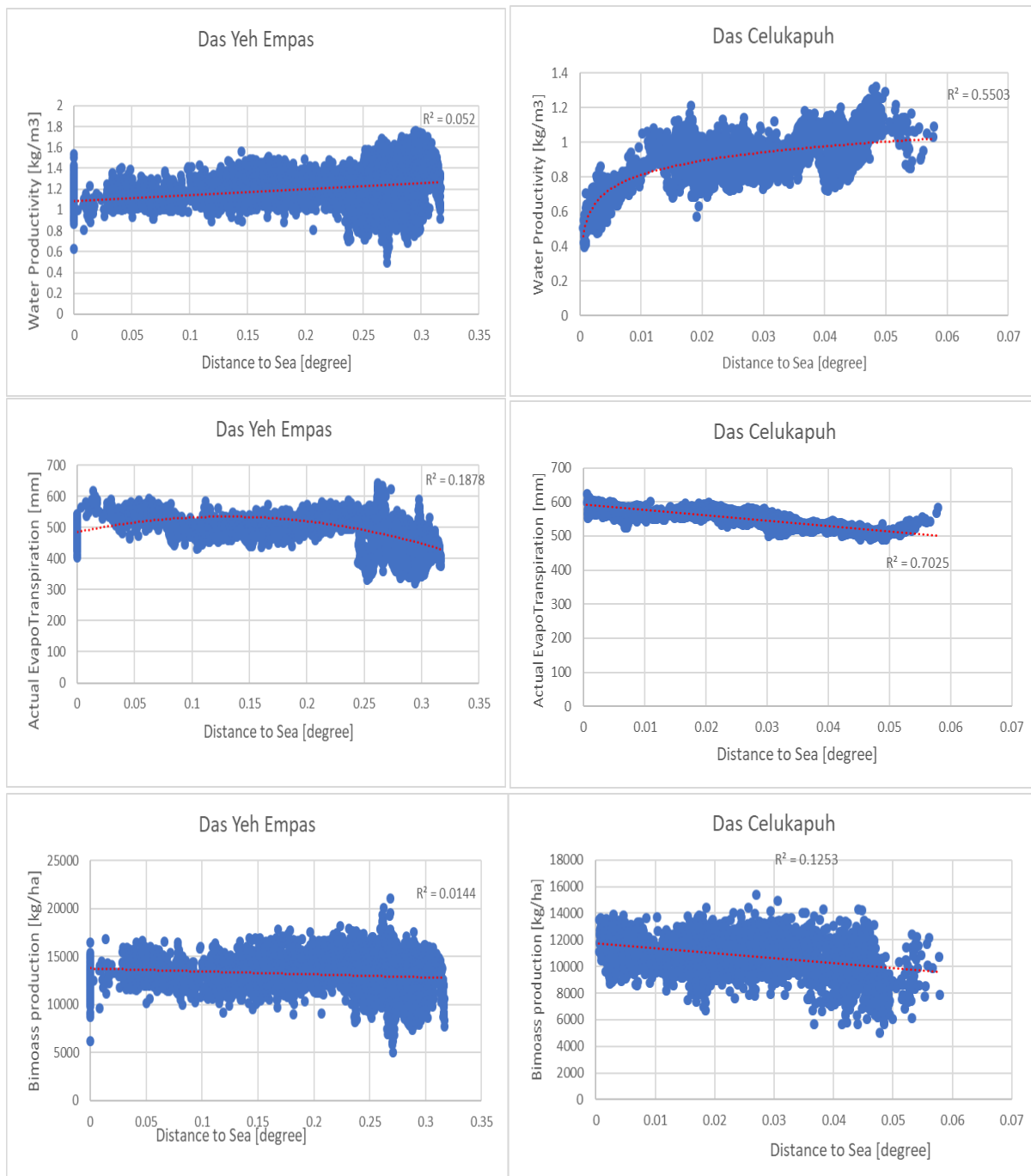


Figure 109: Scatterplots of Waterproductivity, evapotranspiration and bimooass production versus the distance to the sea at the Das Yeh Empas catchment and in the Das Celukapuh catchment

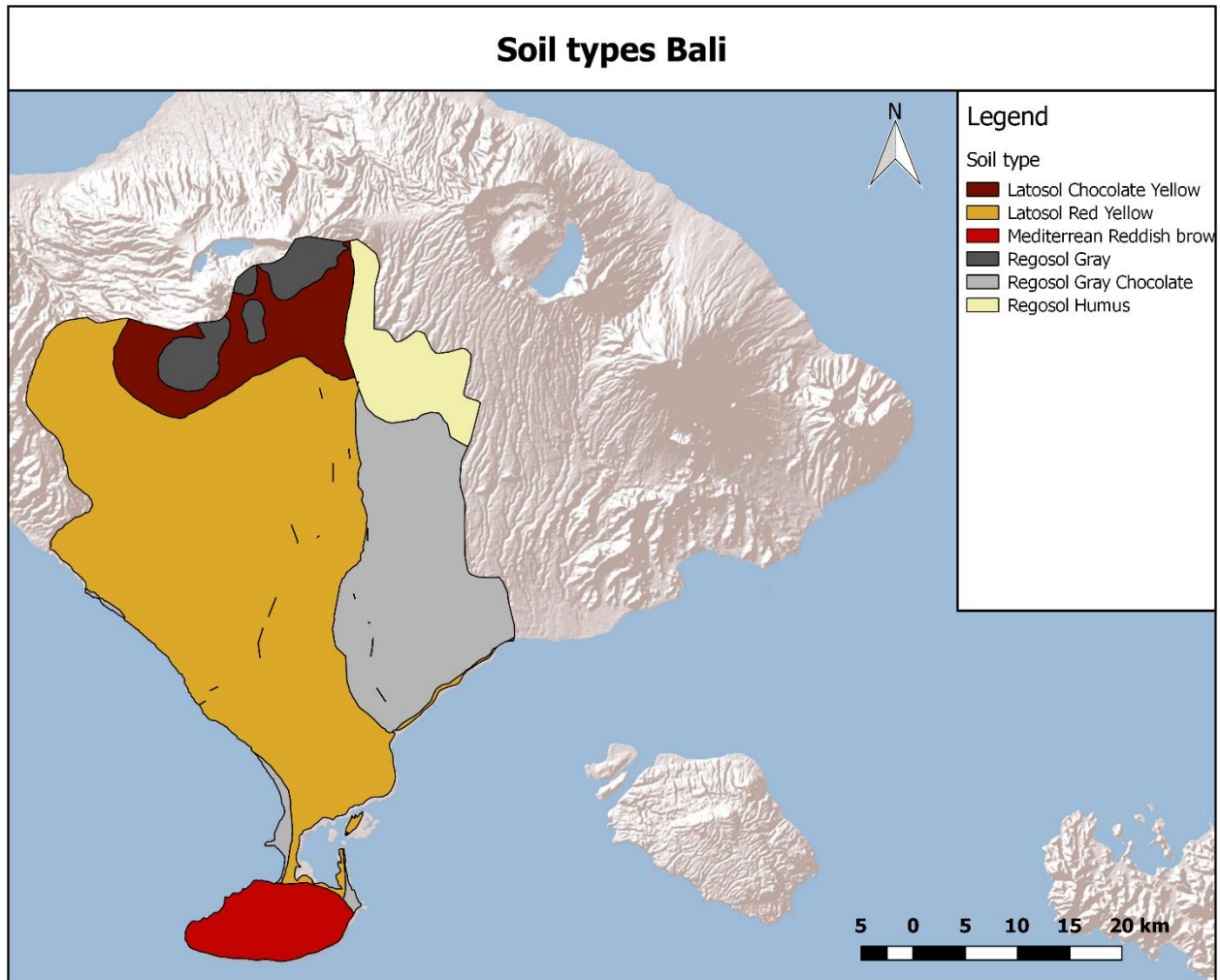


Figure 110 The spatial distribution of soil types

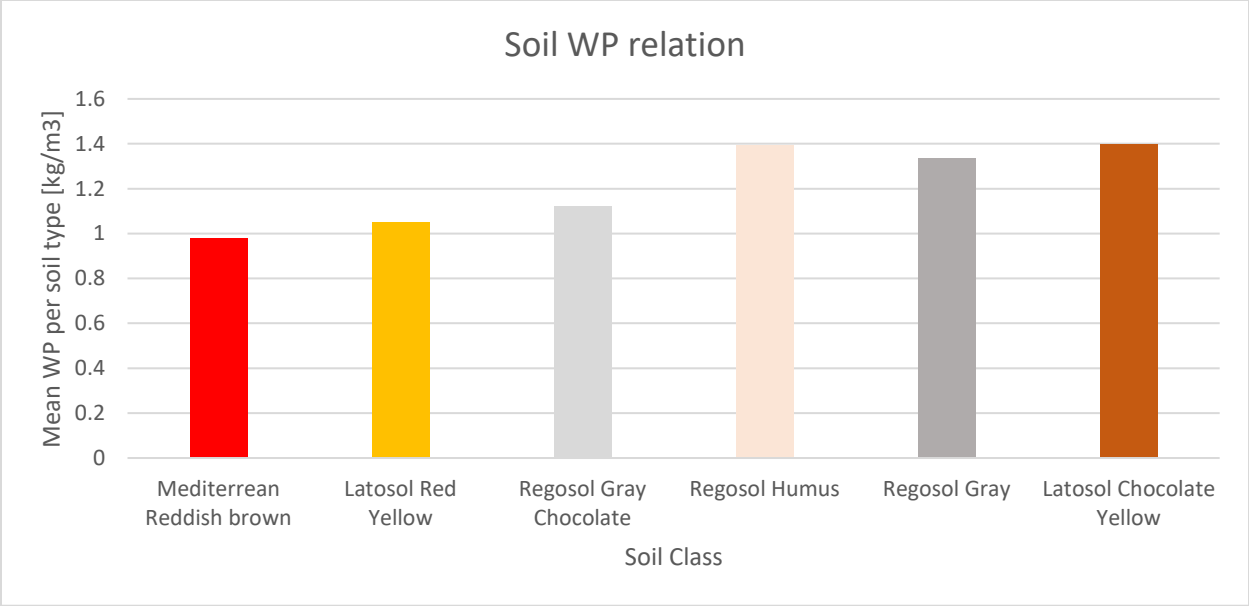


Figure 111 Soil WP relation

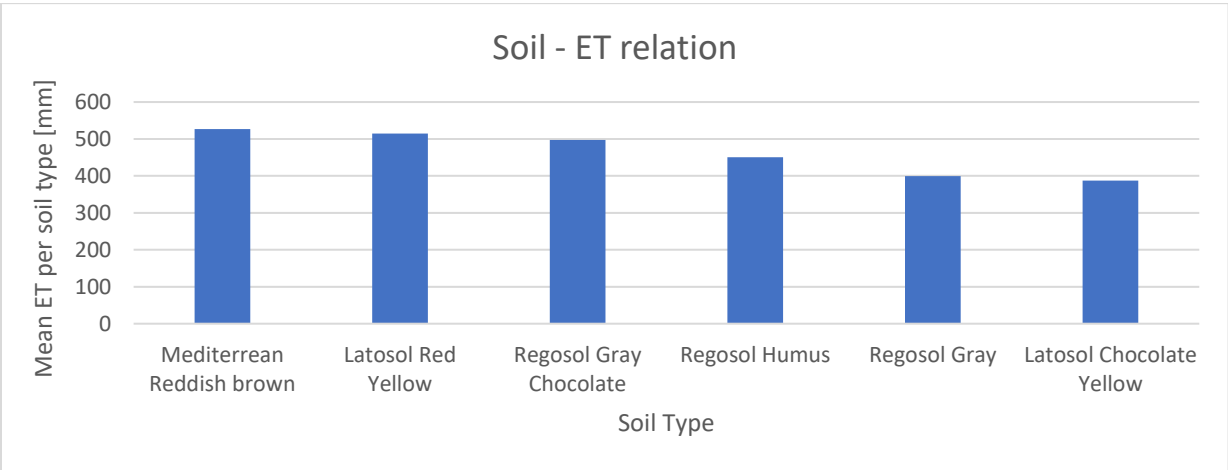


Figure 112 Soil ET relation

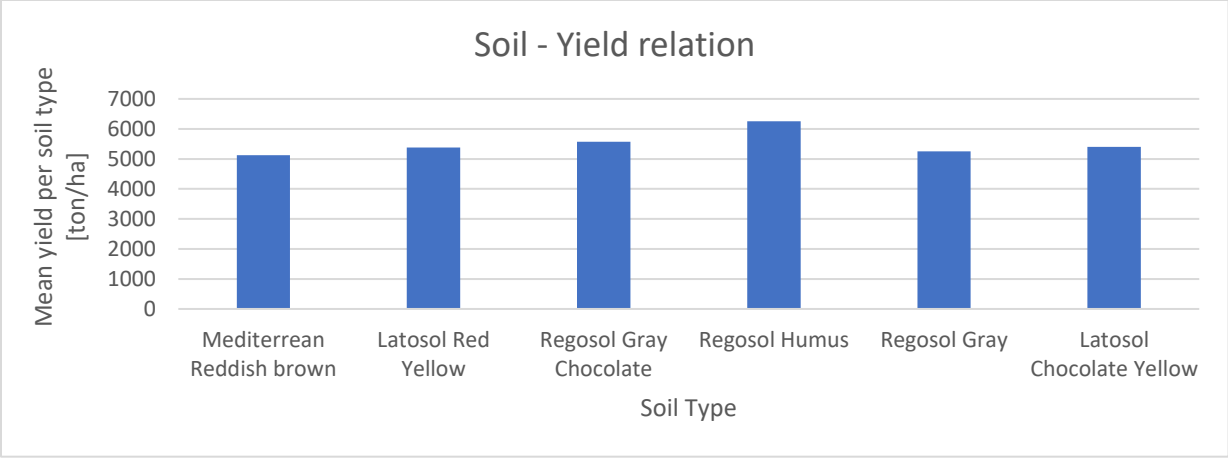


Figure 113 Soil Yield relation

The figures above (Figure 111, Figure 112, Figure 113) show the mean of each factor (WP, ET, yield) per soil type, constructed using zonal statistics. In order to analyse these graphs, further knowledge should be obtained on soil characteristics. When sorting the graphs on ET from high to low the relationship with the WP seems to be most linear. This will only be logical if Mediterranean Reddish Brown is the most impermeable, Latosol Chocolate Yellow is the most permeable, and Humus the most fertile of all soils (as Humus distorts the linear relationship because of its high yield).

7.2.2. Java

Yield

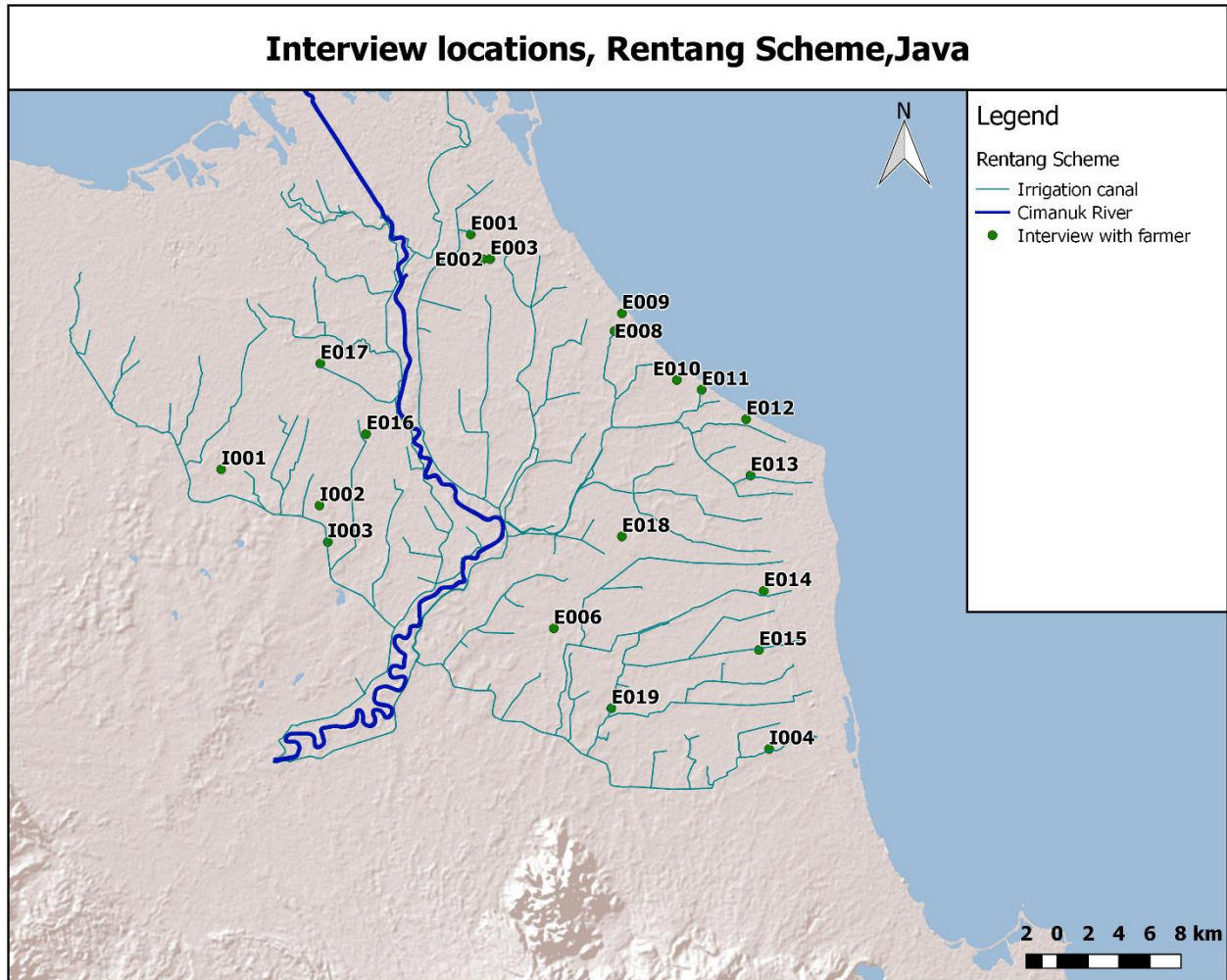


Figure 114 Interview locations Java

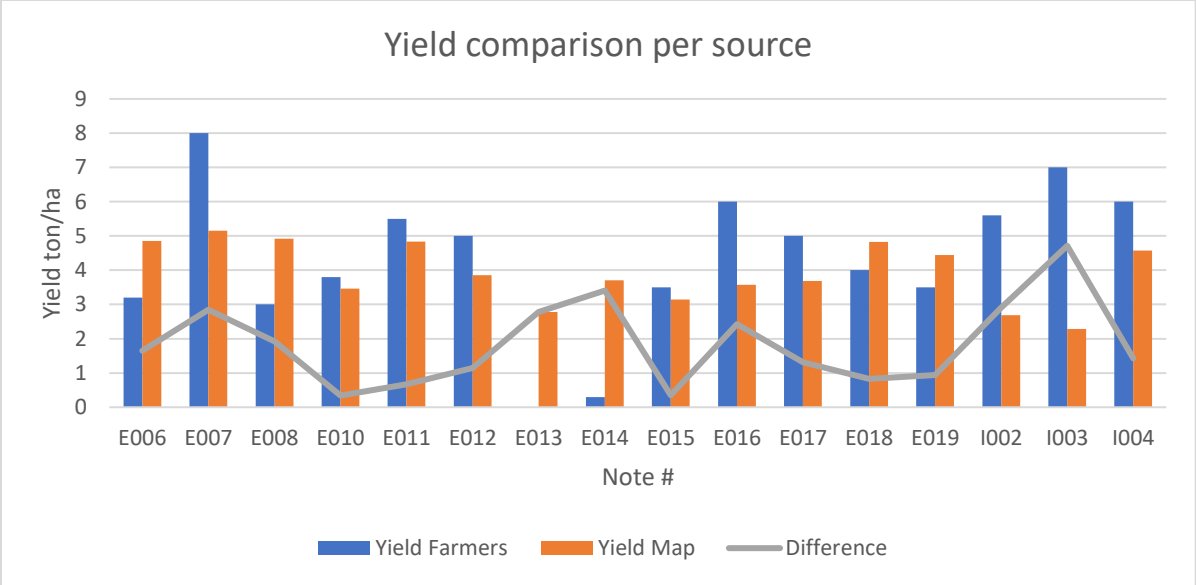


Figure 115 Yield comparison per source

Figure 115 shows the comparison of the yield derived from two different sources for each sample point of the locations where interviews with farmers and Kelompok Tani leaders were held. The graph shows the yield of the point (with a buffer of 100m) according to the yield map from SEBAL. Additionally, the figure shows the yield according to the farmers themselves, based on the interviews. The *Difference* line in the figure indicates the absolute difference between the yield values of the point from the two sources. This difference is between 0.5 and 4.9 ton/ha.

Season

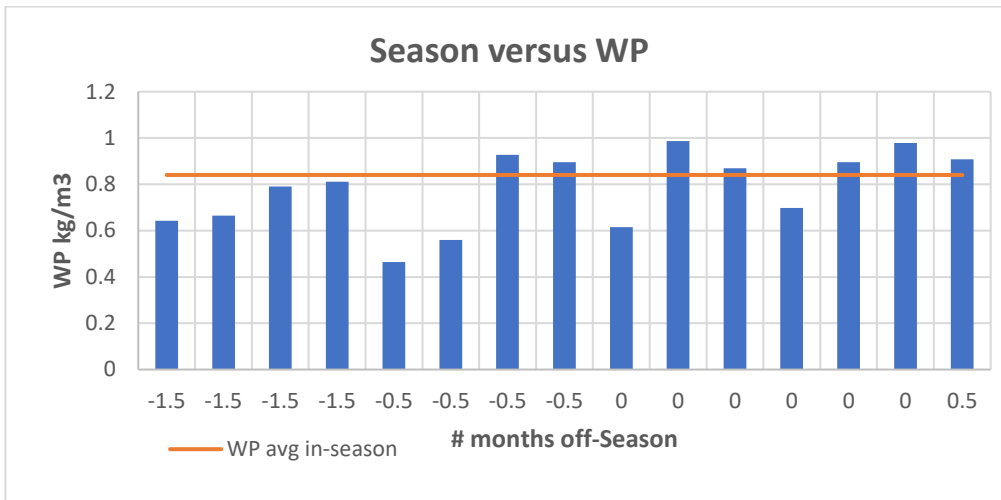


Figure 116 Season versus WP

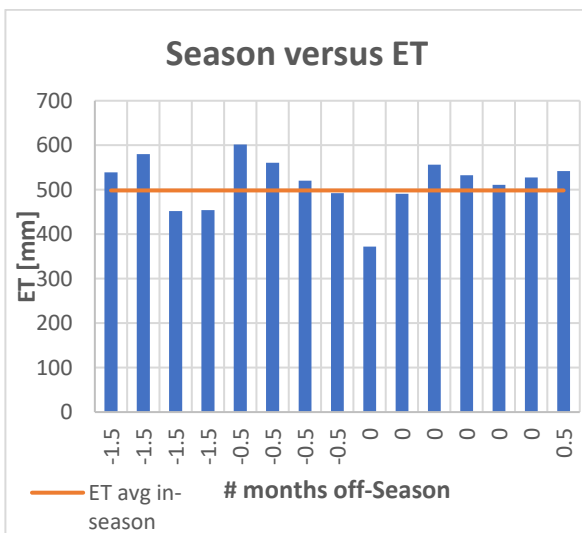


Figure 117 Season versus ET

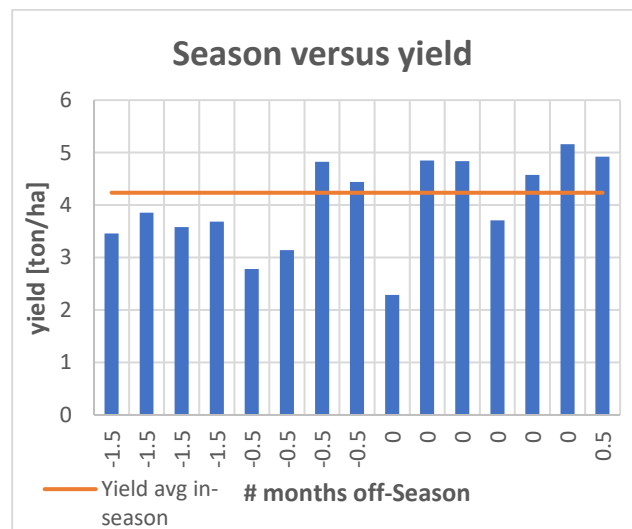


Figure 118 Season versus yield

Figure 116 shows the WP from the SEBAL map (using zonal statistics) of the locations where farmers and Kelompok Tani leaders were interviewed (with a buffer of 100m) sorted on production season which were indicated by the interviewees. The values on the x-axis indicate the number of months of which the regions were off the seasons on which the WP maps are based for each data point collected (see Figure 116). The value -0.5 corresponds to a planting season which started in the beginning of June, while the WP map is based on a period starting mid-June. The value 0.5 corresponds to a harvesting period which occurred around 1 November, while the WP map is based on a period ending mid-October. The orange line represents the average WP, ET or Yield, respectively, for the in-season locations. When comparing the in-season areas to the off-season areas based on WP, ET (Figure 117), and Yield (Figure 118). Two things can be observed. First, the WP, ET and Yield values for the in-season locations fluctuate greatly. Second, the locations which are 1.5 months off-season seem to have a lower yield than the average yield of the in-

season locations. It should be noted that these are very specific qualitative analyses and further research should be conducted in order to confirm (or reject) a relationship.

Soil

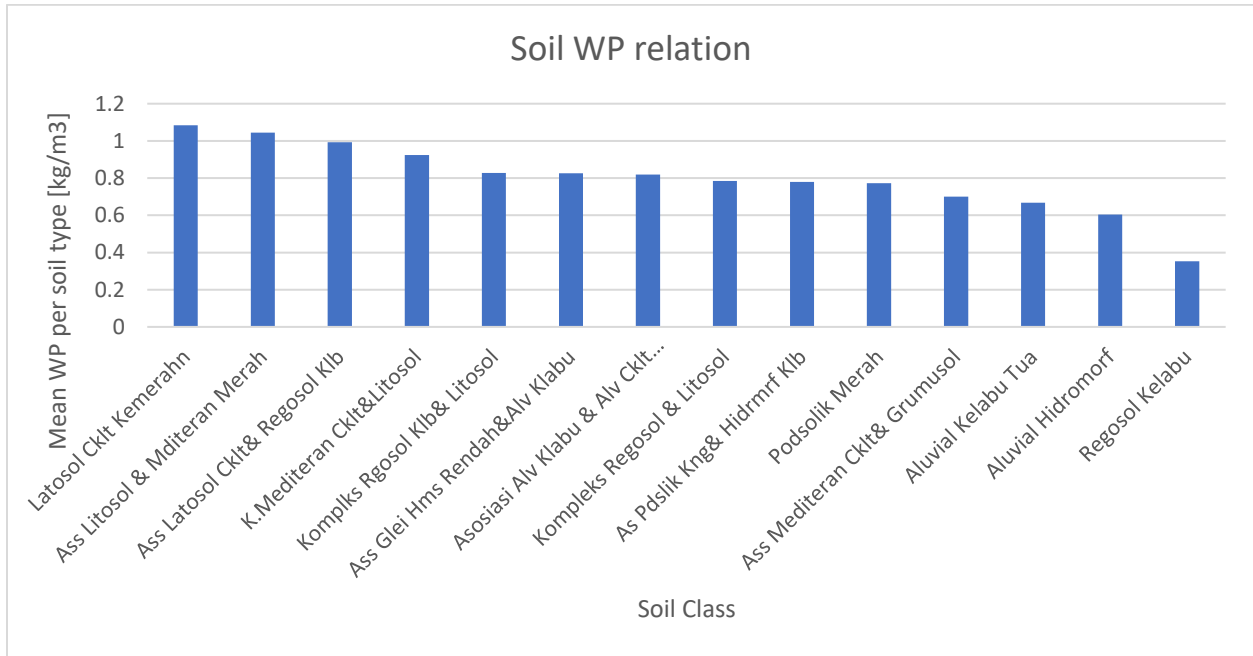


Figure 119

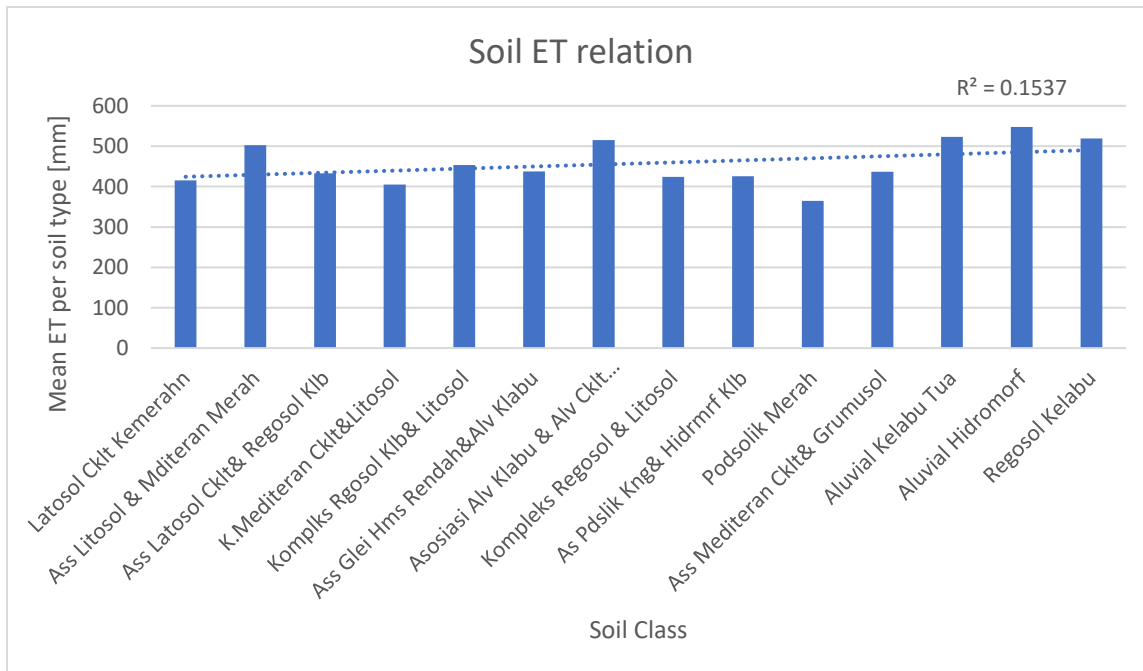


Figure 120

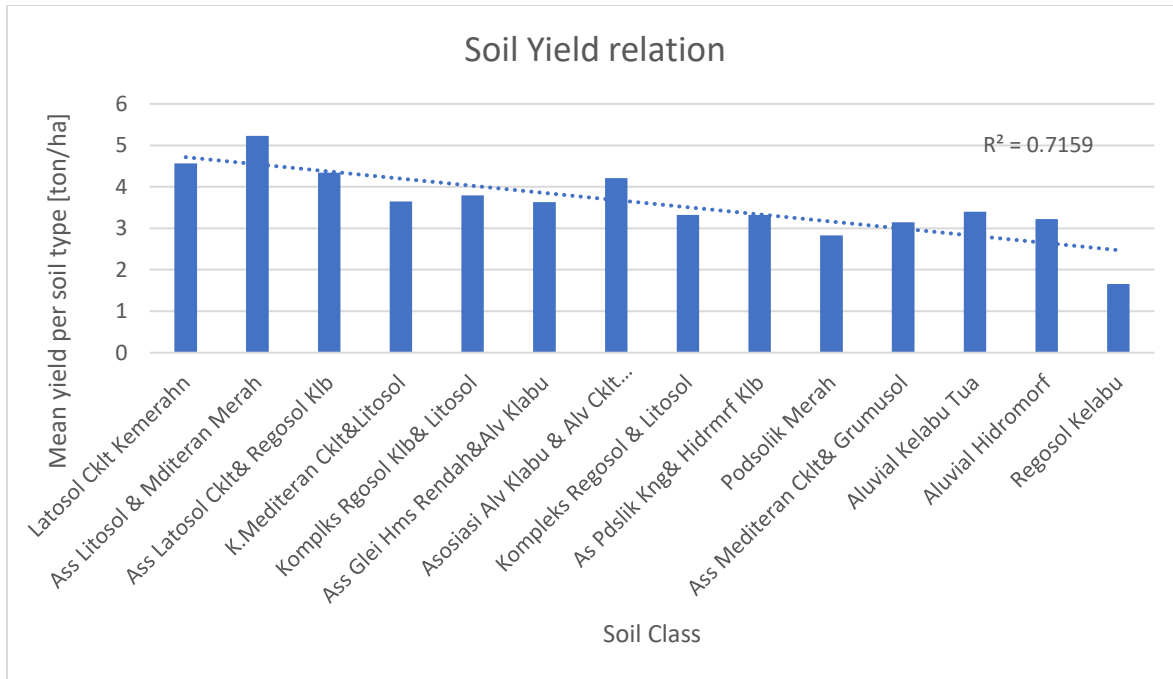


Figure 121

The figures above (Figure 119, Figure 120 Figure 121) show the mean of each factor (WP, ET, yield) per soil type, obtained using zonal statistics. In order to analyse these graphs, further knowledge should be gained on soil characteristics. When sorting the graphs on WP from high to low, corresponding Yield seems to show a slight linear decrease, and the ET remains approximately constant. However, without having knowledge on the specific properties of the soil, it is difficult to state whether the more fertile soil leads to a higher WP.

Distance to salt bodies

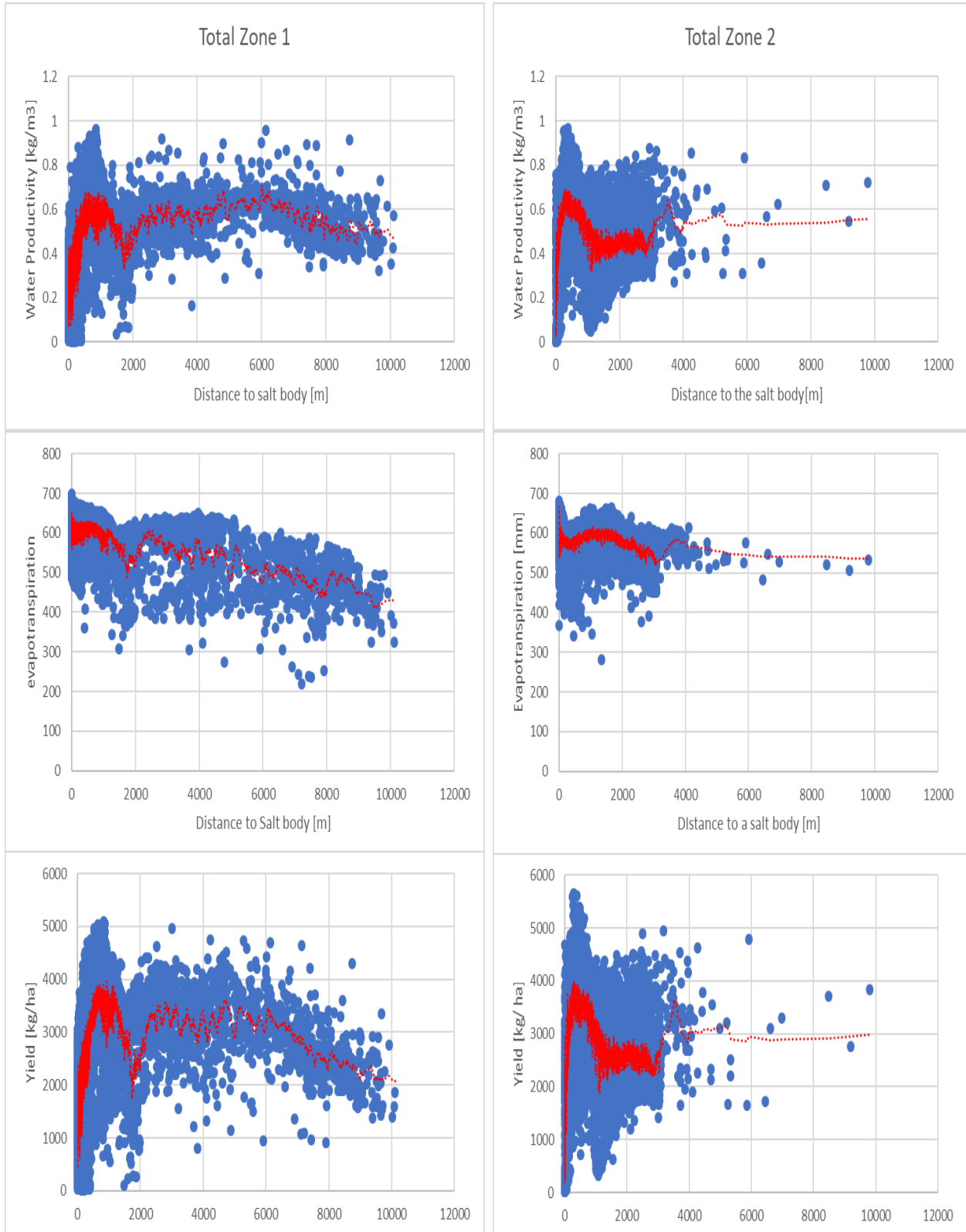


Figure 122: Water Productivity, Evapotranspiration and Biomass Production versus the distance to a salt body in total zone 1 and 2

Pests

In Java, data about pests was acquired for the Cirebon- district in 2016 (Table 6), as well as the Indramayu district in 2017 (Table 7). In Figure 123 the comparison between the average biomass production, the water productivity and the areal percentage influenced by pests per sub district is shown. WP and BM are shown in relative differences compared to the district's average and the absolute relative difference to the district's average areal percentage influenced by pests is plotted. Arjawinangun, Klangeran and Gegesik all have a relative low influence of pest (all below 6%) and all three have a biomass production of at least 15% above average. Palimanan and Plumbon both have the highest influence of pests and have produced respectively 18% and 4% less biomass in 2016. The other four sub districts show the inverse pattern of a higher areal percentage influenced by pests combined with a higher biomass.

Table 6: Area influenced by a pest from June to October 2016, district Cirebon

| Kecamatan | Pests2016[ha] | Pests2016[%] | Biomass Production [kg/ha] | Biomass Production [%] | WaterProductivty [kg/m3] | WaterProductivty [%] |
|--------------|---------------|--------------|----------------------------|------------------------|--------------------------|----------------------|
| Arjawinangun | 31 | 2% | 9033 | 20% | 0.88 | 14% |
| Klangenan | 51 | 3% | 8988 | 19% | 0.88 | 13% |
| Susukan | 92 | 3% | 6801 | -10% | 0.73 | -6% |
| Gegesik | 238 | 5% | 8932 | 18% | 0.83 | 7% |
| Kapetakan | 163 | 5% | 6165 | -18% | 0.55 | -29% |
| Ciwaringin | 66 | 6% | 6413 | -15% | 0.73 | -6% |
| Weru | 26 | 10% | 8265 | 9% | 0.86 | 10% |
| Palimanan | 128 | 12% | 6182 | -18% | 0.74 | -5% |
| Plumbon | 134 | 18% | 7237 | -4% | 0.79 | 2% |
| Average | 103 | 7% | 7557 | 0% | 0.78 | 0% |

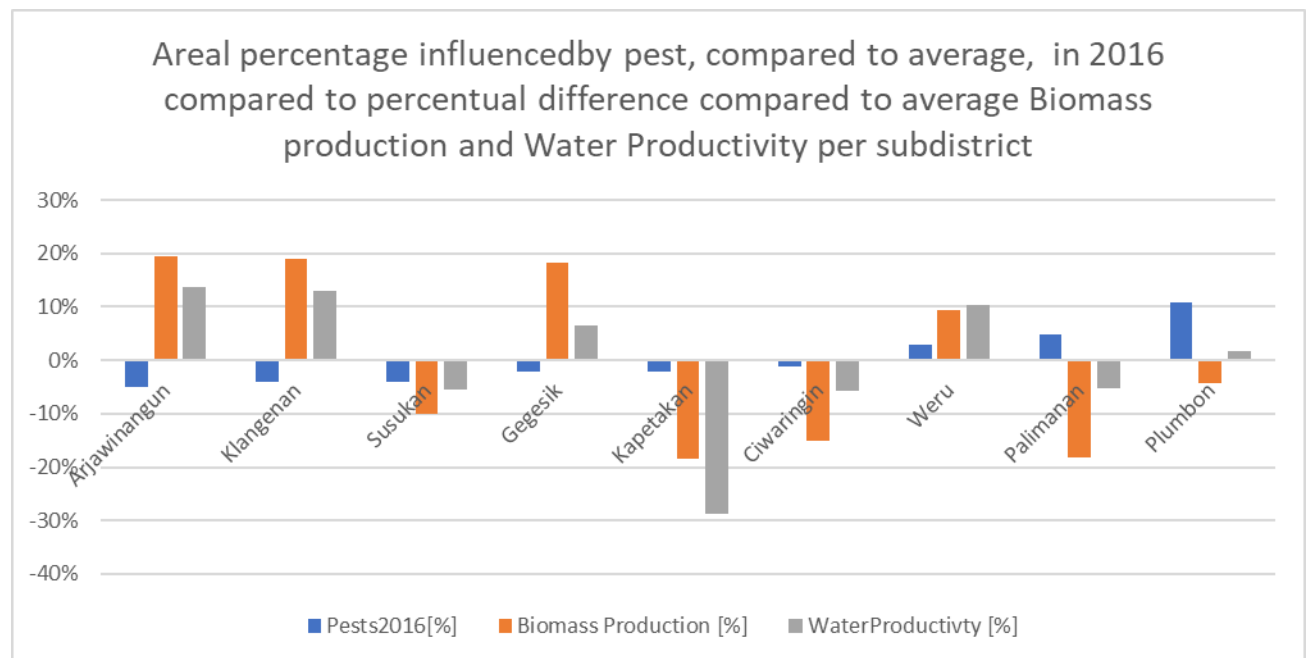


Figure 123: Areal percentage influenced by Pests, compared to average, in 2016 compared to percentual difference compared to average Biomass Production and Water Productivity per sub district in Cirebon

Table 7: Area influenced by a pest from June to August 2017, district Table 7 shows the documented pests in 2017 for the district Indramayu. Pests are scaled from light to failed harvest. The highest areal percentage influenced by pests occurred in 2017 in the Kertasemaya sub district and was 9%.

Table 7: Area influenced by a pest from June to August 2017, district Indramayu

| Kecamatan | Light[ha] | Medium[ha] | Heavy[ha] | Failed Harvest[ha] | Total[ha] | Total Pests 2017[%] |
|--------------|------------|------------|------------|--------------------|-------------|---------------------|
| Balongan | 8 | 29 | 66 | 4 | 107 | 5% |
| Bangodua | 10 | 0 | 58 | 0 | 68 | 2% |
| Cikedung | 7 | 11 | 17 | 0 | 35 | 1% |
| Indramayu | 14 | 0 | 2 | 0 | 16 | 1% |
| Jatibarang | 17 | 0 | 10 | 0 | 27 | 1% |
| Juntinyuat | 0 | 0 | 0 | 0 | 0 | 0% |
| Kandanghaur | 32 | 0 | 0 | 0 | 32 | 1% |
| Karangampel | 38 | 25 | 12 | 0 | 75 | 3% |
| Kertasemaya | 203 | 28 | 31 | 5 | 267 | 9% |
| Krangkeng | 189 | 66 | 35 | 0 | 290 | 6% |
| Lelea | 0 | 0 | 0 | 0 | 0 | 0% |
| Lohbener | 3 | 25 | 0 | 0 | 28 | 1% |
| Losarang | 116 | 15 | 5 | 0 | 136 | 2% |
| Sindang | 0 | 0 | 0 | 0 | 0 | 0% |
| Sliyeg | 198 | 0 | 0 | 0 | 198 | 5% |
| Widasari | 3 | 0 | 7 | 0 | 10 | 0.4% |
| Total | 838 | 199 | 243 | 9 | 1289 | |

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