

Evaluation of the versatility of WEAP as a planning tool in rice production in the Philippines in view of water-saving techniques



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Abstract

Irrigated rice contributes to a large share of global freshwater consumption and its production is increasingly challenged by water scarcity. To combat the challenge, the International Rice Research Institute developed in close collaboration with national institutes and farmers water saving technologies, such as Alternate Wetting and Drying (AWD), where fields are only periodically flooded. AWD reduces not only irrigation requirement by up to 30%, but also methane emissions and thus, gained increased importance in agricultural research. The water saving potential of AWD is already well studied on field scale, however, only few studies have addressed its effect on larger scales.

The following study uses a modeling approach by employing the commercial water management tool Water Evaluation and Planning (WEAP) derived from urban water planning, to upscale AWD implementation on a catchment within two case studies in central Luzon, Philippines: The experimental farm of the International Rice Research Institute and Angat-Maasim River Irrigation System (AMRIS). In AMRIS, irrigation water is stored in a multipurpose reservoir, which also serves 97% of the freshwater demand of Metropolitan Manila.

To assess the suitability of WEAP for implementing AWD, the model was applied on the experimental farm and results were validated with published experimental results. AWD reduces the water requirement by 27% (± 11.4) on clay, 12.1% (± 4.46) on sandy, 15.4% (± 2.6) on silty clay and 15.3% (± 6.63) on silty clay loam soils per dry season. On AMRIS, the overall water savings with AWD were 34.3% (± 6.2) per dry season. Streamflow was enhanced by AWD, which improved the water availability in up- and downstream areas of the irrigation system. A vulnerability assessment with reduced inflow to the irrigation system showed that irrigation divisions in the downstream area of AMRIS had limited to no access to water. With AWD implementation the water availability was improved by up to 50 %.

Climate change and population growth of Manila was implemented as and with sustained conventional irrigation, water level in the reservoir was lowered to a

critical value. Moreover, inflow in the reservoir was not sufficient to replenish the initial storage volume. AWD implementation lead to a reduced depletion of the reservoir and water levels were always replenished by the end of the wet season.

Upscaling AWD implementation on the water balance of an entire irrigation system shows the full potential of the irrigation technique. On field level it reduces irrigation water requirement, on irrigation system level it improves water availability and even provide farmers in the tail ends with sufficient water. Hence, AWD can help to sustain or even increase rice production levels and therefore contribute to future food security.

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List of Abbreviations

AMRIS	Angat- Maasim River Irrigation System
AWD	Alternate Wetting and Drying
CF	Continuous Flooding
DS	Dry Season
ET	Evapotranspiration
Etc	Crop Evapotranspiration
GWP	Global warming potential
IRRI	International Rice Research Institute
MSD	Mid-Season Drainage
SSC	Saturated soil culture
WS	Wet Season
WEAP	Water Evaluation and Planning
ZES	Zeigler Experimental Station

1. Introduction

Rice (*Oryza sativa*) is one of the world's most important staple food and global rice production is steadily increasing. It is also attributed to the cultural and traditional heritage of several countries, with over 144 million farmers worldwide cultivating it on nearly 158 million hectares. (GRiSP (Global Rice Science Partnership), 2013) Asia and Southeast Asia in particular play a key role in global rice production, contributing to 88 % and 30% to the global rice yield, respectively. (FAOSTAT, 2014) With 4.4 million ha of rice cropping area, the Philippines is the world's eighth largest rice producer. (Mohanty et al., 2013)



Figure 1: Map of the Philippines. Major rice-production regions of the Philippines and percentage of contribution to national rice production. Obtained from: Sander et al., 2016

Rice is cultivated in different environments covering a broad range of geographic and climatic conditions. However, two thirds of the global rice production is cultivated under continuously flooded soil conditions in so called paddy fields (FAO, 2000). Thereby, irrigated paddy rice demands for 34-43% of worlds total irrigation water (Barker et al., 1999). Whereas irrigation is mainly supplementary in wet season, rainfall is often not sufficient during dry seasons, thus, irrigation it is essential in this period (Bouman & Tuong, 2001).

Due to increasing water demand of urban and industrial areas and the increasing climatic variability, rice farmers in Asia will have to adapt to future changes in availability of freshwater resources. (Redfern et al., 2012) Tuong and Bouman (2003) estimated that physical water scarcity will affect 2 Mha of irrigated dry season rice and 13 Mha of irrigated wet season rice due to lack of water. Furthermore, Tuong and Bouman (2003) assume that farmers of another 22 Mha of irrigated dry season rice in South and Southeast Asia will be confronted with economic water scarcity when rising costs, e.g. fuel for pumps, will make intensive irrigation unaffordable. In large-scale irrigation systems, farmers downstream are lacking water in dry seasons due to high upstream water consumption.

To reach potential yields during times of limited water availability, farmers are recommended to apply water saving technologies such as Alternate Wetting and Drying (AWD). AWD is characterized by periodically flooded conditions with several dry phases during the cropping period. Water level in the field is allowed to drop from 5-10 cm above ground to -15 cm below soil surface. This threshold ensures that sufficient water is available for the plants to sustain plant growth, plants are not exposed to drought stress and yield is not affected. (Nelson et al., 2015)

AWD does not only reduce the irrigation requirements, it also reduces the emission of methane, a highly potent greenhouse gas and thus, gained increasing importance in agricultural and environmental research (Richards & Sander, 2014) Much research has already been conducted to investigate and increase the potential water savings and greenhouse gas mitigation of AWD on field level. (Bouman et al., 2007); Lampayan et al., 2015; Belder et al., 2004)

However, there is very little focus on how AWD affects the hydrological cycle and the water availability on a larger scale.

For the first time, a holistic water balance based tool i.e. “WEAP” will be used to upscale the effects of irrigation management changes on field level to the water balance of an entire rice irrigation system.

WEAP is a decision supporting tool designed for water management and planning by simulating water flows from different supply and demand sides. Since WEAP comprises a crop water requirement tool as well as other hydrological models and links them to each other, it seems an appropriate water balance model. However, its versatility and applicability on catchment scale will have to be evaluated. So far, WEAP was used in urban planning systems and only rarely with agricultural implementations. Although rice is one of the most water-intensive staple crops and water management plays a key role for sustainable production, it is the first time that a rice irrigation system is simulated with WEAP or a comparable large-scale water management tool.

This unique approach of integrating an irrigated rice system into a water balance of a whole catchment aims to assess the possible impacts of AWD on water availability and demand coverage in the irrigation system. Moreover, the water shortage mitigation potential under different climate change scenarios will be assessed.

2. State of the Art

2.1 Irrigated rice production in the Philippines

Rice production in the Philippines is mainly focused on six different regions: Ilocos Region, Cagayan Valley, western Visayas, Bicol, Soccsksargen and the central Luzon, which is due to its high share of irrigated rice also known as the country's ricebowl (Global Rice Science Partnership (GRISP), 2013).

In Central Luzon, the climate is tropical with low annual deviations in temperature. The annual mean temperature is 27 °C with a minimum relative humidity of 70 %, the average rainfall is 2,417 mm with an interannual unequal distribution. (Figure 3)

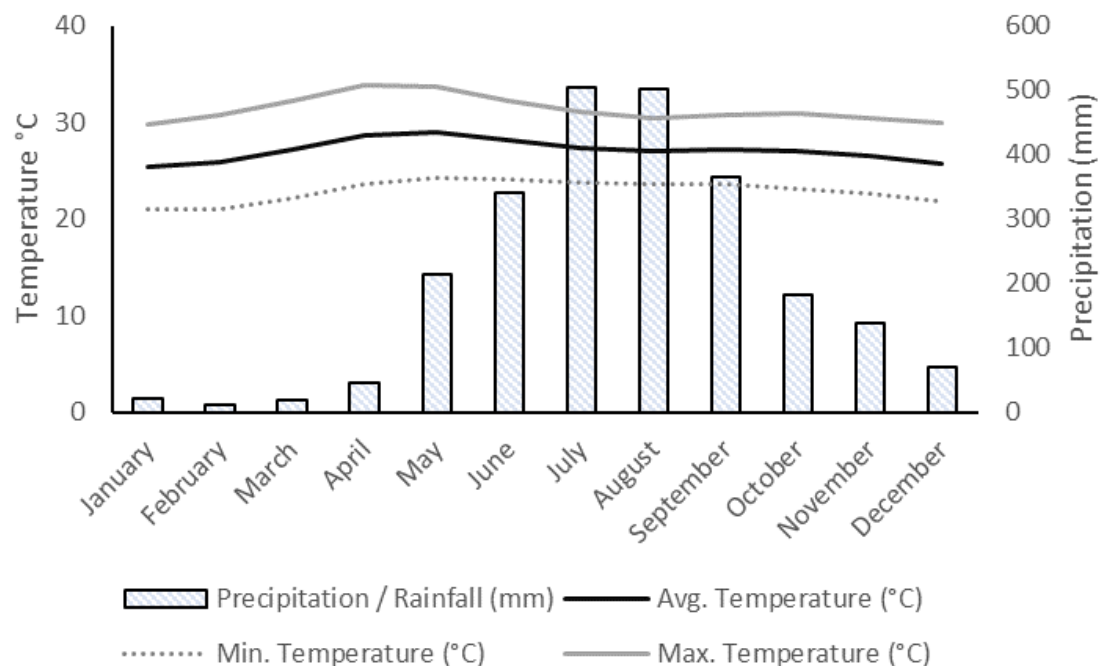


Figure 2: Climate Diagram Bustos, Central Luzon. Bustos is in the northern part of the case study irrigation system AMRIS. Annual mean temperature 27.1°C, Annual average precipitation 2412mm. Data obtained from: www.climate-data.org

In Central Luzon two distinct seasons determine the cropping schedule. The dry season lasts from November to April and the wet season lasts from May to October.

Central Luzon contributes nearly 20% of the national rice yield and has the majority of national irrigation areas (GRiSP (Global Rice Science Partnership), 2013). However, it's agriculture accounts for 82% of national freshwater withdrawal. With 34, 000 ha, the Angat-Maasim River-Irrigation System (AMRIS) located in northern Manila is one of the largest irrigation systems in the Philippines. Water for irrigation is stored in a multipurpose reservoir, which also covers 97 % of the freshwater demand of metropolitan Manila.

Water is not only required during the growth period, but also for land preparation. The vast majority of rice production systems in Asia are transplanted or direct seeded in bunded fields that are continuously flooded with 5-10 cm throughout the growing period. Before crop establishment, the land is prepared by soaking, ploughing and puddling. Soaking is a single process where the soil is saturated and a ponded water layer is created. Puddling suppresses weeds and pests, increases water and nutrient retention and establishes a plough pan, which limits water losses from percolation during the flooding period. However, land preparation is a water intense management step. It can vary from 150 mm up to 900 mm, depending on infrastructure, soil type, and length of the land preparation phase. Due to this unique cropping environment, water input for rice is particularly high and water use efficiency is low. Tuong et al., (2005) estimate that one kilogram of rice requires 1000-2000 liters of water; compared to other irrigated crops, rice receives 2-3 times more water. By virtue of the extent of its cultivation, rice is an obvious target for water savings.

2.2 Water Use and Water Productivity

Depending on soil type and groundwater table, water requirements for rice on paddy soil range between 400 mm to over 2000 mm. (Table 1) Stated in Rice Almanac, a typical value for irrigated rice in Asia is 1300 mm. (GRiSP (Global Rice Science Partnership)., 2013) The water balance in a paddy rice field can be described with the water balance in (1) and Figure 3:

$$R + I + C = E + T + P + S + O \quad (1)$$

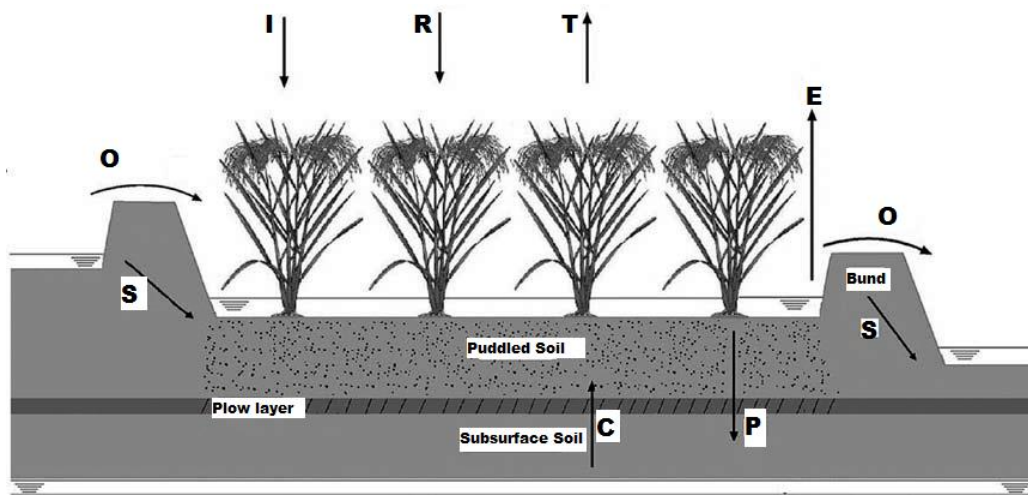


Figure 3: Schematic display of the water balance in a paddy rice field. Retrived from: Bouman et al., 2007

Whereby

R= Rainfall

I= Irrigation

C= Capillary Rise

E = Evaporation

T = Transpiration

P = Percolation

S = Seepage

O = Overflow (Surface Runoff)

In most cases, runoff or overflow occurs only in wet seasons, when heavy precipitation events are common and cause bunds to overflow. Seepage and percolation describe water movement in the soil. Seepage is the lateral flow and percolation the vertical flow of water into the groundwater. Those parameters are often difficult to distinguish and so are combined into one factor, SP. Like most of the other factors, the extent of SP depends on the soil type. Runoff, seepage, and percolation are considered non-productive outflows. Since they can amount up to 60-80 % of the water inputs, reducing them is a target objective of any water saving approach (Lampayan et al., 2015). Transpiration is related to productive losses, because its water loss is directly linked to crop development / metabolic processes / plant related activities. Water is taken up by the roots, transported through the xylem, vaporized in the leaves and then released to the atmosphere through the stomata.

Table 1: Average daily and seasonal water requirement in irrigated rice for different production phases and loss pathways.

Retrieved from: Bouman et al., (2007)

	Daily (mm day ⁻¹)	Duration (days)	Season (mm)
Land preparation			
Land Soaking	4-6	7-30	100-500
Evaporation	5-30	7-30	28-180
Seepage and percolation			35-900
Total land preparation			160-1580
Crop growth period			
Evapotranspiration			
Wet Season	4-5	100	400-500
Dry Season	6-7	100	600-700
Seepage and percolation			
Heavy clays	1-5	100	100-500
Loamy / sandy soils	15-30	100	150-300
Total crop growth			500-3700
Total seasonal water input			660-5280
Typical range of values for seasonal water			1000-2000

According to a report published by FAO, rice and wheat show similarities in transpiration efficiency, evapotranspiration efficiency, and water productivity. (Sadras et al., 2012) This indicates that although rice is sensitive to drought stress, the productive water requirements are comparably low.

2.3 Water Scarcity and Climate Change

Water is essential resource for life and although 75% of the earth's surface is covered with water, only 2.5% of this is fresh water and can partially be utilized. (Gleick, 1993)

‘Water scarcity’ is a frequently mentioned concept, but rarely explained. Firstly, it needs to be established, whether water is physically scarce or available but inefficiently used. Water scarcity is either due to a demand problem (physical scarcity) or a supply problem (inefficient use). According to Rijsberman (2006) the definition of water scarce area depends on “how people's needs are defined—and whether the needs of the environment, the water for nature, are taken into account in that definition; what fraction of the resource is made available, or could be made available, to satisfy these needs; the temporal and spatial scales used to define scarcity.”

There are several driving factors behind water scarcity: Human induced factors such as population growth create a correspondingly increase in demand for freshwater and food. Industrial water consumption also increases, creating pollution, silting of reservoirs and resource exploitation (due to groundwater mining) decreasing both water availability and quality. (Rosegrant, 1997) Future changes in climate and rainfall distribution will likely exacerbate areas suffering from water scarcity. In China, water scarcity already affects rice production. The Zhanghe irrigation system experienced in the late 90's a reduction of 20% of diverted water due to competitive increase in demand for domestic use. Consequently, cropping area and rice production was reduced. (Bin, 2008)

The Philippines, with a humid tropical climate theoretically have fewer problems with water scarcity. However, due to seasonality, rainfall distribution, and demand, which remains consistently high year-round, a spatial and temporal water scarcity can occur. They are mostly the result of climate change, population

growth, urbanization, and poor conditions of irrigation systems (GRiSP (Global Rice Science Partnership), 2013).

The seasonal patterns are projected to intensify and climate change effects, such as El Nino, are predicted to intensify (Bouman et al., 2007). The dry season will have less precipitation and higher temperatures, but to feed a larger population, agricultural systems will require more water. Moreover, freshwater availability is decreasing through population growth and urbanization. This leads to reduced stream flow and declining groundwater tables. Consequently, the hydrological cycle is affected by altering the recharging and discharging patterns (FAO, 2011).

Flooded conditions found in paddy rice production emit methane (CH_4), a greenhouse gas, therefore contributing to global warming. As shown in Table 2, rice has the greatest effect on global warming compared to other staple crops.

Table 2: Global warming potential of rice, maize and wheat. Adopted from: Linquist et al., (2012); Mosier et al.,(2006)

Crop	GWP in mg CO ₂ /ha and season
Rice	3.8
Maize	1.4
Wheat	0.7

2.4 Water saving technologies and mitigation strategies

To counteract future and current water scarcity, there is a need for an integrated water management concept, which includes water saving, management, and enhanced productivity combined with well-designed and -maintained irrigation facilities. Water recycling and implementation of water saving irrigation techniques are key to combatting water scarcity.

Below, some of the most promising irrigation techniques for saving water in upland rice production are introduced.

Aerobic Rice

Aerobic rice is a recent innovation, where irrigated rice is grown similarly to other cereals such as maize and wheat in unflooded and unsaturated soils (Belder et al., 2004). As stated in Amudha et al. (2009), the soil conditions throughout the seasons are unsaturated. Irrigation is triggered when soil water content goes below a defined value, which is usually between field capacity and permanent wilting point (Tuong & Bouman, 2003). There is no necessity of labor- and water intense land preparation as in paddy fields and percolation and seepage losses are through a reduction of the hydrostatic pressure reduced to a minimum. The greatest water saving potential is on light soils since they have high seepage and percolation rates. Moreover, a reduction in evaporation contributes to the reduced water demand. (Bouman & Tuong, 2001)

Saturated Soil Culture (SSC)

In saturated soil culture, the soil water content is kept at a maximum. This ensures readily available water for the plants while losses through percolation and seepage are reduced. Fields are periodically flooded with 1-2 cm standing water depth. After the disappearance of ponded water, irrigation is applied until fields are flooded again with a shallow water layer. (Bouman, 2002)

SSC also has potential for reducing water inputs. As stated by Bouman and Tuong (2001), water requirements were reduced by an average of 23%. However, from a practical point of view, this method requires skilled management and

constant monitoring of soil moisture conditions. Moreover, frequent shallow irrigation applications result in a high labor requirement. When irrigation water is pumped and transported a long distance, requiring a high pumping time, more electricity or diesel are consumed, making it less sustainable.

Mid-Season Drainage (MSD)

Mid-Season Drainage (MSD) is an irrigation management technology which interrupts flooding conditions for a short period of time during the vegetative growth phase. The length of interruption depends on the soil type and climatic conditions (5-20 days), and is before the end of rice tillering. As reported by (Hussain et al., 2015) the short drought stress leads to a physiological response and reduces the number of ineffective tillers, preventing rank growth and sterility induced yield loss. Moreover, in MSD- managed fields the global warming potential (GWP) is reduced. As Hussain et al (2015) noted, “Mid-Season drainage aimed a GWP reduction of 27 % (Towprayoon et al., 2005)”.

Due to the short duration of absence of water the water saving potential of MSD is low. However, it is important to mention that MSD was developed to reduce greenhouse gas emissions from paddy fields and lays the foundation for further research in intermitting irrigation technologies for water saving purposes.

Alternate Wetting and Drying (AWD)

Alternate Wetting and Drying is a water-saving irrigation technology, mainly promoted by the International Rice Research Institute (IRRI). As reported by several researchers, AWD has already been implemented in China, the Philippines and Japan (Belder et al., 2004; Richards & Sander, 2014; Tuong & Bouman, 2003; Chapagain & Yamaji, 2010)

The underlying principle of AWD is simple and similar to SSC. It saves water through the reduction of non-productive outflows (percolation and seepage). The field is periodically flooded with intermitting periods of non-flooded conditions. Starting with a ponded depth of around 5 cm, the water level is allowed to fall below the surface of the soil before irrigating (Belder et al., 2004; Bouman & Tuong, 2001).

In the first design of AWD, irrigation scheduling was based on the number of days without irrigation. This has been recently changed by IRRI to when the water level falls below a surface depth of -15 cm and lays the foundation for the recommendations of “safe AWD” implementation. This ensures that enough water is available in the soil, soil water potential never falls below 10 kPa, and water stress does not occur (Lampayan et al., 2015). For practical implementation, farmers use a plastic or bamboo perforated tube to monitor the water level in the field. (Figure 4)

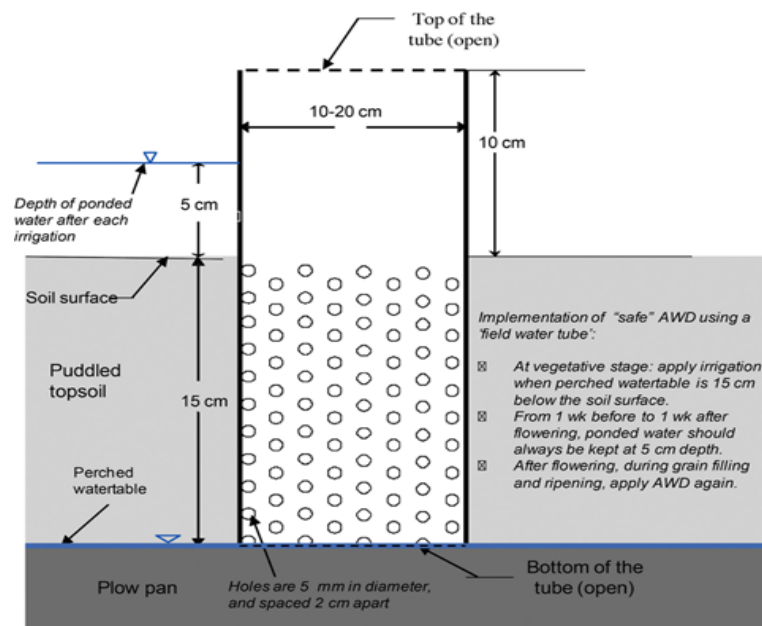


Figure 4: Field water tube for monitoring water levels in the soil. Adopted from Lampayan et al., (2015).

One week before and one week after flowering rice is very sensitive to water stress, potentially compromising development and yield. Therefore, in ‘safe’ AWD, during this period rice should be ponded (IRRI, 2009).

The length of the dry period and the extent of the water savings highly depend on soil type, crop growth stage, and capillary rise from groundwater. The dry periods can vary between 1 to more than 10 days (Bouman et al., 2007).

Heavy clay soils with shallow groundwater table and low percolation losses under continuous flooded conditions, which are often found in the Philippines and China, show a smaller water saving potential. Soils in northwest India tend to have a deeper groundwater table and are mainly sandy soils, which indicate high rates of non-productive outflows under flooded conditions. These losses can be reduced by implementing AWD (Lampayan et al., 2015).

Water saving results from experimental studies are summarized by Lampayan et al., (2015) as varying between 10-40%. The impact of AWD on yield performance has reached concordant results: Eriksen et al. (1985) and Bouman & Tuong (2001) reported yield declines through AWD, Cabangon et al., (2004) and Chapagain & Yamaji (2010) reported no significant effect on yield, whereas Belder et al. (2004), Ceesay et al. (2006), and Zhang et al. (2009) found a yield increase by AWD implementation. The yield increase through AWD implementation could be the result of an increase in lodging, resistant culms, tillering, reduced pest and diseases, and favorable soil conditions at harvest. (Sander et al. 2015). However, recent research shows yield decreases by AWD implementation is more frequently observed. As stated in a meta-analysis of 31 AWD-field experiments in Bouman & Tuong (2001), AWD decreases yields in over 90% of the trials with a yield reduction of >0-70%. However, the reduced water requirements were always greater than the yield decline and water productivity was enhanced by AWD.

Variations in outcomes can be explained by differences in soil type, nitrogen fertilization regime, and rate of nitrogen uptake, and the methodology applied (Dong et al., 2012). With a decrease in irrigation water, costs for irrigation decreases. Alam et al. (2010) reported a reduction of diesel by AWD implementation of 41 Liter / ha on clay soils in Bangladesh and lowered production cost by 23-42 USD /ha. Similar results have been provided by Quicho, (2013) where AWD reduces the costs of irrigation by 30 %.

Although AWD increases costs for weeding and labor, studies report an over 200% greater revenue by using AWD that the costs saved by not practicing continuous flooding. (Alam et al., 2010; Kürschner & Henschel, 2010) However, the economic savings of AWD depend on the pricing of irrigation water. The savings are primarily caused by reduced direct costs for water fees and indirect costs

from fuel for pricing water. In many Asian countries, including the Philippines, water prices are area- or season-based and that makes it difficult to convince farmers to adopt AWD. Monetary incentives are limited to areas with volumetric pricing of water by reduction of production costs. (Sander et al., 2016; Tsusaka et al., 2015)

In addition to its great potential of water saving, AWD is one of the most promising water saving strategies that also reduces greenhouse gases in lowland rice (Richards & Sander, 2014). Aerobic soil conditions reduce CH₄ and N₂O emissions. As stated in Linquist et al. (2015), global warming potential (GWP) was reduced by 45-90% through AWD implementation. AWD is a practical water saving technology, easy to implement and monitor, and reduces both water requirements and emissions.

2.5 Effects of water saving technologies on the hydrological cycle

Rice paddy fields provide ecosystem services. Irrigation canals and reservoirs serve as buffer during peak flow of rivers and thus prevent downstream areas from flooding. Percolation of water from paddy fields, irrigation canals, and reservoirs, recharge groundwater potentially being an essential resource for consumers downstream of the system. In certain irrigation systems, a shallow groundwater pumping in downstream areas is preferable compared to a poorly maintained surface irrigation system with high loss rates. In many Asian countries groundwater tables are shallow and AWD managed soils show saturated conditions due to a high capillary rise as a result (Cabangon et al., 2004; Belder et al., 2004).

Implementing a water saving technology such as AWD also affects the hydrological cycle. Percolation and seepage, and, therefore, groundwater recharge is reduced. As a consequence, the groundwater table drops and reduces capillary rise in the rice field. To compensate for the reduced groundwater influence in rice fields, irrigation is required to increase. In the long run, the water saving potential will decrease over time in fields with shallow groundwater tables at the beginning of the implementation (Belder et al., 2007).

Before implementing a water saving technology, it is important to confirm the effect downstream, and if improved irrigation and water recycling is more beneficial to downstream water users.

2.6 Modelling water requirements and choice of model

Globally, freshwater management is a growing challenge as the demand increases and its availability is predicted to decrease. Water resource planners have tools to assist in developing and implementing strategies for sustainable water use.

Integrated models such as WEAP (Water Evaluation and Planning- Systems), integrate the complex and dynamic interaction of plants, environment, and atmosphere. Single parts of the system or the whole can be assessed in its entirety. Current and future water demands can be also analyzed and the outcomes of system changes evaluated. Water demands are influenced not only by climate change, but also population growth, technological progress and political changes. Based on the assessment of these impacts, mitigation and adaptation strategies can be developed. WEAP is an integrated approach and can link agricultural water demands with other water consumers on the same spatial scale. It integrates agricultural, municipal and environmental water demands and allows a holistic approach and simulation of the impact of future water availability.

There are many crop growth models available to calculate crop water requirements. To verify WEAP's calculations from the agricultural part, the results were compared to Aquacrop, developed by the FAO's Land and Water division with the aim to assess' yield and biomass response of crops to different water regimes.

2.6.1 WEAP

"Water Evaluation and Planning System" (WEAP) is an integrated water resource management and planning tool, developed by the Stockholm Environment Institute.

It is a flexible, dynamic and transparent approach for assessing resource use and allocation of water, taking current demand and supply requirements into account. Moreover, it allows for upscaling the effect of environmental or management

changes. WEAP operates on a simple water balance between consumers and supply sides. Many other conventional water resource planning tools are often supply-oriented, and the impacts of scenarios cannot fully be evaluated.

WEAP allows to implement several different types of water users: agriculture can be linked with municipal and industrial water demands. WEAP combines hydrological models with various crop growth and soil water balance models in one water balance and analysis can be done on either the entire system itself or single parts of it.

The WEAP model can be established in different degrees of complexity and accuracy. The user chooses depending on the available data the between different hydrological and agricultural models.

There are five different approaches to implement agricultural systems into the model, which vary in terms of complexity and required input. More information on WEAP model can be found in the software handbook or on the webpage www.weap21.org

Irrigation Demands Only Method (simplified Coefficient Method)

This method is the simplest and requires the least data. Water requirements are based on crop evapotranspiration only (2), which considers a crop coefficient. Irrigation is determined by the water requirement which cannot be covered by rainfall. This method does not reflect changes in soil moisture, infiltration, or percolation and therefore not suitable for water saving technologies.

$$ET_c = K_c * ET_0 \quad (2)$$

ET_c = Crop Evapotranspiration [mm day⁻¹]

K_c = Crop Coefficient

ET_0 = Reference Evapotranspiration [mm day⁻¹] calculated with Penman-Monteith Equation

Rainfall Runoff Method (Simplified Coefficient Method)

This approach is a further development of the Irrigation Demands Only Method. The water requirements are also only based on potential evapotranspiration. Moreover, rainfall which is not used for evapotranspiration is considered to be runoff to a river and still part of the system.

Rainfall Runoff Method (Soil Moisture Method)

The Rainfall Runoff method is a dynamic soil moisture accounting approach for determining water requirements in an agricultural system. The soil is divided in to two layers with different functions. The upper layer involves processes like evapotranspiration, runoff and shallow seepage, whereby the lower layer takes percolation and changes in soil moisture into account. This method focuses on soils as an essential element for water balance calculation and is quite complex in its implementation. The irrigation scheduling offers only limited possibilities of integration of water saving technologies and cannot suitably model AWD.

MABIA Method

The MABIA Method uses the implemented software MABIA, a crop water requirement model developed by the Institut National Agronomique de Tunisie. The calculation algorithms are based on FAO Irrigation and Drainage Paper No. 56 and includes following steps:

The reference evapotranspiration is calculated with the Penman-Monteith equation (3). The calculations refer to a reference crop. Further details can be found in the FAO Irrigation and Drainage Paper No. 56.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (3)$$

where

- ET₀ reference evapotranspiration [mm day⁻¹]
R_n net radiation at the crop surface [MJ m⁻² day⁻¹]
G soil heat flux density [MJ m⁻² day⁻¹]
u₂ wind speed at 2 m height [m s⁻¹]
e_s saturation vapor pressure [kPa]
e_a actual vapor pressure [kPa]
e_s-e_a saturation vapor pressure deficit [kPa]
Δ slope vapour pressure curve [kPa °C⁻¹]
γ psychometric constant [kpa °C⁻¹]

A daily soil water balance is calculated, based on daily transpiration, evaporation, and irrigation. The calculations use the 'Dual Kc' approach (4) to allow the model to react on wetting and rain events. The crop coefficient Kc consist of a basal crop coefficient (Kcb) and a soil evaporation coefficient (Ke).

$$ET_c = (K_{cb} + K_e) * ET_o \quad (4)$$

To determine the trigger of irrigation, a daily soil water balance is calculated.

MABIA gives the user a more detailed irrigation scheduling that is flexible and dynamic. Moreover, it is suitable for modelling AWD.

Plant Growth Model (PGM)

The Plant Growth Model is a pure crop growth model taking into account plant growth, water use and yield. It focuses on effects of altered environmental conditions and requires significant input in terms of parameters. PGM was not used due to its complexity and narrow focus.

3. Study Aim

3.1 Rationale of the research

Water scarcity is a constantly growing threat for rice irrigated systems in certain areas of the Philippines. Nowadays, farmers in the dry season are already highly depended on irrigation water, often also used by other water users. In future, many factors will further diminish water availability in water scarcity affected areas. Therefore, mitigation and adaptation strategies must be developed to secure the coverage of municipal and agricultural demand, while production level is maintained or increased.

Alternate Wetting and Drying is a promising and widely promoted approach in the Philippines for reducing irrigation demand without a high risk of yield depression, especially for irrigated rice. However, the effects on the hydrological cycle are not well understood.

WEAP offers the unique approach to link crop water models with hydrological models and the demands of other water users. WEAP enables the assessment of the long term impacts of AWD on downstream areas in different scales and water availability within a system of different water users. Moreover, natural and anthropogenic changes will be implemented and AWD is evaluated with regard to its potential for water saving.

3.2 Research objectives

- (i) To evaluate the modelling performance of WEAP as water management and planning tool for irrigated rice systems in the Philippines
- (ii) Implement and upscale AWD and asses its water saving potential
- (iii) Assess effects of changes in irrigated rice systems. Focusing on climate change and population growth with its effects on water availability in different temporal and spatial scales.

The main research questions to address these objectives are:

- Is WEAP a suitable tool to assess the irrigation requirement of paddy rice?
- Is it possible and to which extent can AWD be implemented?
- What is the potential of water savings by implementing AWD?
- Is WEAP able to address the effects of climate change, population growth and change in irrigation technique on downstream area and its water allocation?

3.3 Framework

In the study two different study sites were used with different aims. The Zeigler Experiment Station from the International Rice Research Institute (IRRI) was used to validate the model and AWD implementation. The reference scenario and AWD implementation were compared to values obtained from Aquacrop and from literature and publications.

The approach on AMRIS aimed to generate scenarios and evaluate its effect on water availability and allocation. In Figure 6, the steps and interactions are shown. The baseline scenario consisting of historical climatic information, soil and crop information are validated with the irrigation plan to adjust assumptions made in the modelling process. The generated scenarios aim to answer which effect changes various in sources have on the system itself and how single hydrological and agronomical components are affected. The chosen scenarios aim to address the challenges between climate change, agriculture, and population growth on water availability and its management.

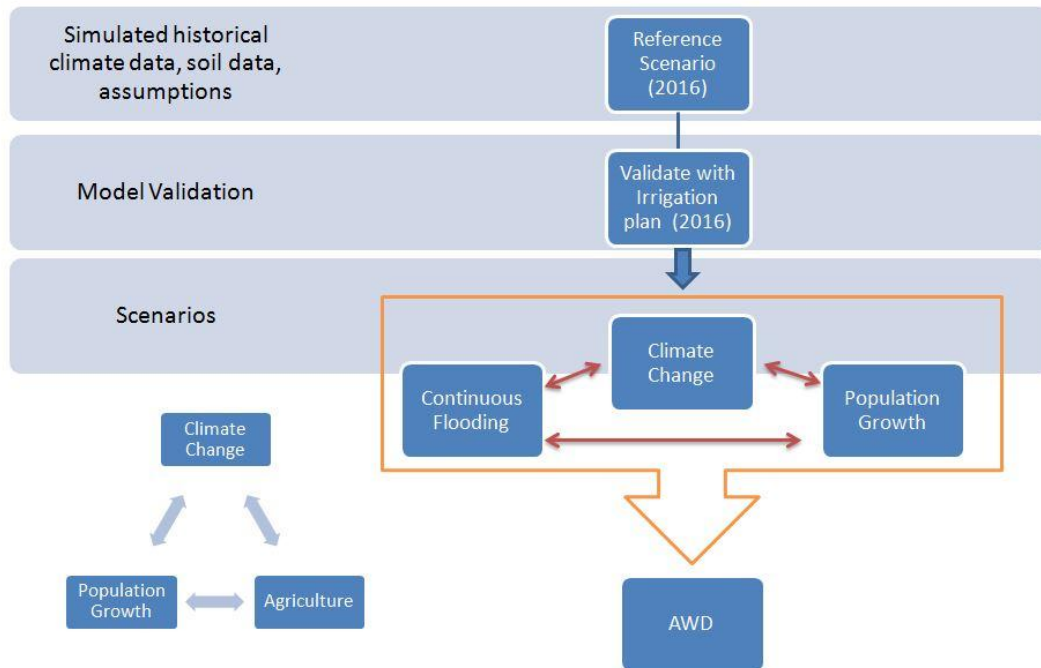


Figure 5: Framework of modeling approach

4. Material and Methods

The following chapter includes information about the study site, data collection, model concept and selected scenarios. There was no field trial for data validation, but the general concept was proven with another model (Aquacrop) and data obtained from literature.

4.1 Study site

4.1.1 Geographical, climatic and agronomic characteristics

WEAP was applied in two different study sites in the warm humid tropics (FAO AEZ classification) in Central Luzon, Philippines: The Zeigler-Experiment Station (ZES) of IRRI and the Angat-Maasim-River Irrigation System (AMRIS). ZES is part of the International Rice Research Institute in Los Baños, Laguna, Philippines on the main island Luzon and approximately 65 km south of Manila. (14°09 N, 121 °15'E).

It serves as an experimental site and production area and covers about 220 ha rice paddy fields.

Irrigation water is obtained from reservoirs, coming from shallow groundwater pumps, and stored precipitation. The distribution of water within the system is via pumps and canals.

The experimental station is subdivided into an upland and lowland part. There are four dominant soil types, categorized according to their main characteristics. The lowland farm (northern part) has about 117 ha and consists of fields with different physical soil properties, which are grouped among their dominating texture class: clay (50% of experimental farm), silty clay (33% of experimental farm) and sandy soils (17% of experimental farm) with shallow groundwater table. The upland farm comprises 84 ha and is characterized by lighter soils. In the model, the whole upland farm was assumed to be sandy soils.

AMRIS is one of the largest irrigation systems in Central Luzon. The total area covers 34 000 ha of paddy fields, whereby the cultivated area varies in dry and wet seasons. There is only little information on the soil type. For modelling purposes, it was assumed to be a homogenous clay soil. AMRIS receives irrigation from the Angat Dam, a multipurpose reservoir of the Angat River. This dam has a significant socioeconomic importance for Central Luzon as it is the main domestic water source for Metropolitan Manila, serves as flood control and includes a hydroelectric power station (Tabios, 2016). The irrigation system is maintained and managed by the National Irrigation Administration (NIA). The administration of the system is subdivided into 12 irrigation divisions. From the Dam, two main canals serve the Northern and Southern Irrigation System. From the main canals, water is subdivided into further canals. Runoff and drainage water is collected in creeks, which then are either returned to the canals, to the river, or outside the system. The amount of water recycled in the system has not been measured, and was ignored in the model. The water distribution in AMRIS relies on gravity from the gentle gradient between northeast to southwest.

The climate is characterized by two distinct seasons, the dry season from November to April and the rainy season from May to October. The annual average rainfall is 1700 mm, of which around 65% of the precipitation is in the wet season

and less than 5% in the dry season. The average temperature is nearly constant at an average 26°C the whole year (Jose et al., 1996). The climate in AMRIS shows only small deviations in temperature and rainfall from Los Baños.

The baseline scenario set up comprises two cropping rotations of rice in monoculture system. The simulated rice varieties are reflecting standard varieties and physiological characteristics are adopted from the integrated crop library.

4.2 General theoretical background WEAP

WEAP is a decision supporting management tool for water resource allocation and planning and developed in 1988 from the Stockholm Environmental Institute. (Sieber, 2013). It is a dynamic demand and supply oriented tool with the possibility of up scaling scenarios and evaluating its long-term effect on the system.

Model specifications and calculation algorithms

For this study the currently latest version of WEAP (2016.01) was used. Agricultural water requirements were calculated with the incorporated MABIA approach. WEAP operates on a monthly time step and takes supply and demand requirements into account. However, MABIA uses a daily time step and then aggregates the values by month for incorporation into WEAP.

4.3 Baseline scenario

The basic set up was supported with a GIS-Layer for the Experimental Station and with a vector layer for AMRIS.

ZES was subdivided into 4 zones, which were modelled as single catchments with a further block-wise differentiation. The aim of modelling ZES was to find out the best implementation strategy for rice paddy fields and Alternate Wetting and Drying (AWD) and evaluate the performance of the model. Therefore, the model was only used to model demand and supply infrastructure was neglected.

In AMRIS, the irrigation system was subdivided according to their irrigation diversions (1-12).

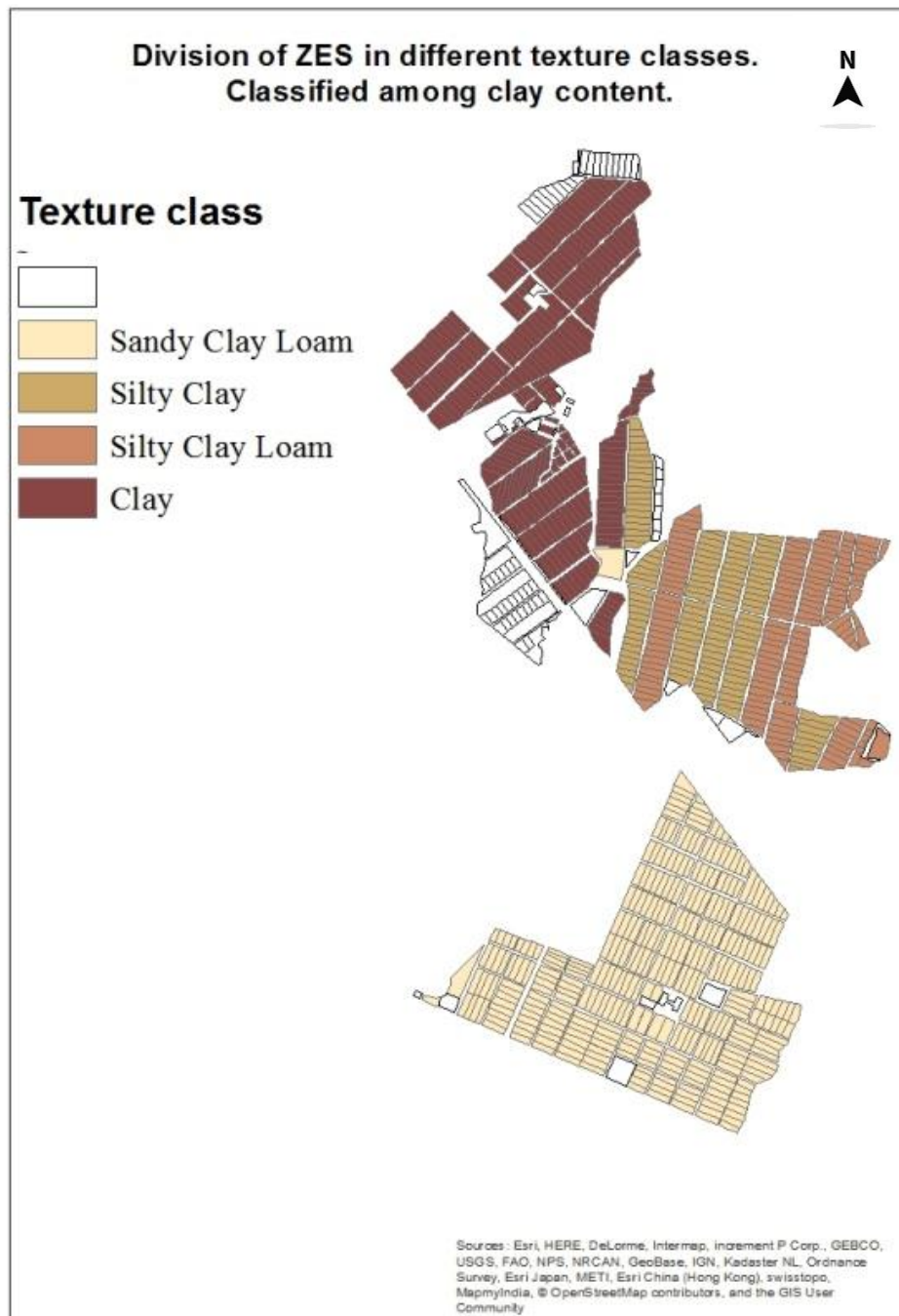


Figure 6: Experimental Farm of the International Rice Research Institute, classified by dominant texture class.

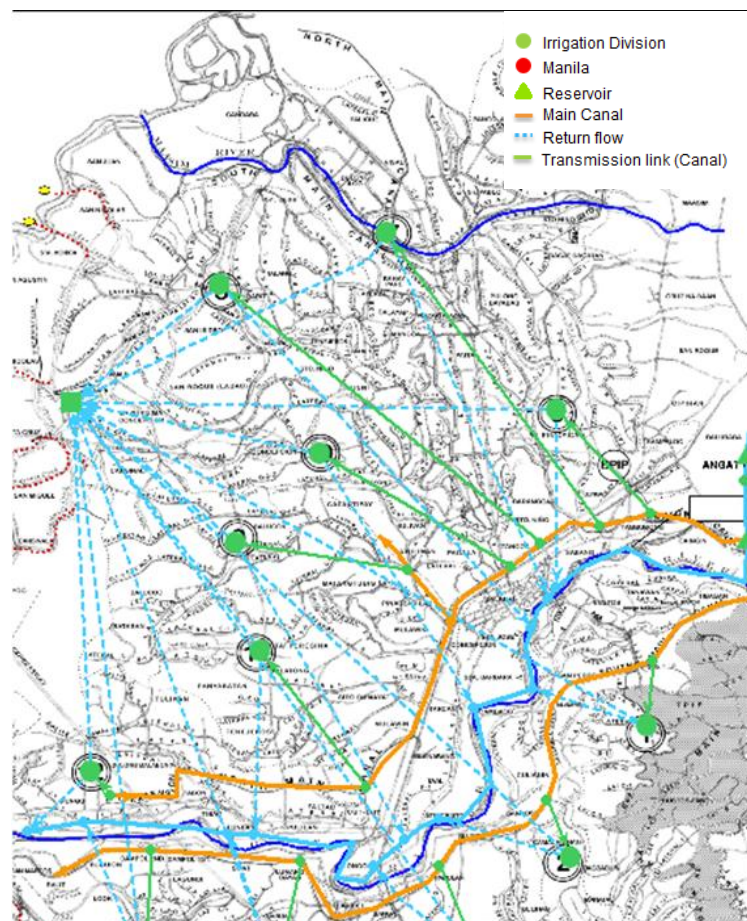


Figure 7: Implementation of the Angat-Maasim River Irrigation System in Central Luzon, Philippines in WEAP (Water Evaluation and Planning Systems). Irrigation divisions as green dots, connected with light blue lines (canal) to the northern or southern main canal (orange line). Angat Dam and Bustos dam are represented with green triangles, Angat River is schematic drawn as a blue line. Manila is represented as a red dot right of the irrigation system.

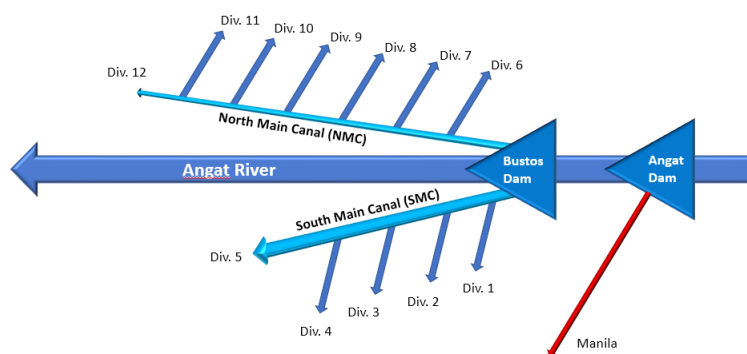


Figure 8: Schematic overview of water distribution and canal allocation in Angat-Maasim River Irrigation System, Philippines

Irrigation water in AMRIS comes from the central reservoir Angat Dam and is then subdivided into the south and north main canal.

To assess the effects on storage volume of municipal water demand and population growth, Manila is implemented. Manila receives water from the Angat Reservoir and is prioritized. During water shortages, after the water requirements of Manila are met, the remaining water is released to AMRIS.

4.4 Climate, Soil and Plant Data Collection

Required data for running WEAP was provided either by IRRI (ZES), by NIA Region III Central Luzon or are based on assumptions based on discussions with researchers from IRRI.

Climatic data were provided by the Crop and Environmental Science Division from IRRI and includes daily records for solar radiation [MJ m^{-2}], rainfall [mm], maximum, minimum and mean temperature [$^{\circ}\text{C}$], vapor pressure deficit and actual vapor pressure [kPa], relative humidity [%] and wind speed [m/s] (average of 24 Hrs.). The dataset comprises data from 2005-2015. The dry season was classified in three categories according the total precipitation (Table 3).

Table 3: Dry season classification scheme among the total precipitation

	Low	Medium	High
Precipitation amount (mm)	<100	100-250	>250

For simulations on AMRIS weather information was obtained from the Climatology Resource for Agro climatology, NASA (NASA, 2016). The weather files contained daily information on solar radiation [MJ m^{-2}], rainfall [mm], and minimum and maximum temperature [$^{\circ}\text{C}$]. Assumptions were made on minimum relative humidity (70%) and wind speed (2m/s). Information on soil parameters were given for the upland part of ZES. These contained information about clay, sand and silt content per plot. The values were averaged for each block. Estimations were made on soil depth (60 cm), infiltration and percolation rate. The upland farm on ZES was assumed to be sandy clay loam soil.

Table 4: Assumptions on infiltration, percolation, and soil properties on different texture soil groups on ZES.

	Maximum Infiltration Rate [mm / day]	Maximum Percolation Rate [mm/day]	Soil Properties, as a % of volume			
			Saturation	Field Capacity	Wilt Point	Available Water Capacity
Clay	6.0	1.5	38.5	34.1	22.3	11.7
Sandy clay loam	10.0	7.0	33.0	25.1	12.2	13.0
Silty Clay	7.0	5.0	42.3	36.7	22.5	14.3
Silty Clay Loam	8.0	6.0	43.2	36.0	19.4	16.6

The crop input parameters were obtained from the model crop library and adjusted to transplanting conditions: The initial stage was set to 5 days to take into account transplantation shock. The total length of growing period on the fields, or the days after planting was 99 days. It was assumed that planting and harvesting takes place in one day. Land preparation is neglected, since it's not important for assessing the potential of water saving of AWD. The planting and harvest schedule is simplified and shown in table 5:

Table 5: Cropping schedule for modeling approach with WEAP

	Planting	Harvesting
Dry Season	01. Jan	09. Apr
Wet Season	01. Jul	07. Oct

4.5 Irrigation scheme

Baseline scenario – Continuous Flooded

The irrigation schedule was established after common farming practice and follows the recommendations from the IRRI Rice knowledge bank (IRRI, 2009). The initial water depth for and after transplanting was 3 cm and increases with further plant development up to 5-10 cm. One week before harvest the field was drained and soil is allowed to dry out.

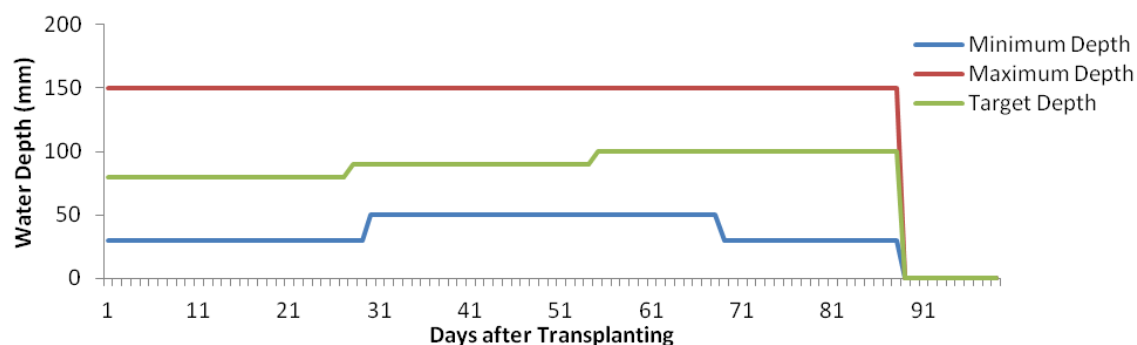


Figure 7: Minimum, maximum and target water depths of paddy rice for modelling approach with WEAP

Irrigation schedule AWD

The principles for AWD follow the recommendations for safe AWD. The irrigation scheduling is divided into irrigation trigger and irrigation amount. The irrigation trigger defines the threshold when irrigation is induced. It is based on the readily available water (RAW). As soon as the soil moisture depletion exceeds the defined threshold in RAW, irrigation is applied. Irrigation amount is determined as a fixed depth in mm. The irrigation schedule is shown in table 6. The irrigation period was from 1- 89 days after transplanting.

Table 6: Irrigation schedule for AWD implementation in WEAP in dry season for different texture classes.

Soil texture class	Irrigation trigger	Irrigation amount
Clay	25 % of RAW	50 mm
Silty Clay	26 % of RAW	60 mm
Silty Clay Loam	27 % of RAW	80 mm
Sandy	28 % of RAW	80 mm

In wet seasons the irrigation amount of 50 mm was used in both irrigation scheduling approaches.

4.6 Proof of concept

There was no experimental data available to validate the model, hence model simulations for experimental station were confirmed with Aquacrop.

In Aquacrop, the crop water requirements for paddy rice fields with a percolation rate of 0.1 mm per day was calculated and compared to calculations obtained by WEAP for continuous flooding and AWD under same climatic conditions for the same time period.

The results can be used for orientation and to assess the accuracy range of MA-BIA for continuous flooded systems and under AWD implementation.

For AMRIS the simulated water requirement from WEAP were compared to irrigation plan for 2016 obtained from NIA.

4.7 Scenario development for AMRIS

For AMRIS following scenarios were developed:

- **Climate Change:**
To simulate climate change impacts on the water availability and water allocation, simplified climate change scenarios were created (Table 7).

Table 7: Climate change scenarios in WEAP on AMRIS.

Scenario	Effects on precipitation		Effects on headflow Angat River	
	DS	WS	DS	WS
Climate Change I	-10%	-	-10%	-
Climate Change II	-20%	-	-20%	-
Climate Change III	-30%	-	-30%	-

- **Manila demand growth**
In the scenario of increasing freshwater demand by Metropolitan Manila, the demand increases from 46 cms to 50 cms.

5. Results

5.1 Zeigler Experiment Station (ZES)

5.1.1 Comparison with Aquacrop

Water requirements for AWD and CF were compared to minimum water requirement calculations from Aquacrop and potential Evapotranspiration (ET_0) for the dry season 2006. The calculated averaged water requirements and ET_0 are significantly different from each other ($p\text{-value} < 0.05$).

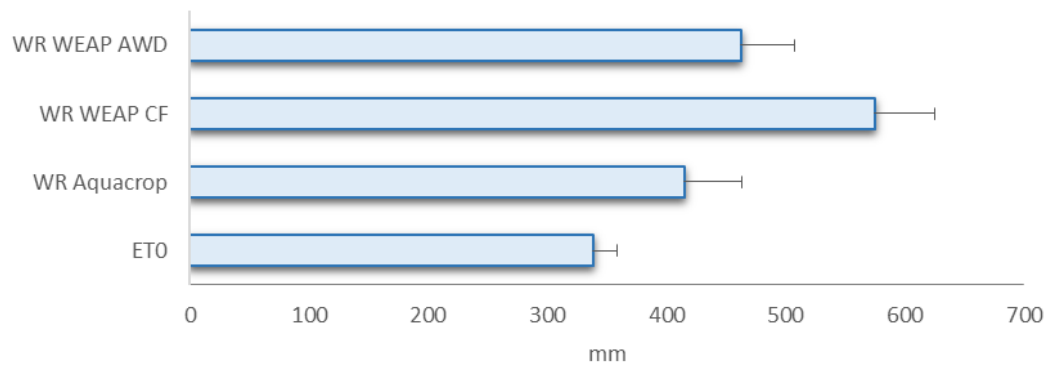


Figure 8: Average water requirements (Rainfall + Irrigation) calculated by Aquacrop, WEAP (MABIA - Method) for continuous flooding (CF) and Alternate Wetting and Drying (AWD). Results display averaged values for 2006-2015 on clay soils.

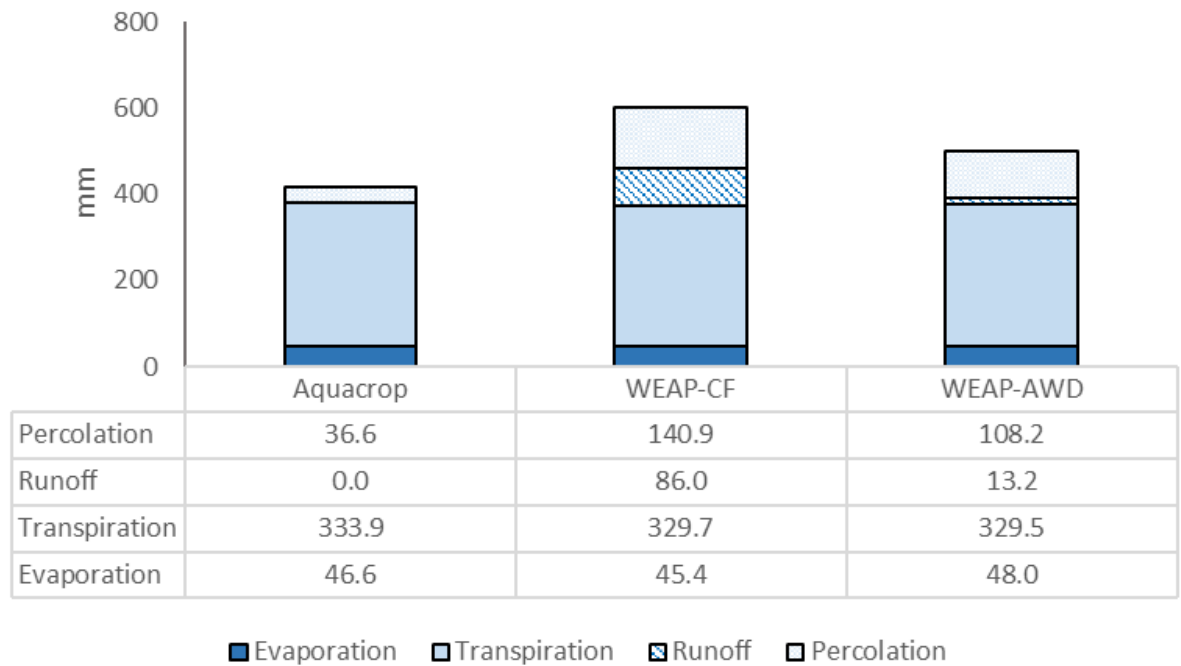


Figure 9: Loss pathways calculated with Aquacrop, WEAP (MABIA-Method) under Continuous Flooding (CF) and Alternate Wetting and Drying (AWD) for clay soil in the DS 2006. Aquacrop calculations refer to minimum crop water requirement calculations.

To evaluate where exactly the methods differentiate, loss pathways of water in one dry season are analyzed. Figure 11 shows single loss pathways for a clay soil in dry season 2006, calculated by WEAP for continuous flooding and AWD and by Aquacrop for minimum water requirements. Transpiration and Evaporation differ not substantially in all calculation methods. Runoff is highest in CF; AWD and Aquacrop show negligible values. The largest differences are found in percolation. Percolation is reduced by 18.4 % in AWD compared to CF, whereas Aquacrop calculates nearly 75 % lower percolation losses in the minimum water requirement scenario. However, irrigation requirements for AWD and minimum crop water requirements for 10 years of simulation are not significantly different on a significant level of $p < 0.05$. Irrigation requirements for CF is significant different from AWD and Aquacrop.

Table 8: Comparison Lines for Least Squares Means of different modeling methods. CF = continuous flooding, calculated with WEAP; AWD = Alternate Wetting and Drying, calculated with WEAP; Aquacrop = minimum crop water requirements, calculated with Aquacrop. LS-means with the same letter are not significantly different

	Irrigation LSMEAN	Calculation Method	LSMEAN Number
A	396.861	WEAP-CF	3
B	285.000	WEAP-AWD	2
B			
B	237.160	Aquacrop	1

The average irrigation requirements are highest in WEAP-CF and lowest in Aquacrop. Figure 12 shows differences within the distribution of values.

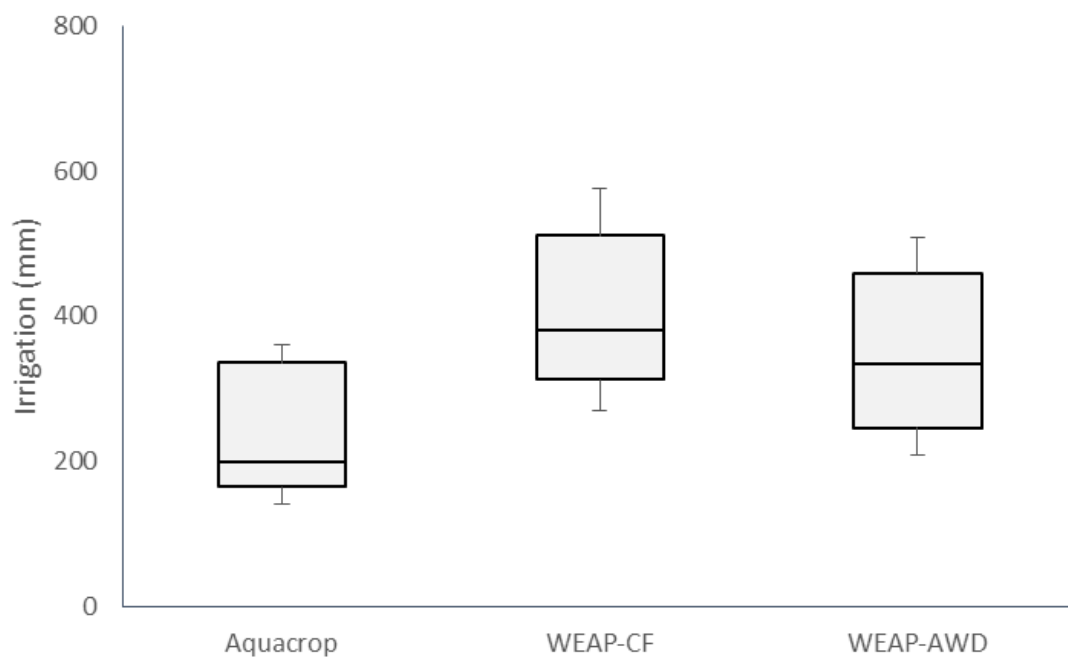


Figure 10: Irrigation requirements calculated by Aquacrop, WEAP (MABIA-Method) for continuous flooding and AWD for the dry seasons 2006-2015 on clay soils.

5.1.2 AWD implementation

Looking in more detail on the ponded depth irrigation scheduling verifies the fulfilment of above surface requirements for AWD, as shown in figure 11 for a normal dry season. Even in 2014, a dry season with total precipitation amount of 33 mm, the result of the model shows periodically flooded conditions (Figure 12).

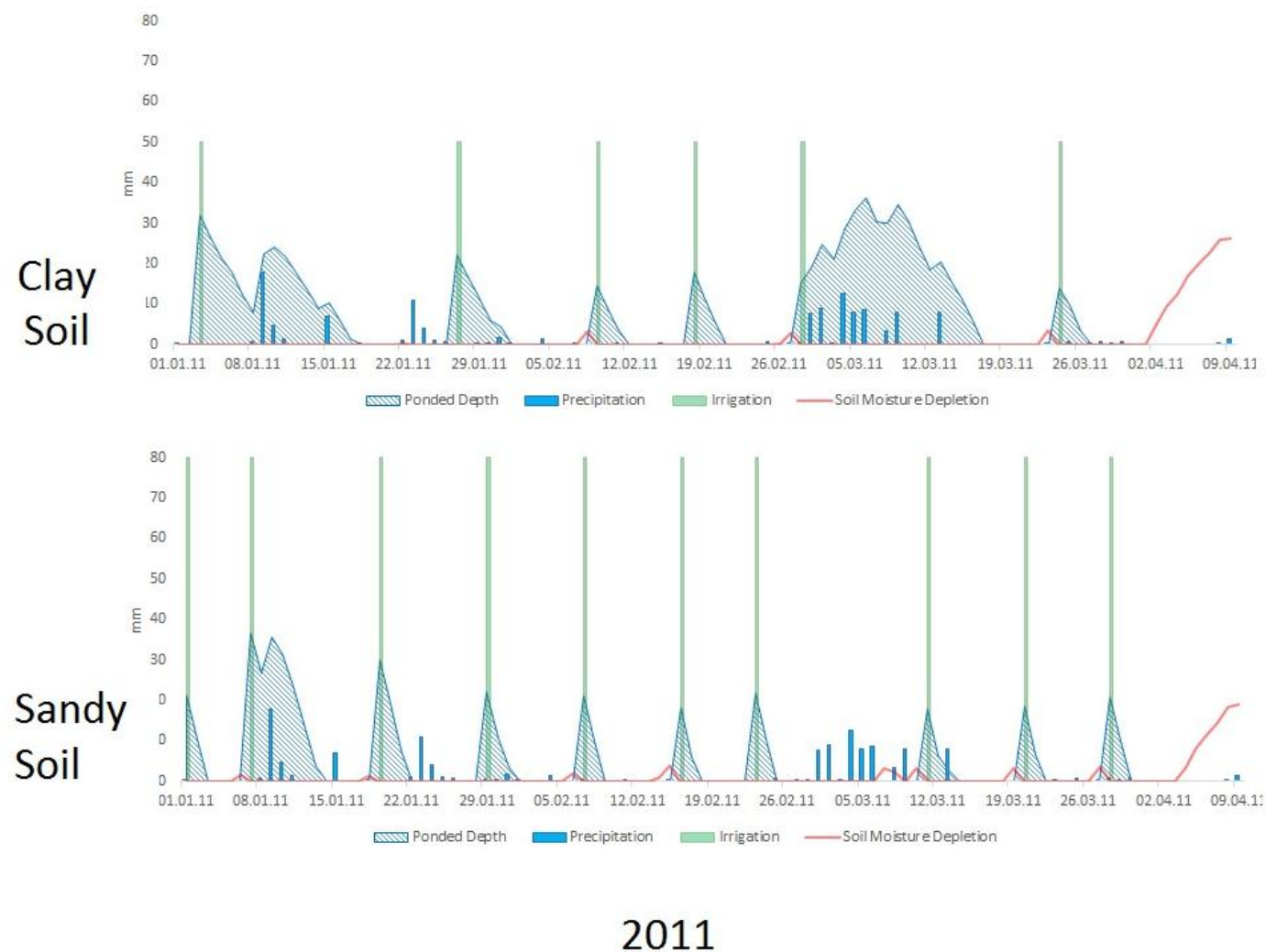


Figure 11: Simulated ponded water layer, irrigation, precipitation and soil moisture depletion for rice fields with AWD water management on clay and sandy soils in 2011 with a total seasonal rainfall of 134 mm.

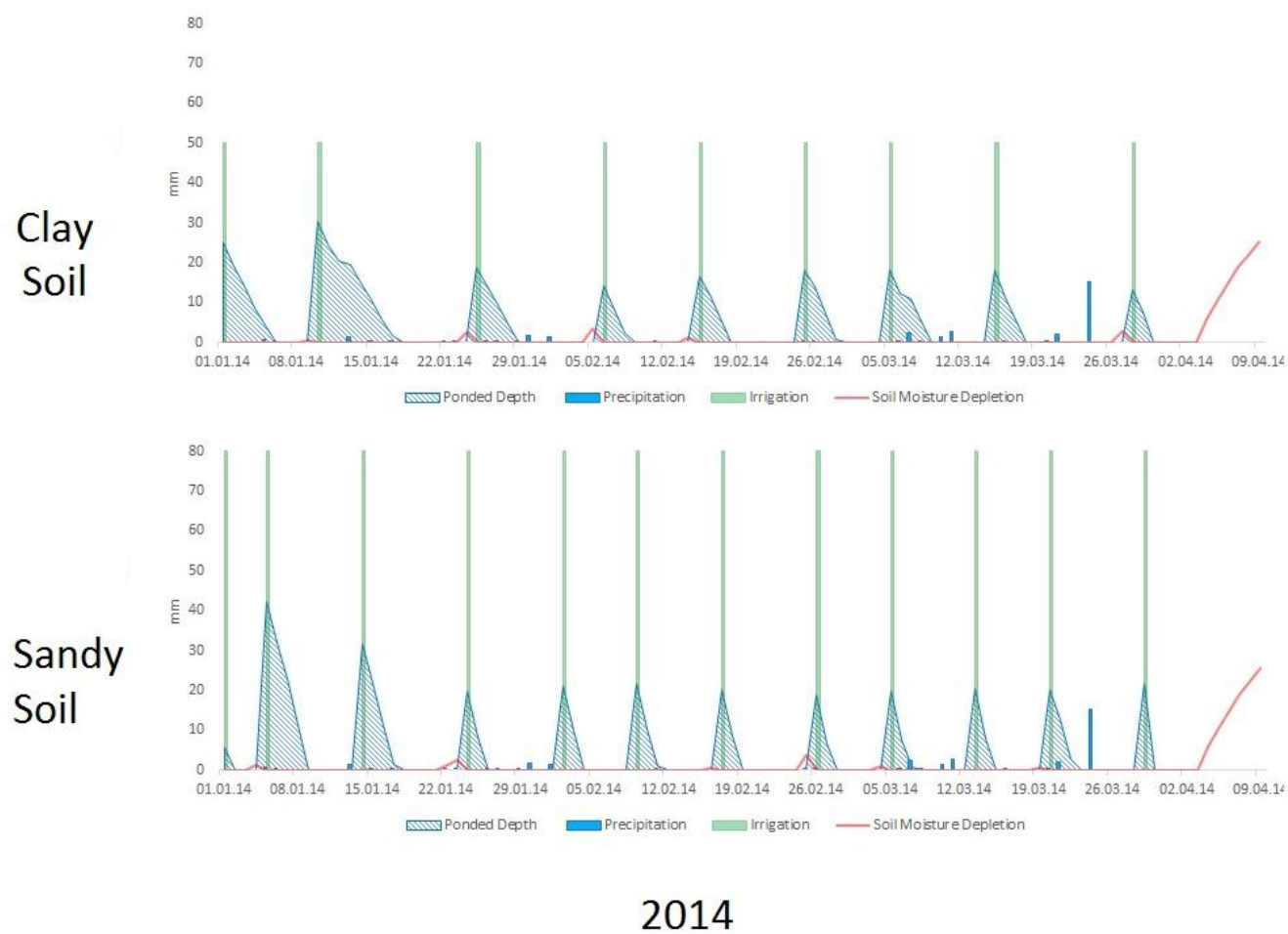


Figure 12: Simulated ponded water layer, irrigation, precipitation and soil moisture depletion for rice fields with AWD water management on clay and sandy soils in 2014 with a total seasonal rainfall of 33 mm.

5.1.3 Water saving with AWD

On average water savings through AWD in the dry season have been 17.5% (± 7.7). The modeled average irrigation requirement for continuous flooded and AWD scenarios for Dry and Wet Season are shown in Figure 13, which reflects average values for the entire experimental station under the selected treatment.

Broken down by soil type, the highest average savings are achieved in clay soils with 27% (± 11.4) followed by silty clay 15.4% (± 2.6), silty clay loam 15.3% (± 6.63) and sandy soils 12.1% (± 4.46). The detailed results for water saving potential for each soil type for wet and dry season 2006-2015 can be obtained in the Appendix, Table 13.

The overall water saving potential for the whole experimental station is on average 255340 m³ per dry season. Detailed annual results are shown in table 9.

Table 9: Seasonal irrigation water savings by AWD implementation on the experimental farm at the International Rice Research Institute, Philippines.

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Water savings m ³ (x 1000)	227.1	205.8	284	218.8	157.2	227.3	220.1	284.1	194.1	234.9	2253.3
Precipitation	228.5	88.9	245.1	268.5	60	158.4	322.8	321.5	33.4	99	

Water saving potential differs in spatial and temporal scale with rainfall amount and the soil type as main driving factors. For spatial analysis, results were visualized with ArcGis to identify areas with a high suitability for AWD.

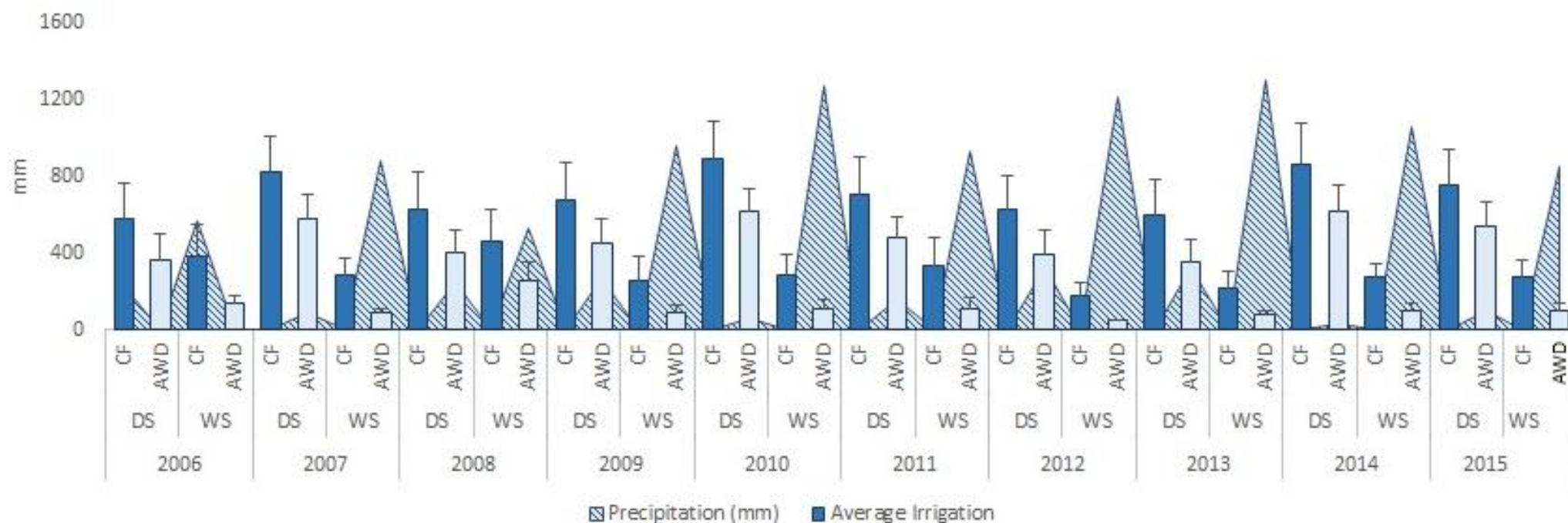


Figure 13: Simulated irrigation requirements for the Experimental Farm of the International Rice Research Institute, Philippines under continuous flooded and AWD irrigation scheme. Averaged values for different texture classes.

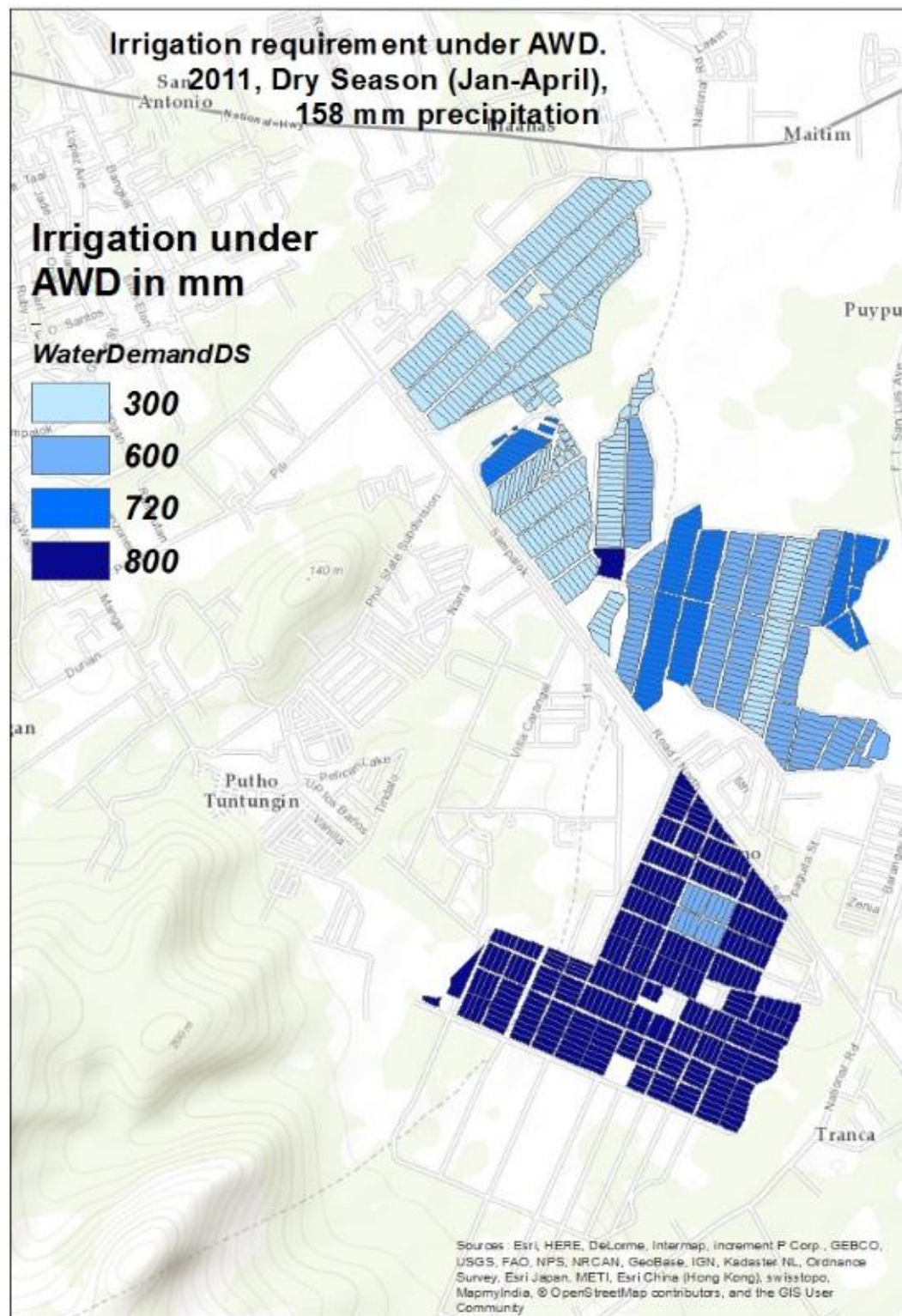


Figure 14: Irrigation requirement with Alternate Wetting and Drying irrigation technique on ZES in dry season, 2011. Total Seasonal precipitation is 158 mm. Results calculated with WEAP and graphically realised with ArcGIS.

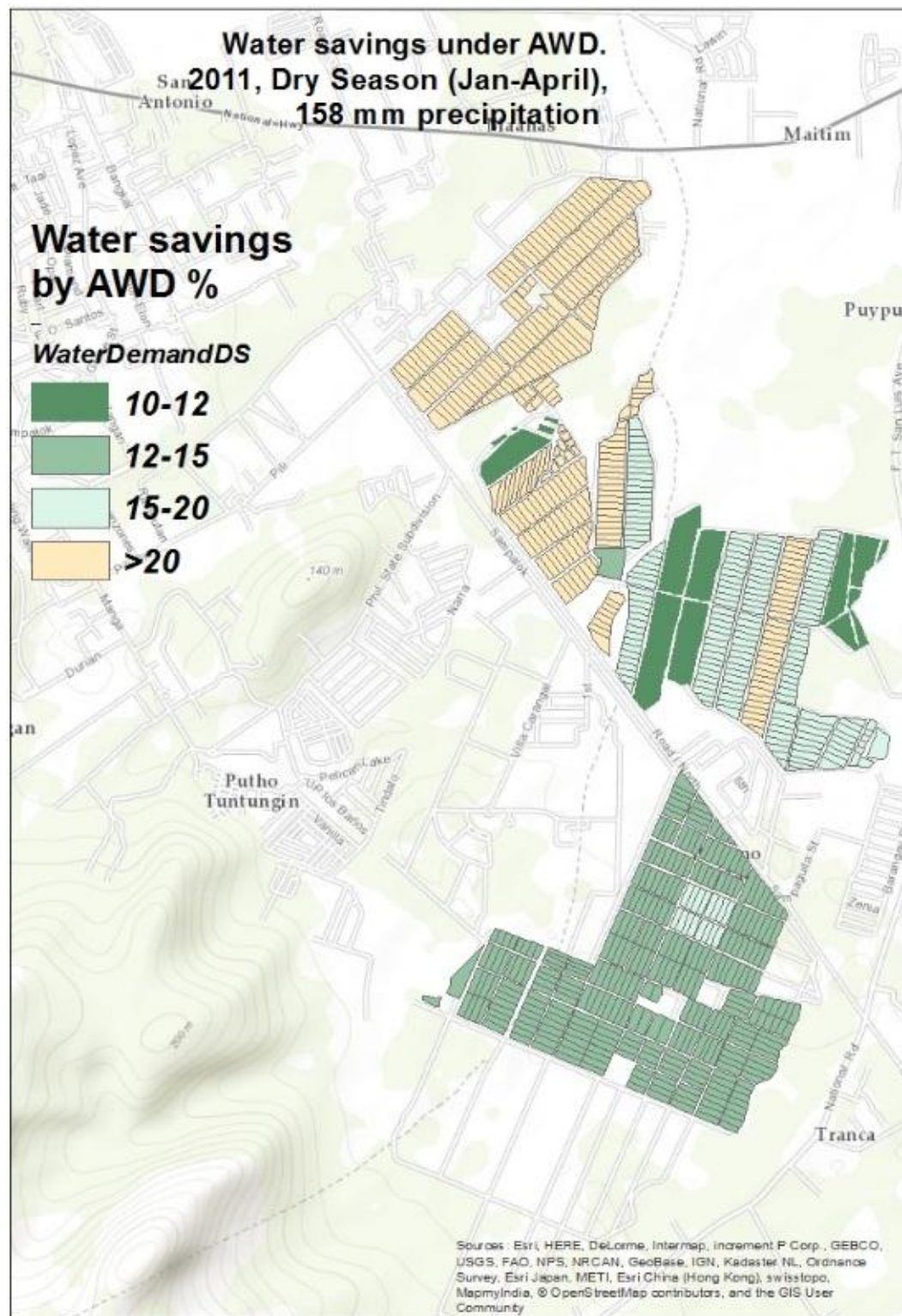


Figure 15: Irrigation water savings in % in dry season 2011 (total seasonal precipitation 158 mm) with AWD implementation. Results calculated by WEAP and graphically realised with ArcGIS.

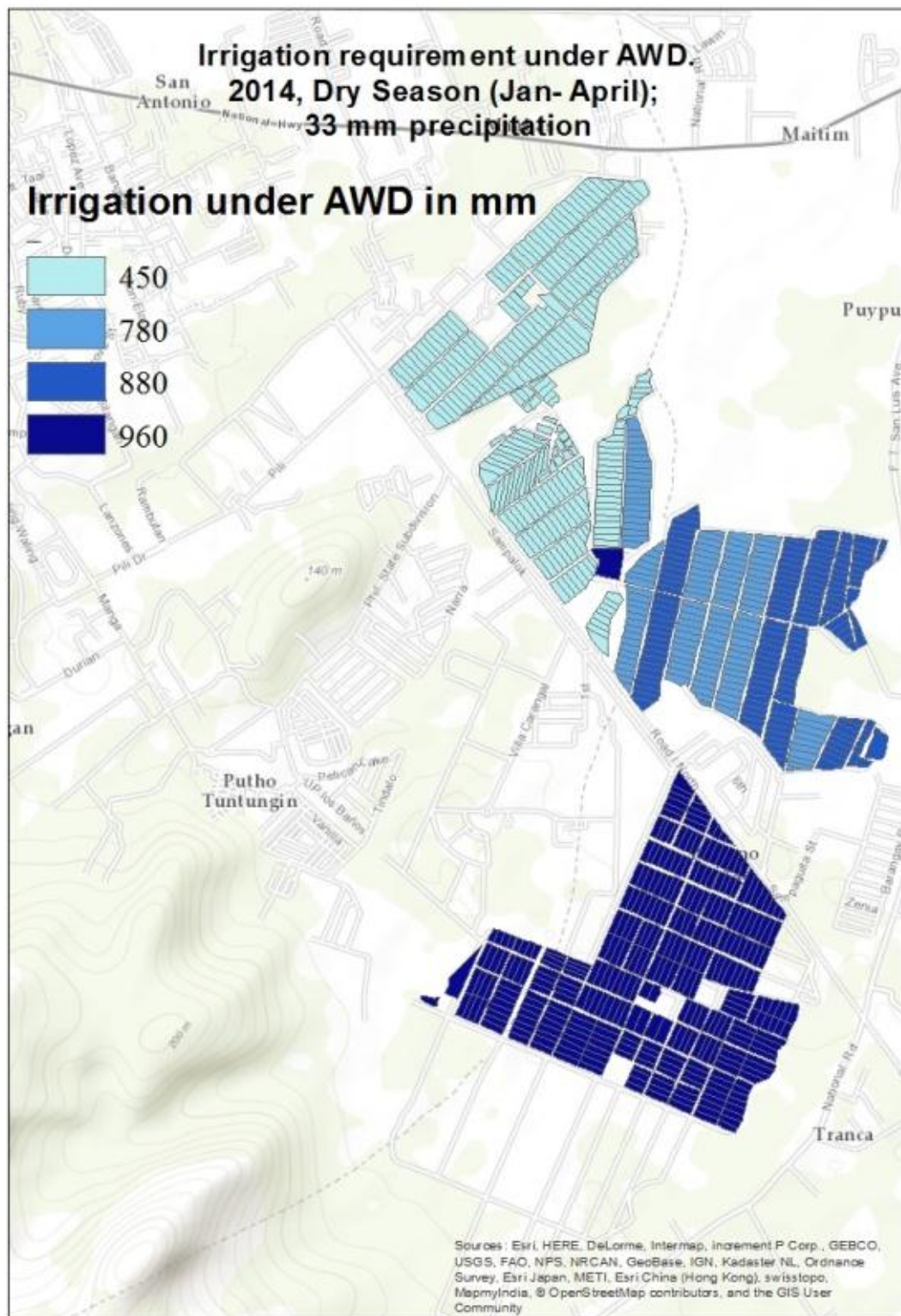


Figure 16: Irrigation requirement with Alternate Wetting and Drying irrigation technique on ZES in dry season 2014. Total season precipitation is 33 mm. Results calculated with WEAP and graphically realised with ArcGIS.

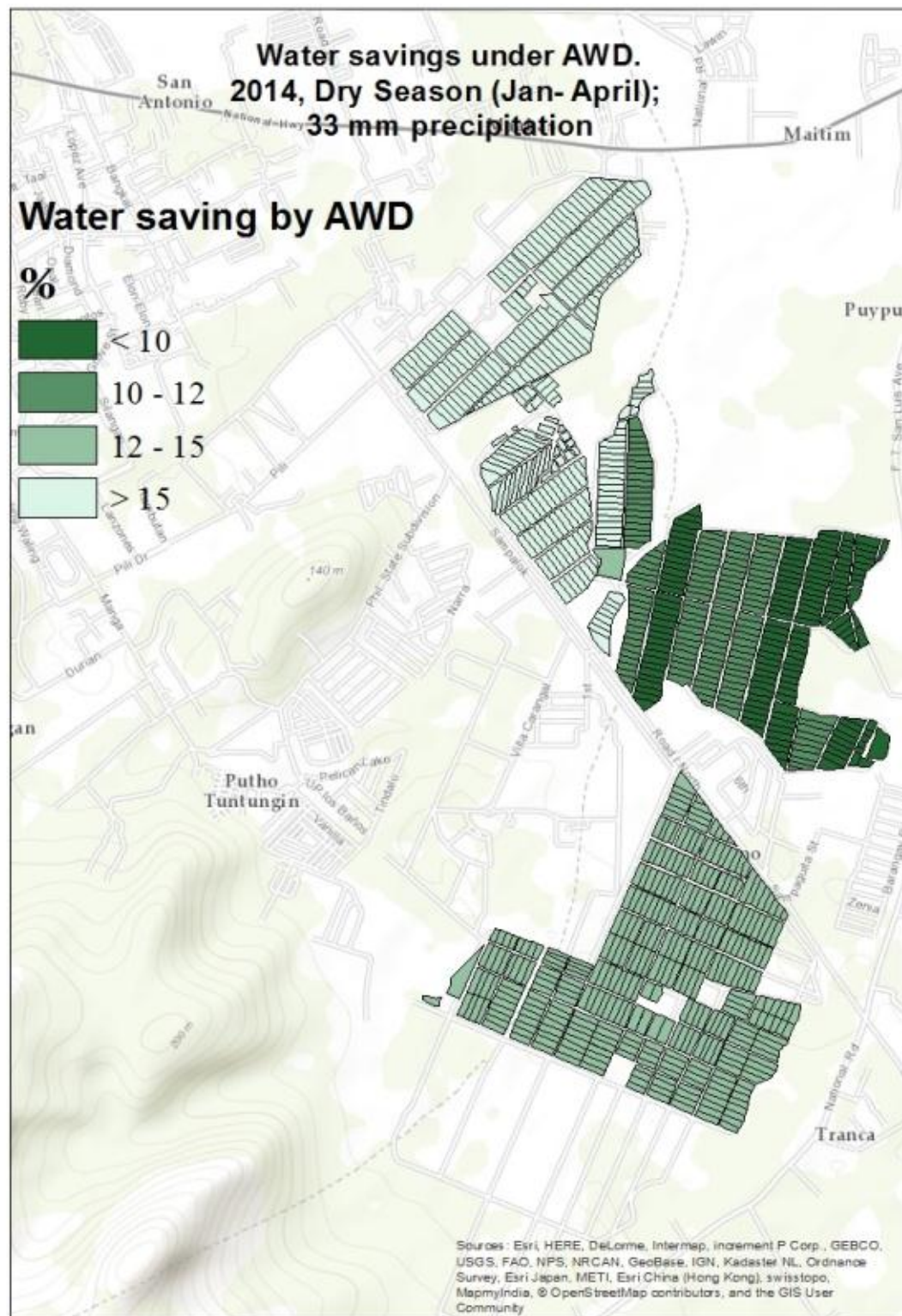


Figure 17: Irrigation water savings in % in dry season 2014 (total seasonal precipitation 33 mm) with AWD implementation. Results calculated by WEAP and graphically realised with ArcGIS.

Water saving performance differs with total precipitation amount (Table 10).

Table 10: Water savings in % in different rainfall-intense dry seasons.

	Water savings by AWD in %		
	Low (< 100 mm precipitation)	Medium (100-250 mm precipitation)	High (> 250 mm precipitation)
Clay	16.3 ± 5	34.8 ± 6.9	34.8 ± 9.5
Silty Clay	13.7 ± 2	16 ± 2.1	16.8 ± 3.3
Silty Clay Loam	9.4 ± 2.4	18 ± 8	20.3 ± 2.6
Sandy	8.6 ± 4	13.2 ± 2.2	15.5 ± 4

AWD reduces the number of irrigation events and increases the average amount per irrigation. Also, the extent is depended from the soil type and differs in seasons. In the wet season, the average amount per irrigation and the number of irrigation events is decreased by AWD.

Table 11: Effects of AWD implementation on irrigation pattern. Number of irrigation events and irrigation amount under continuous flooded (CF) management and Alternate Wetting and Drying (AWD) technique. Results calculated by WEAP for dry seasons 2006-2015 on soils with different dominating soil textures.

	Irrigation events	Irrigation amount (mm)	Irrigation events	Irrigation amount AWD	% decreased irrigation events	% of average amount per irrigation increased
DS	CF		AWD			
Clay	7	396.86	5	315.00	22.86	2.90
Sandy	26	906.92	10	800.00	61.39	128.46
Silty Clay Loam	14	816.88	10	618.00	30.56	7.12
Silty Clay	13	728.11	9	683.00	30.77	38.40
Average	15.08	712.19	8.60	604.00	36.39	44.22
STD	7.90	222.54	2.18	206.86	17.07	58.35
WS						
Clay	2	120.23	2	78.00	0.00	-19.00
Sandy	7	391.93	5	225.00	23.08	-17.00
Silty Clay Loam	6	354.58	3	145.00	47.37	-20.00
Silty Clay	5	288.70	4	185.00	13.04	-19.60
Average	4.70	288.86	3.50	158.25	20.87	-18.90
STD	1.96	120.25	1.29	62.68	20.03	1.33

5.2 AMRIS

For AMRIS, the modeled water savings for AWD systems were on average 34.3 % (± 6.2) or 54.88 MCM (± 6.4) lower in the dry season compared to continuous flooded systems. Detailed modeled results for the irrigation demand in dry and wet season can be obtained from Table 14 in the Appendix.

The analysis of streamflow in the Northern Main Canal shows an increase resulting from AWD implementation. Figure 20 shows the effect of AWD on monthly streamflow in 2010.

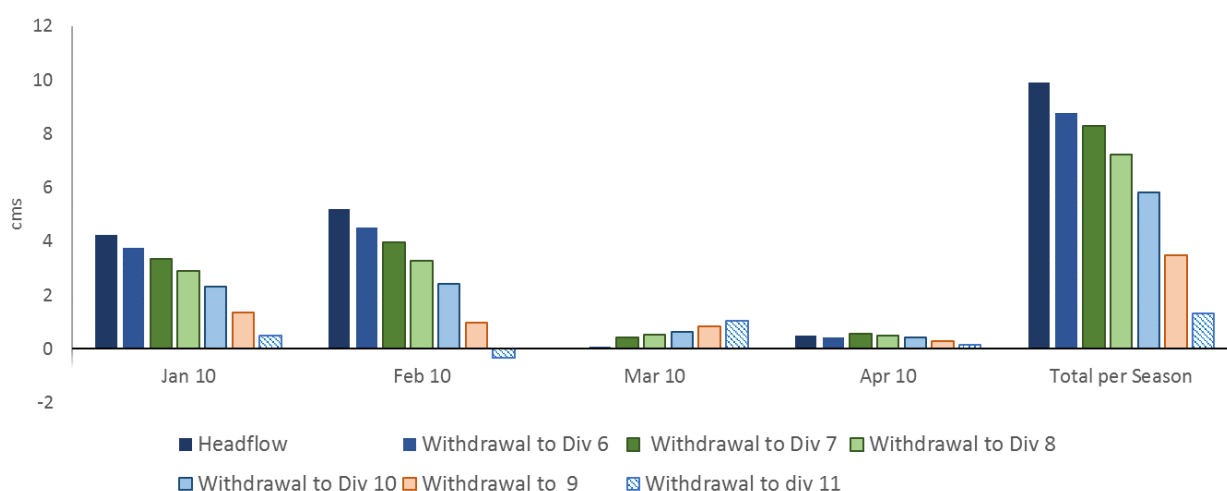
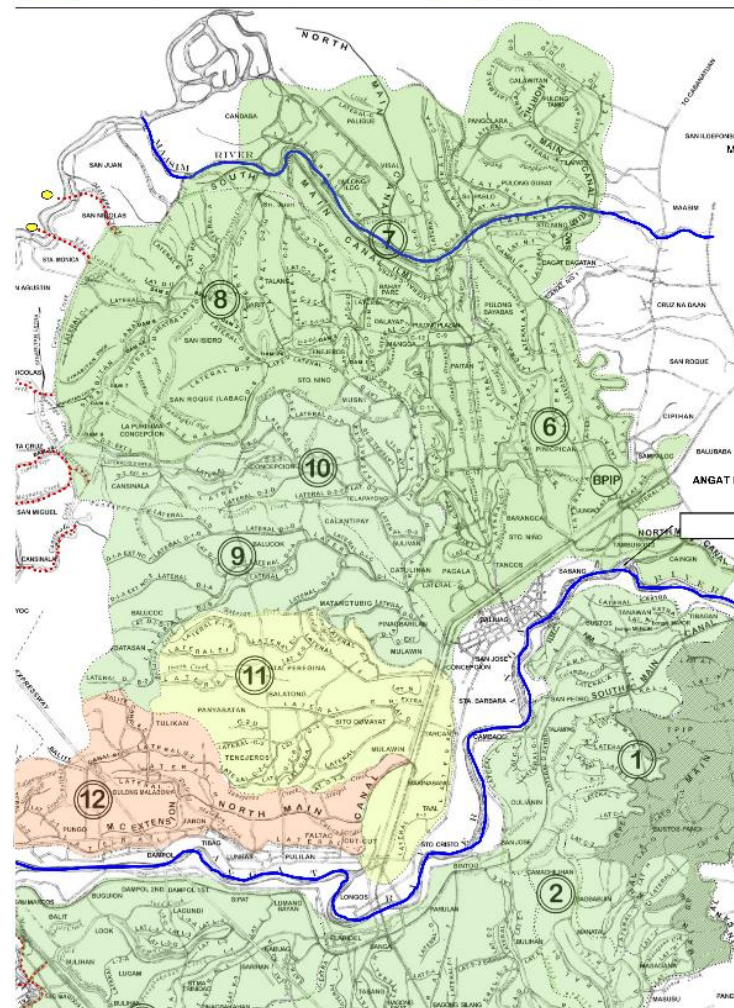


Figure 18: Effects of AWD implementation on streamflow in canals of the northern part of AMRIS. The first column of each month (dark blue) is the headflow of the northern main canal, the subsequent columns represent the following main canals to the irrigation divisions. Results calculated by WEAP for dry season 2010.

The detailed assessment of AWD and climate change scenarios on streamflow and demand coverage can be obtained from Table 15 in the Appendix. In all scenarios, AWD enhanced water availability especially in the tail ends and led to a mitigation of water scarcity in affected areas. In the scenario of climate change I, II and III water shortage occurs in the tail end divisions. Applying AWD on the whole area, water shortage can be reduced. (Figure 21-23)

Demand Coverage in Climate Change Scenario I (DS) and CF

100 % 86 % 21 %



Demand Coverage in Climate Change Scenario I (DS) and AWD

100 % 91 % 53 %

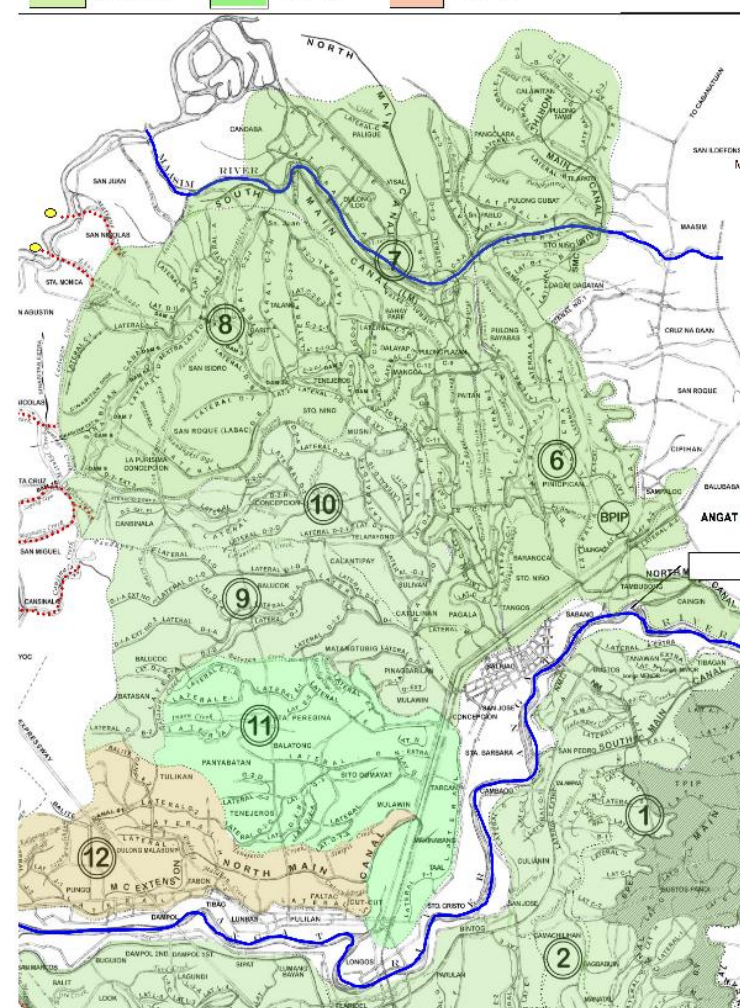
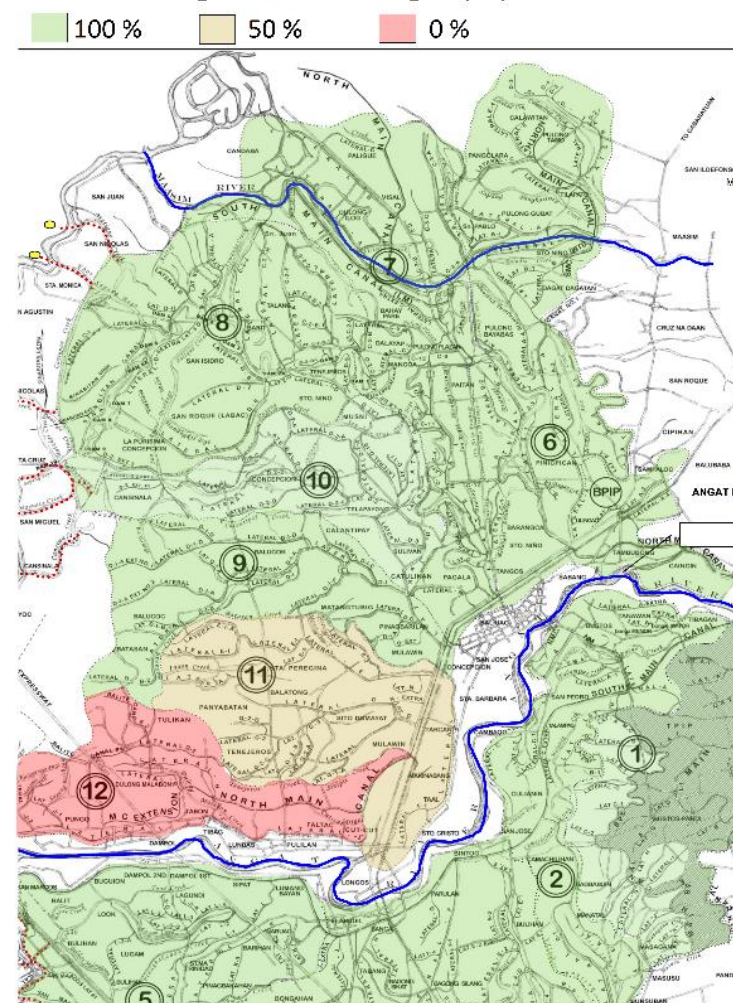


Figure 19: Irrigation water demand coverage (in %) of single irrigation divisions of the northern part of AMRIS. Results are based on calculations with WEAP for a dry season under the climate change scenario I (10% reduced inflow and precipitation). Left: Irrigation technique: continuous flooded (CF); Right: Irrigation technique: Alternate Wetting and Drying (AWD)

Demand Coverage in Climate Change II (DS) and CF



Demand Coverage in Climate Change Scenario II (DS) and AWD

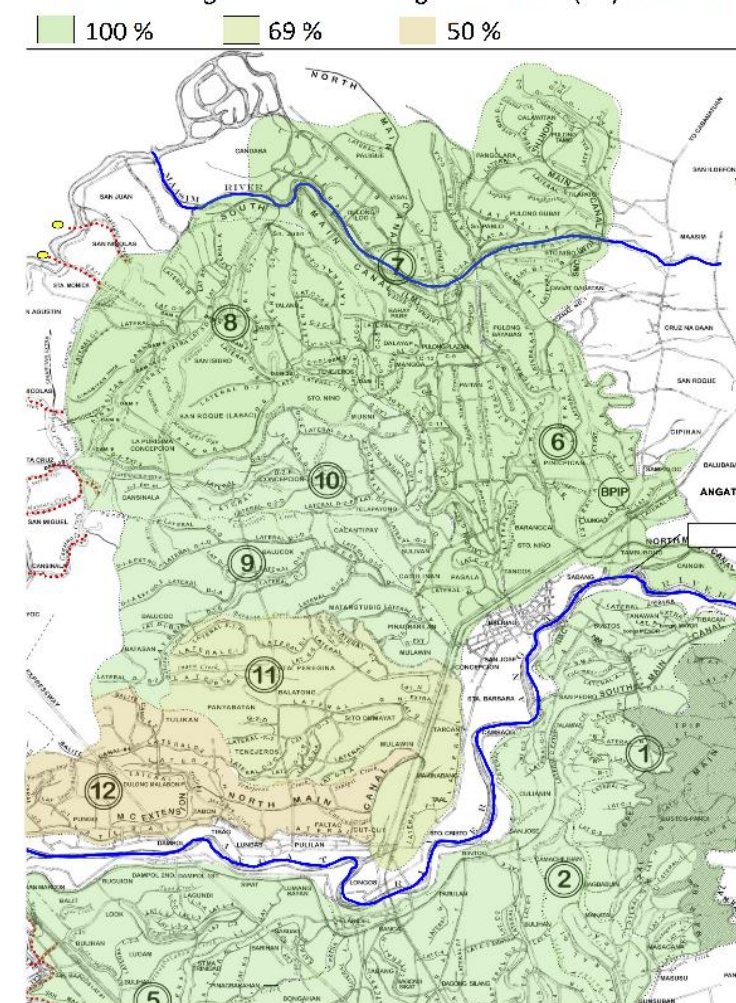


Figure 20: Irrigation water demand coverage (in %) of single irrigation divisions of the northern part of AMRIS. Results are based on calculations with WEAP for a dry season under the climate change scenario II (20% reduced inflow and precipitation). Left: Irrigation technique: continuous flooded (CF); Right: Irrigation technique: Alternate Wetting and Drying (AWD)

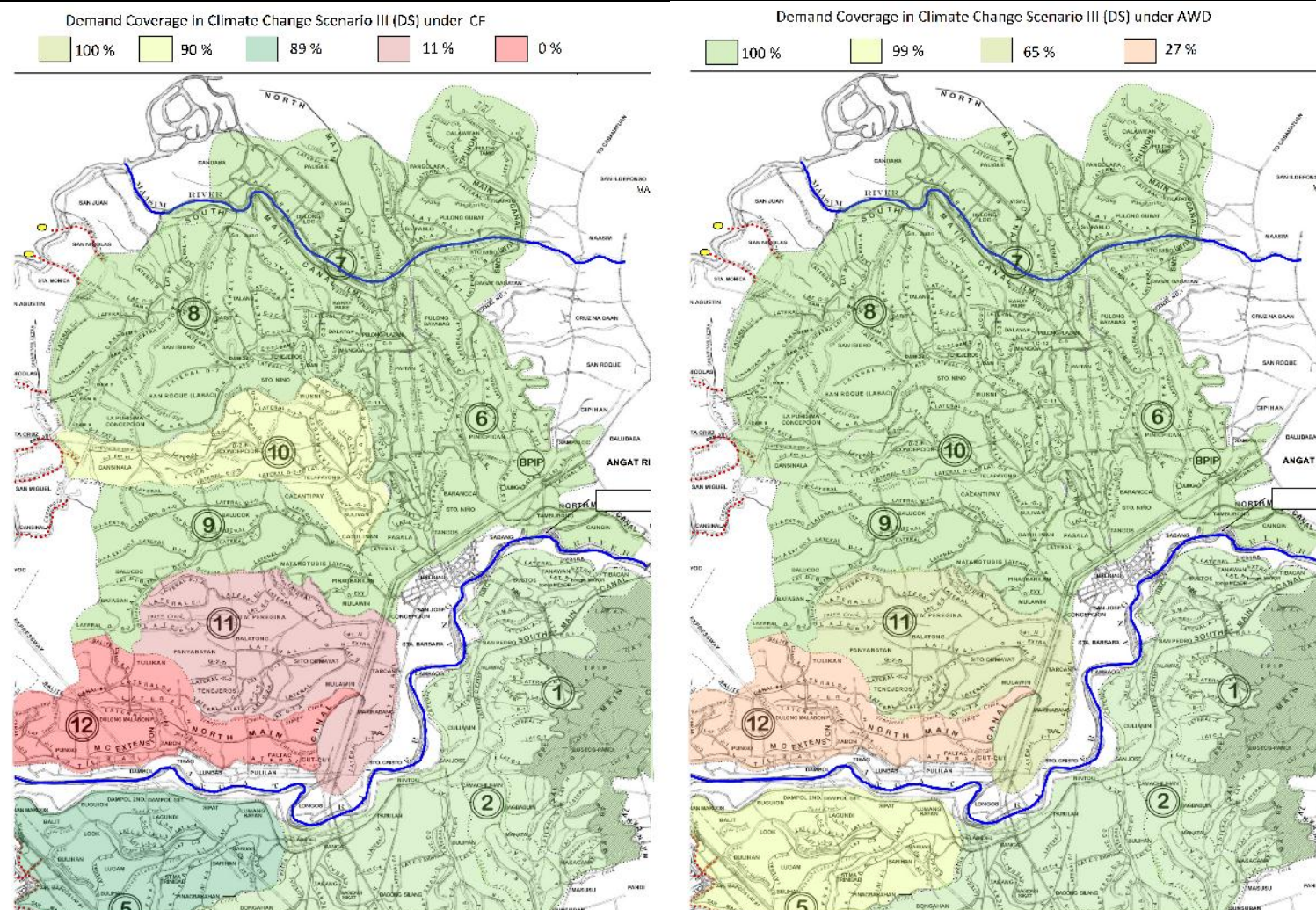


Figure 21: Irrigation water demand coverage (in %) of single irrigation divisions of the northern part of AMRIS. Results are based on calculations with WEAP for a dry season under the climate change scenario III (30% reduced inflow and precipitation). Left: Irrigation technique: continuous flooded (CF); Right: Irrigation technique: Alternate Wetting and Drying (AWD)

The Climate Change scenarios had impact on the storage volume in Angat Dam as visualized in Figure 20-23. The combination of the climate change scenario III and Manila demand growth had a substantial effect on the water level in the reservoir. Within 10 years of simulation the combination of both scenarios had an on average 38.15% (± 20.02) larger depletion with its maximum towards the end of simulation. The effects of the climate change scenarios on the lowering of water level in the dam range between 4-15%, Climate Change and Manila demand growth 13-39% and AWD as mitigation option for combined scenarios 3-14% as reflected in Table 12.

Table 12: Impact of scenarios on modeled storage volume on the Angat Reservoir. Results are based on a simulation of 10 years calculated with WEAP. CC I, CC II, CC III describe the scenarios of reduced inflow and precipitation to the catchment of 10 -, 20- and 30%. The scenario Manila means an increase of water demand from $46 \text{ m}^3\text{s}^{-1}$ to $50 \text{ m}^3\text{s}^{-1}$. AWD was implemented to assess the effects on supply system.

Scenario	average reduction of storage volume	STD	maximal reduction of storage volume
CC I	4.93	3.35	11.04
CC II	9.93	6.73	22.48
CC III	15.15	9.9	36.15
CC I and Manila demand growth	13.52	8.54	26.89
CC II and Manila demand growth	18.99	11.5	38.12
CC III and Manila demand growth	38.15	20	97.33
CC I and Manila demand growth, AWD	3.3	4.11	10.66
CC II and Manila demand growth, AWD	8.05	6.82	21.56
CC III and Manila demand growth, AWD	13.99	9.88	32.67

The potential impact of AWD in water scarce conditions entails also effects on water resources upstream the irrigation system. In the model, the lowering of the water level in the dam was prevented by large scale AWD implementation. In the beginning as well as the end of all climate change with AWD simulation, the water level never reaches a critical volume and the initial volume was always replenished.

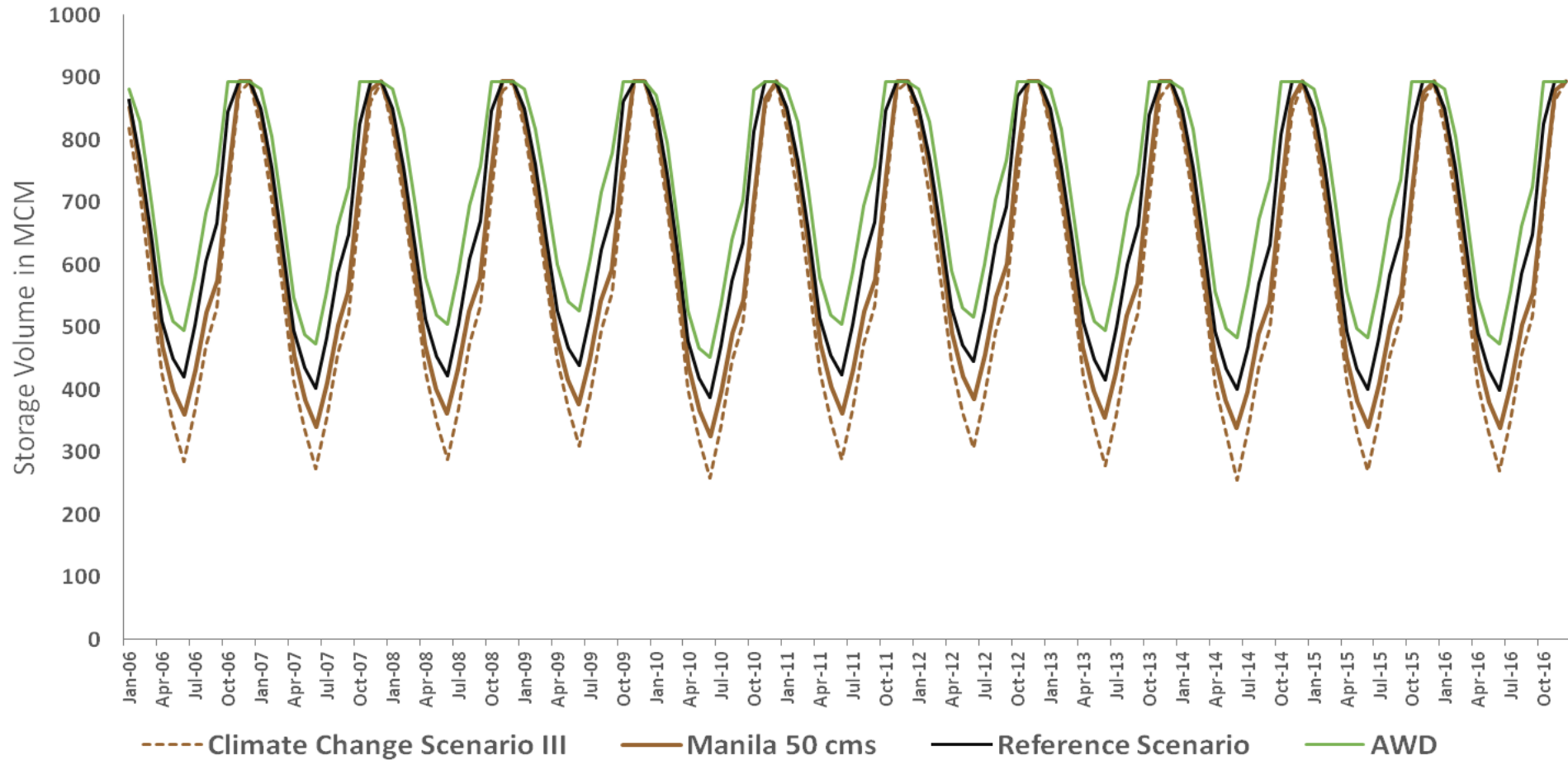


Figure 22: Storage volume of Angat Reservoir under different scenarios for a simulation period of 10 years. Reference scenario = continuous flooded; AWD = Alternate Wetting and Drying implementation on the whole irrigation system; Manila 50 cms = Population growth and respectively increase in freshwater demand from $46 \text{ m}^3\text{s}^{-1}$ to $50 \text{ m}^3\text{s}^{-1}$. Climate change scenario III = 30 % reduced inflow to catchment

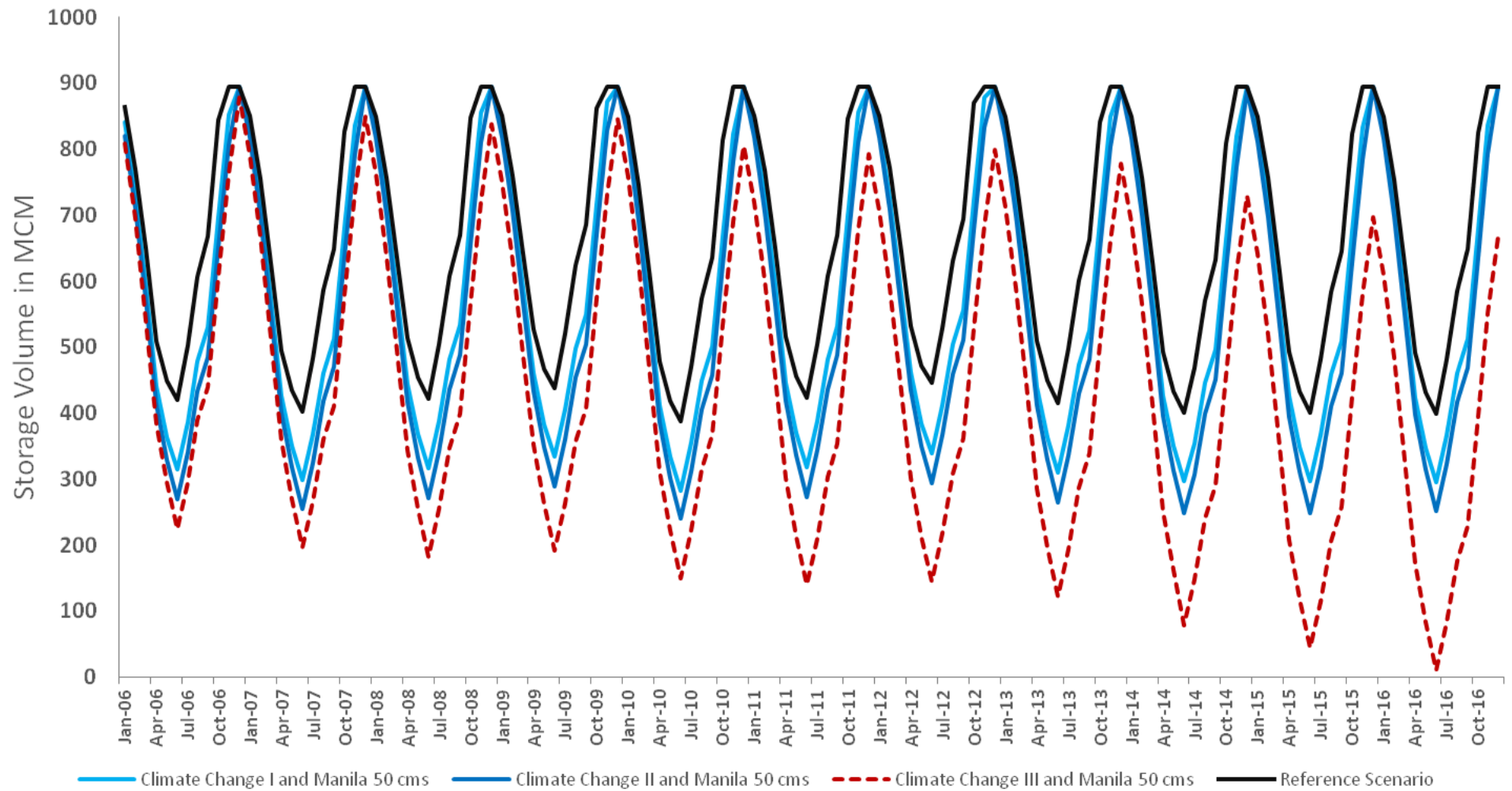


Figure 23: Storage volume of Angat Reservoir under different scenarios for a simulation period of 10 years. Reference scenario = continuous flooded; Climate change scenario I, II, III = 10, 20, 30% reduced inflow to catchment in combination with Manila freshwater demand growth from $46 \text{ m}^3\text{s}^{-1}$ to $50 \text{ m}^3\text{s}^{-1}$

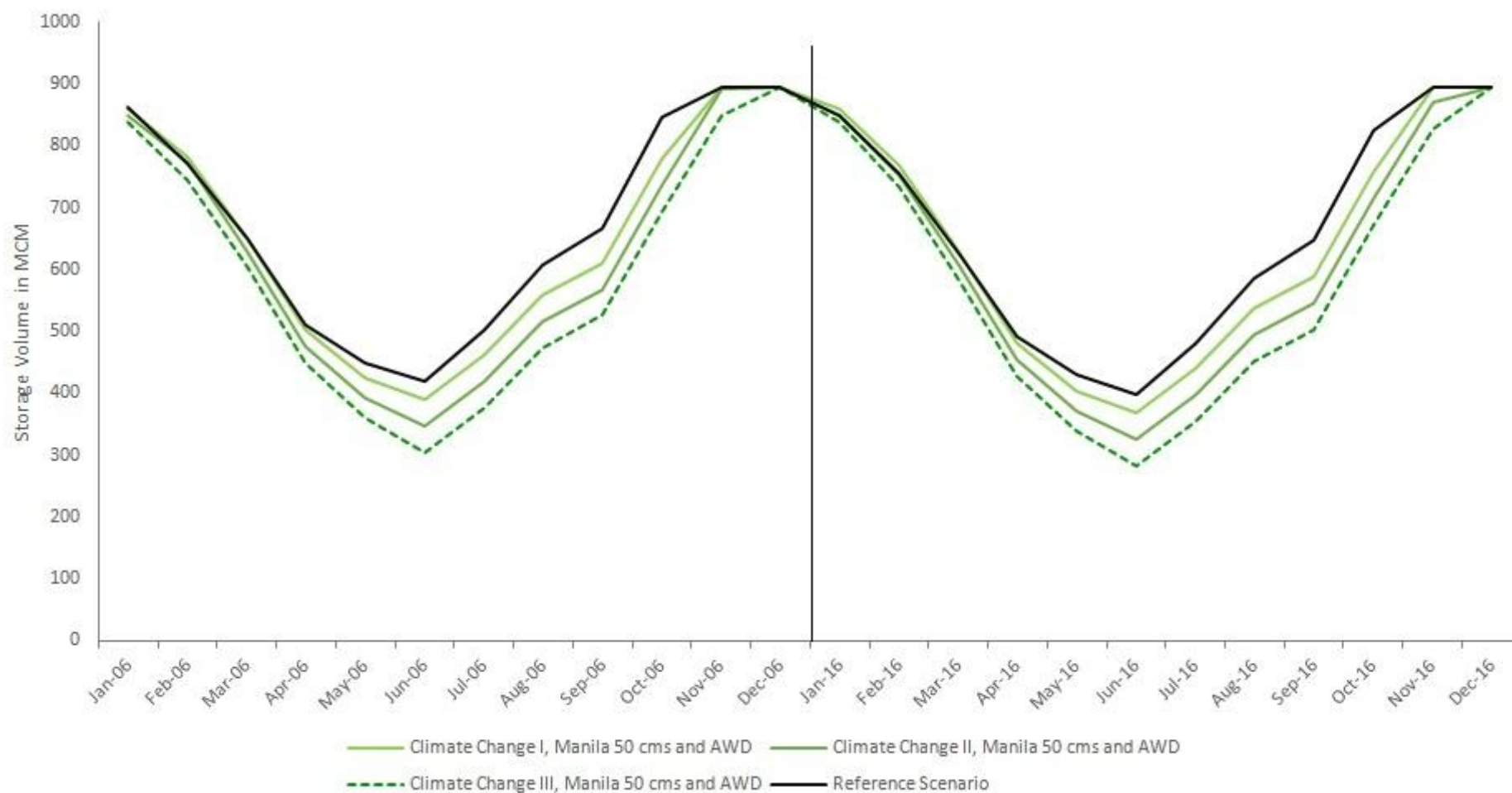


Figure 24: Storage volume of Angat reservoir under different climate change and AWD scenarios. Left side: 2006; Right side: 2016. With AWD implementation storage volume reached in none climate change scenario a critical limit.

6. Discussion

6.1 Appraisal of usability

The application of WEAP is very user oriented and is supported by a self-explanatory interface, a handbook and training material. The interface of WEAP has a user-friendly menu structure with a set of three important main views on the area or dataset. In the Schematic View, the mode is built within a spatial layout, which can also be supported by a GIS layer. All components of the demand and supply system can be created and linked with each other. The set-up is created by a drag-and drop menu and demand and supply nodes are arranged by their spatial relations. A vector or raster file can be uploaded to assist the arrangements in the schematic view. Physical hydrological components can be easily implemented. Rivers, Reservoirs, canals and further transmission links or return flows can be easily implemented and connected with the demand side. Connections between each can easily be established by transmission links or return flows. After establishing the model in the schematic view, the data can be added and edited in the Data View. The data view is well structured and depending on the modelling approach, different amount of data are required. However, a preliminary set of default values or assumptions can be used, if required data are not available. Information for crop and soils can be pre-chosen from the library or they can be adjusted. Moreover, physical or contractual limitations on supply links can be implemented to simulate a realistic management of hydrologic components. WEAP offers the possibility to connect with further hydrological models like MODFLOW, a tool for groundwater flow modelling. With this, the full potential of modelling hydrological cycle processes can be exploited. Results for demand and supply are displayed in the Results view. Depending on the modelling approach, a various range of results are available in clearly visualized graphs and tables. The clear structure of WEAP makes it a very user-friendly and comprehensive tool. Moreover, it is a very flexible approach since it can operate on a wide range of data variability and scope of study. It enables a multi-scale assessment and can link rivers, reservoirs, irrigation facilities and agricultural areas and based on this a various set of outputs can be created.

6.2 Application of WEAP as irrigation planning tool and AWD implementation

The overall applicability of WEAP application can be assessed as very positive; calculated water requirements achieve results comparable to reference values found in literature. Moreover, it is possible to investigate changes in the system on the supply side, as visible in AMRIS. A comparison with the minimum water requirement calculated by Aquacrop and ET_0 affirms the conclusion. ET_0 provides orientation, since the K_c factor in rice ranges between 0.6 (in the last 25 days of vegetation period) and 1.15 (Mid-Season Stage, from 34 – 74 DAT). Minimum water requirements calculated by Aquacrop include minimal losses through percolation.

The water demand of AWD is, as anticipated between continuous flooding and minimum water requirements. The ANOVA test shows no significant difference between both and indicates a high irrigation efficiency of the chosen irrigation schedule.

However, comparing the boxplots of the irrigation requirements of averaged irrigation requirements in a modeled period of 10 subsequent dry seasons, WEAP computes a lower standard variation and a more even distribution of the values compared to Aquacrop. It can be therefore deduced that crop water requirements of WEAP are more sensitive compared to Aquacrop. The differences can be explained by different approaches of calculating crop water requirements. Crop water requirements in WEAP are calculated on the basis of a dual K_c approach, based on FAO Irrigation and Drainage Paper No. 56. Calculations for Aquacrop are based on FAO Irrigation and Drainage No. 33 and incorporates canopy cover rather than K_c values in different physiological stages.

Evaporation and transpiration achieve results similar to the irrigation water requirements. Runoff is highest in the CF-Scenario, though this can be accounted for by the drainage of the field before harvest. Percolation shows targeted substantial differences between the calculation methods and confirms the irrigation schedule.

6.3 Water saving potential of AWD and related benefits

Overall, simulated AWD implementation in all years and seasons indicates high water saving potential when compared to CF. The modeled water balance reflects the values from field trials. Belder et al. (2004) reported 17 % irrigation water input reduction in fields with 1 mm percolation and shallow groundwater table (comparable to clay soil). Simulated results under similar conditions aimed a reduction of about 15 %. AWD not only reduces the total irrigation quantity, it also enhances the irrigation efficiency by reducing the number of irrigation events and increasing the average amount per irrigation event. In pumped systems, this reduces fossil fuel and electricity use, especially in systems with long pipelines. As a result, AWD reduces greenhouse gas emissions and production costs, which are related to fuel consumption and hence lower the environmental impact of irrigated rice systems.

The potential water savings can be divided and further investigated in terms of spatial and temporal resolution. The water saving potential is in both study sites during the wet season high. This is due to frequent and intense rainfall events which replenish soil moisture and delay irrigation trigger activation. The combination of precipitation and considerably reduced irrigation is still sufficient to achieve intermitted flooded conditions with a shallow water layer, which leads to the high water savings. In view of a water saving technology and under application with a soil-water content threshold, AWD reduces the irrigation requirements. Due to high and frequent rainfall, the additional irrigation is limited to a minimum and irrigation or water saving are of minor importance. For reducing greenhouse gases with AWD only 34 % of the rice area in central Luzon is suitable for wet season, as described by Sander et al. (2017). In addition, rice paddy fields as well as reservoirs and rivers contribute with a buffering capacity to flood control of a watershed during the wet season. With AWD implementation in the wet season, the benefits of GHG reduction could be offset by negative effects on downstream areas by reducing the buffering capacity of the paddy field and implementation of AWD is not always technically possible. Therefore, implementation needs to be carefully considered.

Regarding the dry season and the temporal analysis, the results of the model reflect similar patterns as in the wet season. When precipitation is abundant and

equally distributed, AWD achieves high savings and reliability despite a decrease in irrigation. When precipitation is low (< 50 mm) or not well distributed, AWD still reduces irrigation demand by 8-15%.

Resulting from Risk map analysis following conclusions can be drawn for the ZES:

- In the dry season, soils with a high clay content have a low irrigation requirement under AWD and also have the highest saving potential.
- Soils with the lowest clay content have the highest irrigation requirement under AWD, but also high water saving potentials compared to continuous flooded management practice.
- In a “dry” dry season, the modeled results for AWD show similar results to a regular dry season. Water requirements are with low differentiation similar to the reduced amount in precipitation. This suggest that AWD is also under water short seasons highly effective in terms of water saving.

With regard to management decision support, the results can be used as follows:

- If parts of the field need to be sustained as CF, it should be done on clay soils. They show the lowest water demand under CF Scenario.
- If the production area should be reduced, sandy soils should be taken out of production.
- To reduce conveyance losses, pumps should be installed close to fields with a dominating sand content with high water demand. Soils with a dominating clay texture component have a decreased demand for irrigation in frequency and amount of irrigation events and thus, conveyance losses are lower.

The inter-annual and spatial variations are mainly caused by different precipitation levels and soil types. In conclusion, it can be said that soil type and precipitation amount and its distribution are key for modeled water saving potential of AWD.

Under climate change, water supply is reduced and water shortage in the system occurs. In the model, AWD increases streamflow and water availability, especially

in water scarce areas. Implementing a water saving technology like AWD, enhances water availability and demand coverage not only in the upstream areas, but mostly in the downstream and tail end areas, where water scarcity mainly occurs. Although the chosen scenarios reflect only a minor part of the complexity of global climate change models, this simplified simulation can indicate potential tipping points and freshwater resource vulnerabilities as well as the potential of AWD in a large-scale assessment.

6.4 Limitations

Within an in-depth analysis, implementation impediments regarding AWD and weak points were identified. The irrigation schedule does not allow a continuous flooded period one week before, during or one week after flowering, as recommended by IRRI. Within this period, rice is very sensitive to water stress and a ponded water layer prevents sterility and therefore a reduction in yield. However, simulated water depletion never exceeds 25 % of RAW, which ensures that yield is not affected. Resulting from this, it can be expected that on-farm water use is underestimated by ignoring this period.

Capillary rise is an important water balance parameter in soils with shallow groundwater. In this approach and with the given dataset, it was not possible to implement this parameter. The water requirement in continuous flooded systems is assumed to be overestimated, especially in the large-scale assessment since intrasystematic water recycling was not considered.

The results for evaporation show deviation in amount and seasonal development from expected outcomes and literature. Figure 27 shows the simulated development of evaporation and transpiration over the growing period in comparison with simulated values from Aquacrop from a ponded rice field. Theoretically, evaporation decreases during the growth period, whereas transpiration increases. This is not reflected in WEAP, and moreover CF and AWD show the same development.

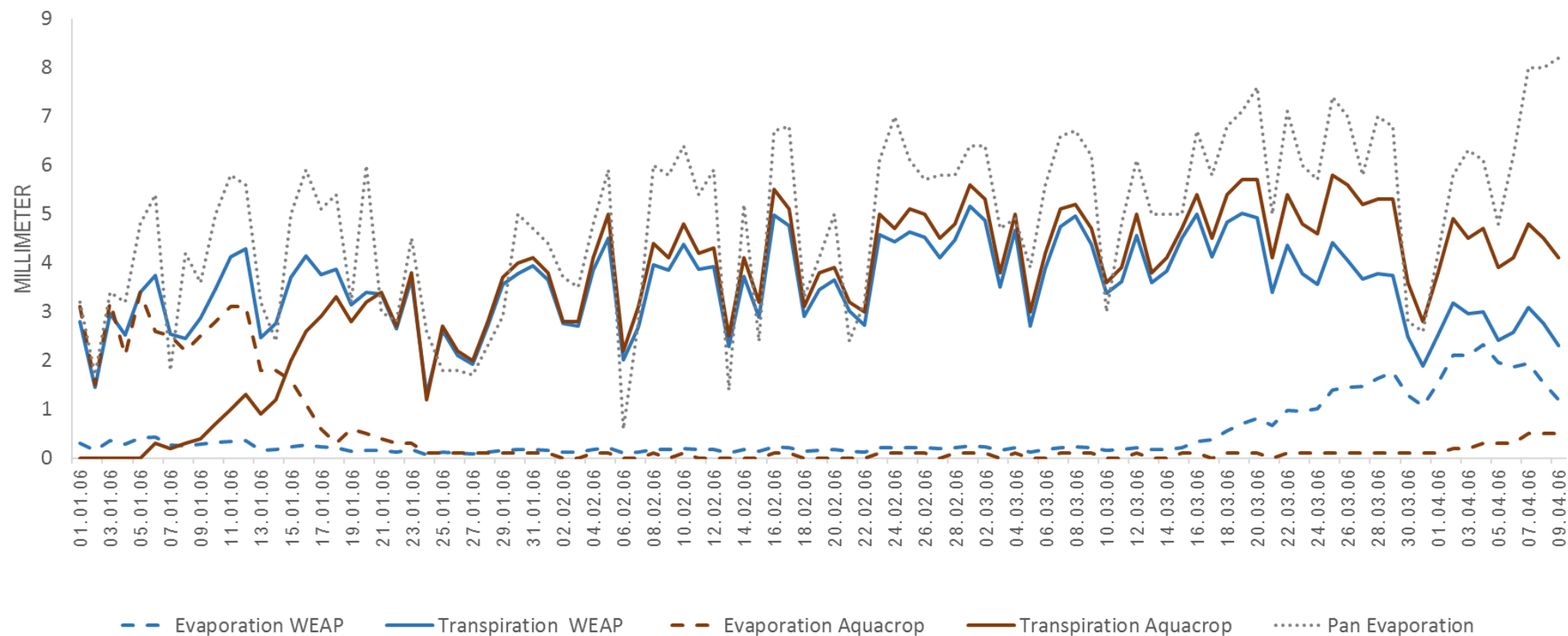


Figure 25: Evaporation, Transpiration and Reference Evaporation (=Pan Evaporation) from different calculation methods (Aquacrop and WEAP) for the dry season 2006.

It can be assumed that results for evaporation in AWD should differ from CF. The amount of readily evaporable water fluctuates with the water table, which should also be reflected by the evaporation rate. This can be explained by the nature of the evaporation process, which is described in two phases: The energy limiting and a falling rate stage. In the first stage evaporation is at its maximum, the soil is at field capacity and energy is the limiting factor. For example, this is generally the case during the flooded period. During the non-flooded period (as soon as the soil moisture content drops below saturation), evaporation is in the falling rate stage and evaporative rate is reduced. The falling rate stage is not only limited by energy, but also by the amount of remaining evaporative water. (Allen et al., 1998)

Aquacrop, WEAP CF and WEAP AWD compute evaporation as 44-47 mm per season, whereby the first calculates minimum water requirement in un-ponded conditions. This comparison leads to the conclusion that WEAP calculates evaporation for saturated conditions. The ponded water layer is not reflected in WEAP-CF and AWD. The results from the simulations were compared with experimental results published by Tuong et al. (2005) and resulting from the comparison it can be concluded that the calculated evaporation underestimates true evaporation. According to the findings from an experiment conducted at ZES in DS between 2001-2003, evaporation in a flooded system was 138-170 mm per season which is 67-73 % higher than simulated values. Those findings are supported by results from Yoshida, (1979) and DeDatta, (1981). DeDatta estimates daily paddy rice evapotranspiration to be 6-7 mm in the dry season, and Yoshida 5 mm. Extrapolated over a typical cropping season of 99 days, WEAP and Aquacrop underestimate ET_c by 25-55%.

The potential source of error can be identified in the calculation algorithms. The formula for the maximal crop coefficient, K_{cmax} , (5), which is interrelated with K_e and evaporation, needs to be adjusted for periods with more than 2 wetting events.(Allen et al.,1998)

$$K_{cmax} = \max \left\{ \frac{1.2 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)] \left(\frac{h}{3}\right)^{0.3}}{K_{cb} + 0.05} ; \right. \quad (5)$$

where

u_2 = wind speed measured at 2 m height [m/s],

RH_{min} = minimum relative humidity [%],

h = plant height during the current day [m]

There is little research on the evaporative losses in AWD, but results from aerobic rice trials can be used as reference. A study of successive dry seasons between 2001-2003 in the Philippines show that evaporative losses in CF ranged between 138-170mm and 54 -95 mm in aerobic rice systems. (Tuong et al., 2005) Since water regime management of AWD is classified between aerobic rice and continuous flooding, expected evaporative losses should lie within these ranges as well. However, these limitations were not serious constraints for the application of the WEAP model in both case studies since the overall results and trends were in accordance to literature and theoretical background.

7. Conclusion

The Water Evaluation and Planning System has been applied in two different case studies in central Luzon, Philippines to evaluate and upscale the impact of AWD, a water-saving technology in irrigated rice production under different objectives and climatic/environmental scenarios. WEAP proved to be a very flexible tool, as it can be applied by a broad range of end-user with different skills in application. Its complexity and the required input information can be defined and chosen by the end user. Moreover, the choice of different built-in tools and a clear structure, supports the application and implementation and makes the model very user friendly. Changes in water supply and consumption patterns can be easily implemented, as shown by AWD application. The results of two case studies showed that WEAP is suitable for assessing crop water requirements and implementing those into a large-scale water balance. In both agricultural and hydrological terms, WEAP fulfils the requirements to assess the potential impact of implementing water saving technologies such as AWD. The results show, that AWD reduces the overall irrigation requirement on field

level, but also influences up- and downstream water resources. AWD can contribute to water shortage mitigation, while at the same time reduce the methane emission, hence it's contribution to climate change.

However, further research is needed to improve and calibrate the irrigation schedule for rice under continuous flooded and AWD managed fields. One conceivable solution could be the linkage of WEAP to the rice crop model Oryza. To improve the impact assessment of AWD, especially on the hydrological cycle, more hydrological data are required. WEAP enables a link to MODFLOW, a groundwater-flow model. This linkage allows the implementation of capillary rise and gives the possibility to analyze groundwater flows and long-term effects of AWD on sub-surface water resources. Results from the simplified climate change scenarios indicate future water resource conflicts. However, a refined analysis with more accurate climate change models is required. Nevertheless, with increasing demand and competitive use the pressure on fresh water resources will increase in the future. Modelling future climate change impacts on water resources will gain in importance, since fresh water resources will get scarce and their fair and efficient use needs to be well planned.

This study provides a framework for large-scale implementations of AWD and indicate how water saving technologies change water availability on a catchment scale. WEAP enhances its possibility for water management by modeling flows in irrigation systems. It can be used in various spatial dimensions which are all linked together: On a field scale WEAP can assist in irrigation planning, on irrigation system scale WEAP can monitor flows and calculate water requirements and assist in establishing a water delivery schedule and upscaled on a catchment, water levels and streamflow can be monitored. By generating scenarios with different water availability water managers can develop appropriate adaptation strategies and support farmers in coping with water scarcity.

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