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Investigating environmental benefits and opportunities of rice cultivation under alternate wetting and drying irrigation in Bangladesh

(バングラデシュにおける湿潤・乾燥交互灌漑による稲作の環境効果と機会の検討)

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Abstract

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by Md Rahedul Islam

(モハマドゥラヘドゥルイスラム)

Oriza sativa known as rice paddy is widely cultivated in South Asia, especially in China, India, and Bangladesh. Bangladesh is the world 4th largest rice producer, consumer, and importer country. Due to the staple food and sources of major employment involvement, rice paddy agriculture sector plays a very crucial role in socio-economic and food security of the country. However, rice production and cultivation management have not been robustly managed and caused a range of significant negative impacts on environments. Especially the precious groundwater consumption and higher global warming potential (GWP) methane gas emission from irrigated rice paddy field leading as the most climate-vulnerable sector. To ensure food security and within a sustainable environmental condition is the great challenges for the country.

To solve the problem, alternate wetting and drying (AWD) irrigation techniques is a potential tool. The AWD system is already proven as climate-smart tools in term of precious water saving and greenhouse gas (GHG) methane emission reduction without production loss. Although several attempts have been taken to evaluate the socio-economic and environmental advantage of AWD irrigation application in Bangladesh. But the national level holistic approaches on advantages of AWD irrigation associated with suitable area determination is the potential research gap. Moreover, the remote sensing data derived modelling is another potential tool, but previous studies did not explore much more. The remote sensing-based model on seasonal rice and irrigated rice area, crop water requirement (CWR) for continuous flooded (CF) and AWD irrigated rice, AWD suitability assessment and methane emission estimation from rice paddy model can complement traditional site-specific models due to their unbeatable spatial and temporal coverage.

Although so far remote sensing dataset has been used to map seasonal rice area and irrigated rice area, yet there is no attempt integrating remote sensing data to model CWR for AWD and CF irrigated rice as well as AWD suitability analysis in Bangladesh. Therefore, the objective of this study was to evaluate the advantages of AWD irrigation system in terms of water-saving and methane emission reduction; and opportunities assessment trough the AWD irrigation suitability assessment using publicly available remote sensing data and platforms in Bangladesh. Leveraging spatial-temporal coverage of remote sensing data, this research was able to test this hypothesis that AWD irrigation has a great potential to reduce

water use and emission and Bangladesh have huge potential to expand AWD irrigation for sustainable rice production. This research fulfilled its objectives through a fourfold step using different space-borne remote sensing associated geospatial and statistical data. Designed steps were: 1) Map seasonal rice paddy distribution; 2) Evaluating the suitable rice area for AWD irrigation implementation in term of physical, physio-climatic and socio-economic suitability modelling, 3) Estimating the irrigated, supplementary irrigated and rainfed rice area, and CWR modelling to evaluate water saving from AWD irrigation; and 4) Estimating the methane emission from rice paddy and emission reduction assessment with AWD irrigated field using the information of steps 2, 3 and 4. The model output were compared with relevant studies and sources of data.

Rice cultivation is the dominant agricultural activities and 80% of arable land under on it. Accurate information on rice paddy is very important. The first steps of this dissertation were to map seasonal rice cropping pattern from 2001 to 2018 (Chapter 2). The consistent methodology of combining field data, ALOS-2 ScanSAR and MODIS NDVI dataset used to map rice area. Firstly, we use multidate ALOS-2 ScanSAR and GPS field data with unsupervised k-means ++ clustering for identifying seasonal rice area in 2018. Secondly, the ALOS-2 ScanSAR rice area map compared with GPS field data for validation and ALOS-2 ScanSAR map used for validating MODIS rice area map. Thirdly, ALOS-2 ScanSAR rice paddy information and MODIS Kalman's NDVI data uses for seasonal rice paddy area map in 2018 and extended it from 2001 to 2018. Finally, the rice area compared with the national statistical data and relevant studies over the country. The result shows that the boro rice area increases (30.44%), amon (4.65%) and aus (11.90%) rice area decrease from 2001 to 2018. The output result from this part used as input dataset for chapter 3, 4 and 5.

To adopt the AWD irrigation, it is very important to assess the suitability of AWD irrigation system in the country. To evaluate the opportunity of AWD irrigation system, this research is an attempt to determinate the AWD suitable rice area in the country (Chapter 3). The methodology adopted combines physical parameters-slope, soil texture, moisture, drainage, permeability, PH; climatic parameters- rainfall and temperature; and the socio-economic parameters- irrigation pump density, poverty, literacy rate, PPP/PEA ratio, and farm holding size that affect the AWD suitability. The remotes sensing data of AW30D for slope, terra climate for temperature, GSMaP, PPP, and poverty data from relevant sources. The dataset was pre-processed, interpolate, reclassify, rasterized and scored according to the importance of suitability. The multicollinearity and sensitivity analysis conducted among physical, physio-climatic, and socio-economic parameters. The three different types suitability asses in terms of (i) physically suitable, (ii) physio-climatic suitable and (iii) socio-economic suitable rice area. The result shows that the country is physically high suitable, physio-climatically suitable area varied among the season and boro season is highly suitable, amon season moderately suitable and aus season is very low suitable. Socio-economically, the country is moderately suitable based on our parameters. The suitability model output from this part will be used for CWR save and methane emission reduction scenario estimation.

The benefits of AWD irrigation is to save precious water use for rice cultivation. To assess the water saving from AWD irrigation, the CWR for CF and AWD irrigated rice is important. We used a remote sensing-based rice area map (Chapter 2), MOD16A2 ET dataset and FAO model with local climate adjusted Kc value to estimate the CWR for rice paddy.

Along with the local climate adjustment, the management practices accounted for water save used as AWD irrigation water save estimation. The annual water save from AWD irrigation result shows a range of 4 to 15.50% of water saved compared to CF irrigation. This study also investigated the rice paddy water source in term of irrigation. Along with the CWR, we estimated effective precipitation from GSMaP dataset. A simple model used for determined irrigated area based on the rice CWR and the sources of supply (effective precipitation). The sensitivity analysis conducted for determined the supplementary irrigated area and finally produced seasonal irrigated rice area map from 2001 to 2018 over Bangladesh. The result from this model compared with government national statistically reported irrigated rice area and relevant studies. The irrigated boro and amon rice area showed very good agreement with national statistics reported irrigated area, the R2 values are 0.87 and 0.55, respectively. The irrigated rice area map will be used as the methane emission estimation model (Chapter 5) input dataset.

Other more advantages of AWD irrigation is to reduce GHG emission especially methane emission from rice paddy field. In this study, we used remote sensing derived seasonal rice (Chapter 2), seasonal irrigated rice area map (chapter 4) and AWD suitable rice area map (Chapter 3) with country adjusted IPCC (IPCC, 2006) model for methane emission estimation from rice paddy field over Bangladesh from 2001 to 2018. We used irrigation regime accounted for seasonal scaling factor and rice straw incorporated organic amendment. The result shows that the irrigated boro rice is the highest methane emission season (218.4 kg CH4 ha-1) and rainfed amon rice is the lowest methane emission season (55 kg CH4 ha^{-1}). Annually, boro rice season is the highest methane emission season (1029.44 $GgCH_4$) followed by amon (780.91 $GgCH_4$) and aus (111.05 $GgCH_4$) rice-growing season in 2018. Based on the AWD irrigated management induced methane emission scaling factor for boro, aus and amon seasonal factors are 61.04, 57.50 and 54.76 kg/CH4/ha, respectively. By adopting AWD irrigation, rice paddy field could reduce methane emission up to 54%, compared with CF irrigation. The result also compared with relevant studies and found a very good agreement.

Finally, we compared the current AWD irrigation implementation status of Bangladesh with major rice-growing countries and found the lowest implementation rate. Furthermore, the study conducted Strength, Weakness, Opportunities and Threats (SWOT) analysis to evaluate the operational performance of AWD irrigation system. The advantages of AWD irrigation system are- reduce CWR from 5 to 15.50% which up to 35% in term of irrigation water save (Chapter 4) and methane emission reduction up to 54% (Chapter 5). The opportunities of AWD irrigation are- the country is physically high suitable, physio-climatically moderate to high suitable and socio-economically low to moderate to low suitable for AWD irrigation application (Chapter 2). Despite the advantages and opportunities of AWD irrigation, farmer level adoption rate is very low. There are several barriers to adopt AWD irrigation in field level. As the potential solution and recommendation, the country needs to reform policy and develop its socio-economic structure to increases the suitability. In conclusion, AWD irrigation system offered advantages for the country and its rice-growing area are suitable for adopting it, but the implementation status is limited. The outcome of this research could be very helpful for the policymakers, academicians, and farmers to adopt AWD irrigation system in wide-scale to mitigate the climate change impacts.

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It is my great pleasure to express my heartiest gratitude and appreciation to my advisor and thesis committee chairperson Prof. Wataru Takeuchi for guiding me through the doctoral degree program at The University of Tokyo. His enthusiasm, encouragement and support from the very beginning have fostered my passion for the research I am presenting here.

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List of Abbreviations

AWD	Alternate Wetting and Drying
CF	Continuous Flooded
CWR	Crop Water Requirement
CSA	Climate Smart Agriculture
ET	Evapotranspiration
ALOS-2	Advanced Land Observing Satellite-2
Ep	Effective Precipitation
Kc	Crop Coefficient
DSM	Digital Surface Model
FAO	Food and Agriculture Organization of the United Nation
BBS	Bangladesh Bureau of Statistics
GPS	Global Positing System
BRRI	Bangladesh Rice Research Institute
IRRI	International Rice Research Institute
GHGs	Green House Gases
MoEF	Ministry of Environment and Forestry, Bangladesh
DAE	Department of Agriculture Extension
GSMaP	Global Satellite Mapping of Precipitation
HH	Horizontal transmit and Horizontal receive
HV	Horizontal transmit and Vertical receive
PPP	Population Per Pixel
PEA	Primary Employment in Agriculture
BARC	Bangladesh Agriculture Research Council
RDA	Rural Development Academy
IWR	Irrigation Water Requirement
USDA	United State Department of Agriculture
INDC	Intended Nationally Determination Contributions
Mha	Million hectares
BCCSAP	Bangladesh Climate change Strategic Action Plan
MODIS	Moderate Resolution Imagining Spectroradiometer
UNFCCC	United Nation Framework Convention on Climate Change
NDVI	Normalized difference vegetation index
PALSAR	Phased Array L-band Synthetic Aperture Radar
R&D	Research and Development
RMSE	Root Mean Square Error
RoI	Region of Interest
RS	Remote Sensing
SAR	Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
Gg	Gigagram
MT	Million Tone

Chapter 1: Introduction

This chapter outlines the background information on rice paddy cultivated agriculture in Bangladesh (section 1.1). In follow the challenges for rice cultivation discussed in section 1.2. The probable solution for sustainable rice cultivation is discussed in section 1.3. Section 1.4 elaborates the necessity of this study followed objectives in section 1.5, originality, and novelty in section 1.6. The section 1.7 discussed the outline of the remaining chapter outline followed the brief description of the study area in section 1.8 in this thesis.

1.1 INTRODUCTION

1.1.1 Background

Rice is the staple food of almost half of the world's population (Kuenzer and Knauer, 2013) and source of 19% of the daily human energy supply (Elert, 2014). Globally, more than 12% of the total cropland used as rice paddy cultivation (*FAOSTAT*, 2018). More than 90% of total world rice produce in Asia. **Figure 1.1** shows the world top ten rice producing country and except Brazil, all of them are in Asia. Among the Asian countries, Bangladesh is the globally 4th largest rice producing country with 91st ranked by surface area. The country population will be 300 million in 2050 and need 35% more rice to extended population. Rice paddy also play an important role in other environmental issues like as; greenhouse gas emission (especially methane), climate change, fresh water uses and diseases transmission. To achieve the food security and clean environment for sustainable development goal (SDG), sustainable rice production is very important in future decade. Alternate wetting and drying (AWD) irrigation techniques for sustainable rice cultivation could be a potential tool for sustainable rice paddy production.

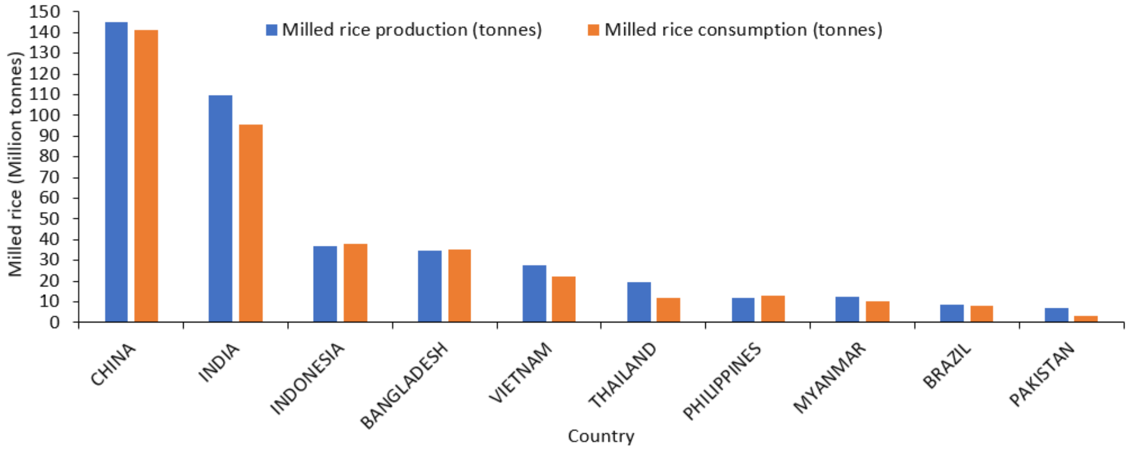


Figure 1.1 Globally top rice production's country and the annual consumption of those country (USDA, 2019).

1.1.1.1 Agriculture and rice production in Bangladesh

Historically, Bangladesh is an agrarian country. The country with 91942 sq. km agricultural land which almost 70.63% of total land area (*BBS*, 2018). The major cultivated crops are Rice paddy, Wheat, Jute, Potato, Sugarcane, various types of vegetables etc. Among the agricultural land almost 80% of land used for rice paddy cultivation. Rice paddy is the major crop and cultivated as single double or triple cropping pattern. Three different rice growing season in the country area - boro rice season (December/January to March/April), aus rice season (April/May to July/August) and amon rice season (July/August to November/December). The rice is cultivated all over of the country from the seasonal wetland to mountain area. Among the major crop practices, the rice area increasing over time, whereas the other crop cultivated area decreasing. The seasonal rice area fluctuated over the time especially the boro rice area increasing over the time whereas the amon and aus rice area decreasing. The golden fiber of Bangladesh Jute cultivated decreased up to 2010 and again start to increase. The Potato cultivated rice area slightly increased over time, but the wheat cultivated area decreased with the time. Among the major crops the rice area even the individual season rice area is comparatively very high than the others crop. In **figure 1.2** shows the major crops area of the country along with the arable land from 1990 to 2018. The arable land decreasing over the time but the net rice cultivated area increasing. Due to the high cropping intensity (190) and crop diversity the total cultivated crop land increased (Mainuddin and Kirby, 2015). The agriculture sector of the country almost depends on the rice paddy cultivation.

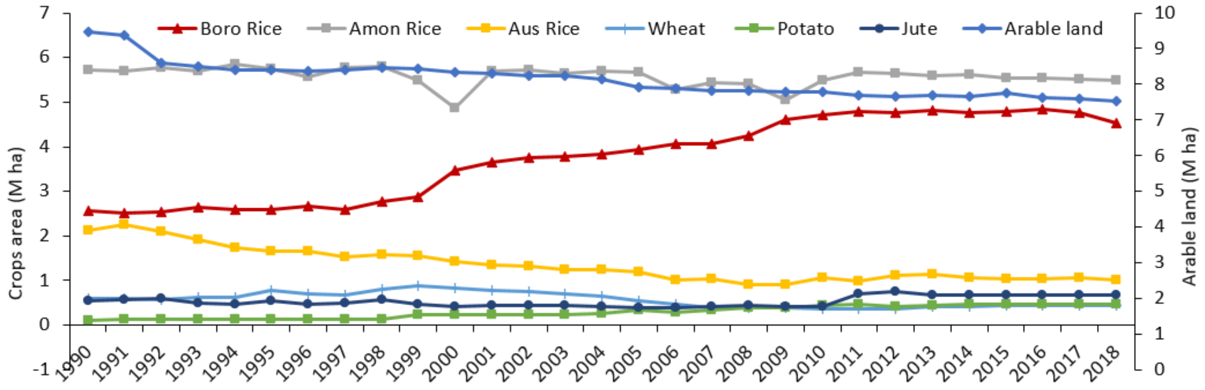


Figure 1.2 The total arable land, major crop including seasonal rice area (boro, aus and amon rice), Wheat, Potato, and Jute cultivated area over Bangladesh from 1990 to 2018(BBS, 2018).

1.1.1.2 Historical trend of rice production in Bangladesh

Rice is the most widely and intensively cultivated over the country. Until 1980s the rice production was labor intensive and depends on the nature, especially on rainfall. Due to the green revolution in 1980s the irrigation facilities installed, fertilizer and pesticide uses, and limited machineries application makes the drastic change in rice cultivation (Mainuddin and Kirby, 2015). Although the gross arable land losing every year, but the net rice cultivated area increasing over the time. In recent globalization trend the country also developed available irrigation facilities, introduces High yield varieties (HYV) of rice, organic and chemical fertilizer, pesticide application, bio-management, agriculture machineries for ploughing, plantation, harvesting etc. inputs induced the increase of rice production.

Although the net rice cultivated area did not increased too much but the rice production increased due to the per unit yield increased. In 1990 the total harvested rice area was 10.41 million hectares (M ha) and become 11.03 M ha in 2018. But the total milled rice production increased almost double from 1.78 million tons in 1990 to 34.70 m tons in 2018 (BBS, 2019). Due to the agricultural revolution and intensive agricultural inputs the rice per unit yield also increased from 1990 (2.57 tons/ha) to 2018 (4.42 tons/ha) (IRRI, 2018). In **figure 1.3** shows the annual harvested rice area, milled rice production and rice yield change over the country from 1990 to 2018. The country needs to produce more rice in future decade to ensure the food security.

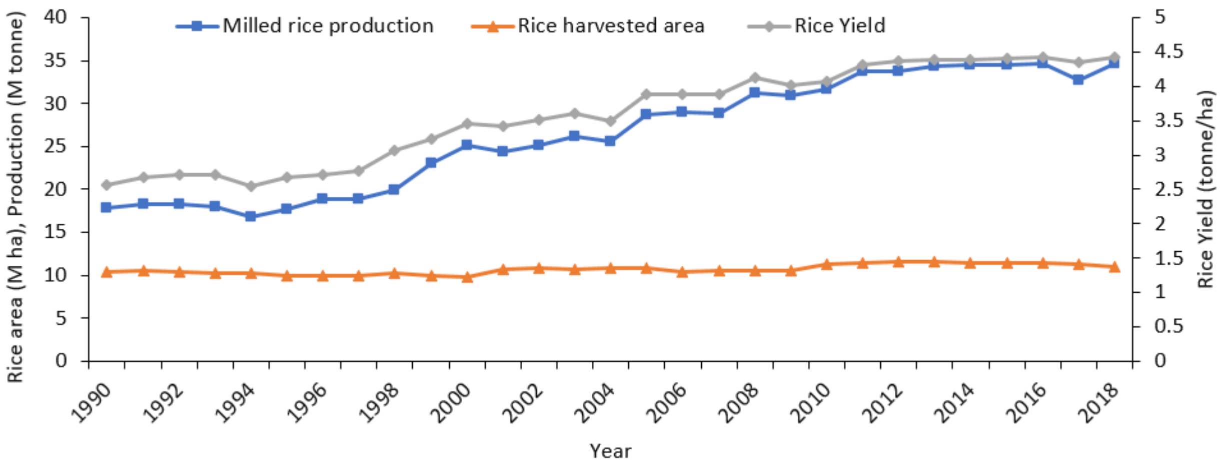


Figure 1.3 Harvested area of rice paddy, annual milled rice production and per unit yield from 1990 to 2018 in Bangladesh (IRRI, 2018).

1.1.1.3 *Socio-economic importance of rice*

Rice paddy is the most important socio-economic indicators of the country. Agriculture contributes 19.2% of total GDP and mostly depends on rice paddy cultivation. The 39.2% of total labor force and 61.2% of women labor force directly engaged in agriculture sector (FAOSTAT, 2019). Moreover, the rice cultivation, processing, and marketing related activities also creates a huge contribution to the national economics. The country's a people take annual average 171 kg in their daily three times meal (*FAOSTAT*, 2018). Moreover, rice is the source of 69.74% of calorie intake, 57.44% of protein intake, and 12.67% of fat intake in their daily dietary (*FAOSTAT*, 2015). In **figure 1.4** shows the annual per capita rice consumption, daily calorie intake, protein intake and fat intake from the rice. As a result, the market price of rice very important for the social and political stability. The government also very concern about the rice cultivation, production and marketing. The department of agriculture extension (DAE), Bangladesh agriculture research council (BARC), Bangladesh rice research institute (BRRI), Rural development academy (RDA), Bangladesh academy for rural development (BARD) are the responsible government institution for agriculture as well as rice related research, planning and implementation in the country. The government also both directly and indirectly invested huge financial and technical support for the farmer irrigation facilities, seed service, paste management, fuel, fertilizer, and agricultural machineries. In socio-economic perspective rice is the most important agricultural commodity in Bangladesh.

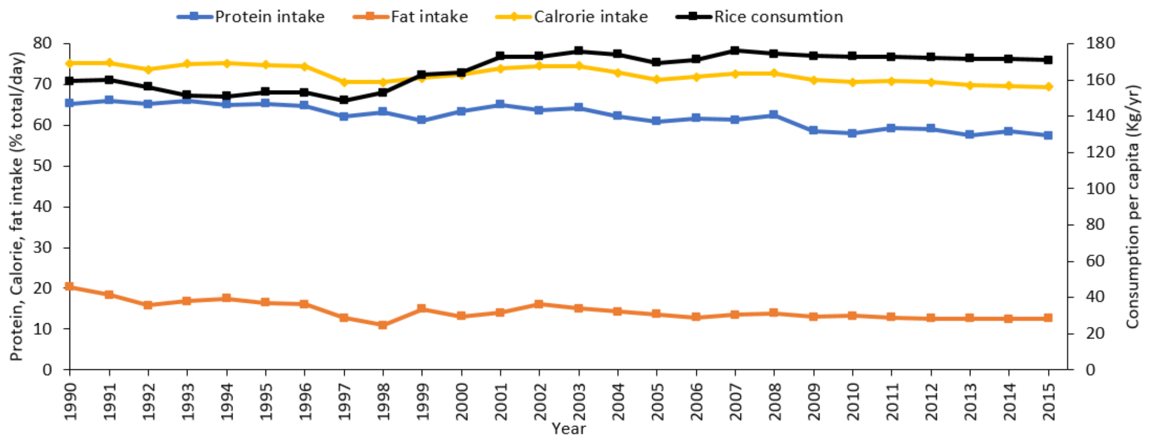


Figure 1.4 The annual per capita rice consumption, daily calorie intake, protein intake and fat intake from the rice in Bangladesh from 1990 to 2015. (source: FAOSAT).

1.2 CHALLENGES OF RICE PRODUCTION IN BANGLADESH

The country produces record 34.70 million tons milled rice in 2018 and cultivated maximum rice harvested area 11.41 million hectares in 2016 (BBS, 2019). Its seems country's rice cultivated area reaches to its saturated stage in 2016 (BBS, 2018c). As a result, the country needs to increase rice production with crop intensification and yield increase. Although due to the technological development (irrigation, high yield varieties, management) rice production increased drastically. But there is a huge comparative yield gap with China (6.94 ton/ha), Japan (6.69 ton/ha), Vietnam (5.91 ton/ha). The government trying to increase the per unit yield but still the country not self-sufficient to rice production and frequently import rice. Additionally, the country needs to produce 70% more food for extend 300 million people in 2050 (Mainuddin and Kirby, 2015). To increase rice production, the country intensively using the arable land, irrigation water, chemical fertilizer, and pesticide which induced several environmental problems. As a result, the rice production of the country facing several socio-economic and environmental challenges to produce rice paddy.

1.2.1 Arable land losses

Bangladesh experienced huge socioeconomic development from last decade. The per capita income (PPP) increased from 2670 USD in 2010 to 5453 USD in 2019 (MoF, 2019). During this time urbanization and industrialization trend with infrastructural development changed in an explosive way. The contribution of industrial sector increased from 24.35% in 2010 to 33.66% of GDP in 2019. The urbanization rate also changed drastically, 30.46% to 37.4% from 2010 to 2019 (MoF, 2019). The rapid urbanization and industrialization stimulated infrastructural development and engulfing the precious arable land over the country. Likewise, the rice paddy cultivated land converting to the aquaculture and orchard plantation due to the high profitable for the farmer. Although, some new land area especially from the river island (Charland), fallen land, forest burned land added to the arable land every year. Overall, the country losing 0.46% to 1% of total arable land every year (Hossain, Islam and Bari, 2013; Rai *et al.*, 2017). The agriculture land loss also impacts on the rice paddy area means to produce more rice within the less land in future decade.

1.2.2 Impacts on environment and climate change

Traditionally, rice is cultivated under fully flooded watered condition. The flooded rice cultivation is a major source of greenhouse gas emission especially the methane (CH_4) gas emission. The flooded anaerobic condition of rice paddy is one of the ideal conditions for the methanogenic. Agriculture sector is the leading greenhouse gas emission sector in Bangladesh, which contributes 39% of total emission followed by energy (33%), land use and forestry (17%), waste (10%) and industrial process (2%) (USAID, 2016). The rice paddy field is the leading sources of greenhouse gas emission within the subsectors- rice cultivation, enteric fermentation, synthetic fertilizer, crop residues and cultivation of organic soil (**figure 1.5**).

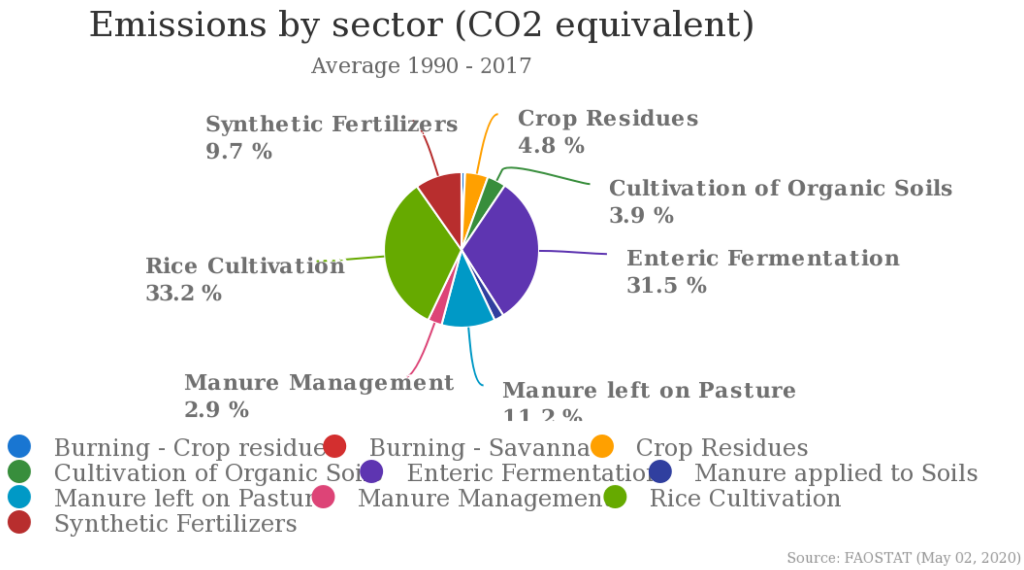


Figure 1.5 Greenhouse gas emission from rice paddy field in entire fermentation and sub-sectoral process in Bangladesh.

Among the greenhouse gas emission from agriculture, methane is the top emitted gas. Though methane is a short living greenhouse gas in atmosphere but it has 28-36 times global warming potential (GWP) than CO_2 within the 100 years lifetime.(US EPA, 2018). Along with the methane, nitrous oxide (N_2O) gas also emitted from rice paddy field which has 265-298 times GWP than CO2 within 100 years lifetime. Annually methane emission from rice paddy field increased from 1037 Gg in 1990 to 1138 Gg in 2017 (*FAOSTAT*, 2017). The country total methane emission was 57.2 $MtCO_2E$ in 2018, whereas the emission from agriculture and rice paddy was 33.5 $MtCO_2E$ and 23.53 $MtCO_2E$, respectively (figure 1.6). The methane emission increasing over the time which accelerating the climate change phenomena. Bangladesh is already a disaster risk vulnerable country in the world.

Moreover, the rice cultivation required 2000-3500 liter water to produced 1 kg of rice (Dong and Xiao, 2016). This water is use as a term of irrigation. In Bangladesh, the irrigated rice area expanding to boost the production. The 79% of irrigated water come s from groundwater and annually 35.1 km3 freshwater withdraw and 31.4 km3 used for irrigation water (FAO, 2014). Due to the over pumping of groundwater table declined 2-3 feet each year over the country (Mojid, Mohammad A. Parvez, F. Mohammad Mainuddin, Mohammad Hodgson, 2019). Some part of the country frequently suffers for ground water shortage especially during the summer season. At the end of 2025, 15 to 20 million hectares of irrigated rice will undergo extreme water scarcity (RAHMAN and PARVIN, 2009). Intergovernmental Panel on Climate Change (IPCC) predicts that the country will possibly decline rice production 8% by 2050 (Cancelliere *et al.*, 2007). Although the country groundwater reservoir is very rich, but the per capita internal freshwater resources declined sharply over the period 1990 to 2018 (**figure 1.6**).

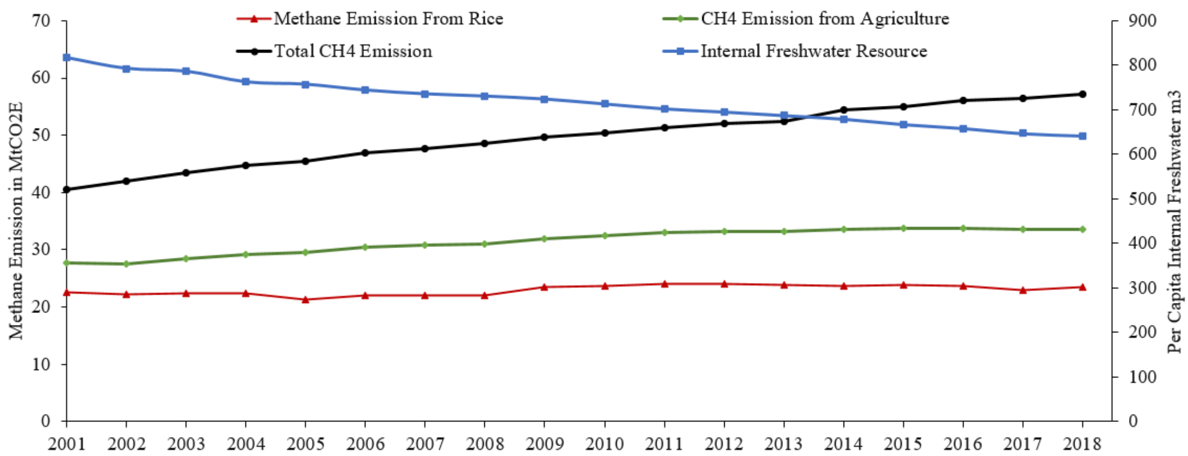


Figure 1.6 Environmental impacts of rice cultivation on perspective of methane emission; the country total methane emission, emission from agriculture and rice paddy field; per capita freshwater availability of Bangladesh from 2001 to 2018 (Sources: USDA, 2019 and FAOSTAT, 2018).

1.2.3 Intensive use of natural resources

Despite the importance of rice paddy in socio-economy of the country, its extension and intensification have not been vigorously handled and caused range of significant negative effects. There is huge demand of rice but limited land resources to produce more rice for meet up the rice demand. As a result, the farmer intensively cultivating the land to produce more rice. The cropping intensity increased and the land fertility decreasing day by day. Most of the case farmers are using more and more chemical fertilizer and very strong pesticide without any scientific measurement to get more production. The excess use of chemical fertilizer and pesticide polluting the land, water, and air. Moreover, it is very harmful for the farmers health as well as the consumer health. The biodiversity of the country also declined due to the harmful and unnecessary uses of pesticide and chemical fertilizer. Due to the arable land losing, the farmers are trying to develop new arable land and as a result the fallen land, dried-up river bed, forest area, and wet land are converting to agricultural land. These land use and land cover change leading biodiversity loss, greenhouse gas emission, and climate change in the country.

1.3 ENVIRONMENT FRIENDLY RICE PRODUCTION

It is a great dilemma for Bangladesh to produce more rice and devastating environmental impacts of rice production. The country is already a high climate risk vulnerable in the world. Environment friendly Climate smart agriculture (CSA) is a potential solution of this problem. Food and Agriculture Organization (FAO) first introduce the term CSA in Hague Conference on Food Security, Agriculture and Climate Change, 2010. CSA is and approach that helps to guide actions needed to transform and reoriented agricultural system to effectively support development and ensure food security in a changing climate(FAO, 2018). CSA is an integrative approach to address the interlinked challenges of food security and climate change, that explicitly aims for three objectives: (i) sustainably increasing agricultural productivity, to support equitable increases in farm incomes, food security and development, (ii) adapting and building resilience of agricultural and food security systems to climate change at multiple levels, and reducing greenhouse gas emissions from agriculture (including crops, livestock and fisheries) (CGIAR, 2018).

Alternate wetting and drying (AWD) irrigation system for rice paddy is a technique, which also proven as low emission and higher production. In this study, the AWD will investigates as a CSA approach.

1.3.1 Alternate Wetting and Drying (AWD) irrigation technique

International rice research institute (IRRI) introduced alternate wetting and drying (AWD) irrigation system is applying successfully for rice water use and methane emission reduction. Traditionally, paddy rice cultivated under fully flooded conditions throughout the entire growing period expect few days before harvesting. But it's don't need continuous flooded except rooting and flowering stage(van der Hoek *et al.*, 2001). In AWD irrigation system, whereby the rice paddy field allowed intermediately flood up 5 to 15 cm and to naturally declined water level below up to 15 cm of soil surface except the critical stages (**figure 1.7**). Normally, after 14 to 21st day of transplanting and 2 to 3 weeks before to the rice harvested time the AWD irrigation cycle repeated several times. The AWD cycle means the time between the watering to dry up and re-watering period. The length of AWD cycle and the number of AWD of AWD cycle depends on the rice cultivated regions, land and soil types, cultivation practices, weather condition and farmers attitude.

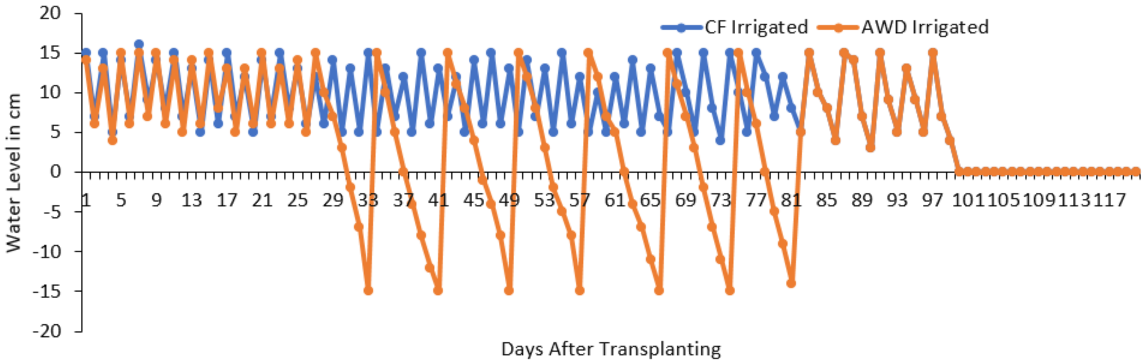


Figure 1.7 Conceptual Irrigation schedule of AWD and CF irrigation technique.

The amount of water apply for rice irrigation is not fully used for the crop growth. The rice paddy only could accept the amount of water loss through the evapotranspiration. The excess amount of water used for rice paddy field keep always flooded condition is loss through the drainage loss, leaching, percolation, and evaporation. As a result, the irrigation water supply based on the rice crop water requirement does not affect the crop growth or yield. Furthermore, due to the periodic irrigation in midseason for rice cultivation, the irrigation water use decreased significantly (**figure 1.8**).

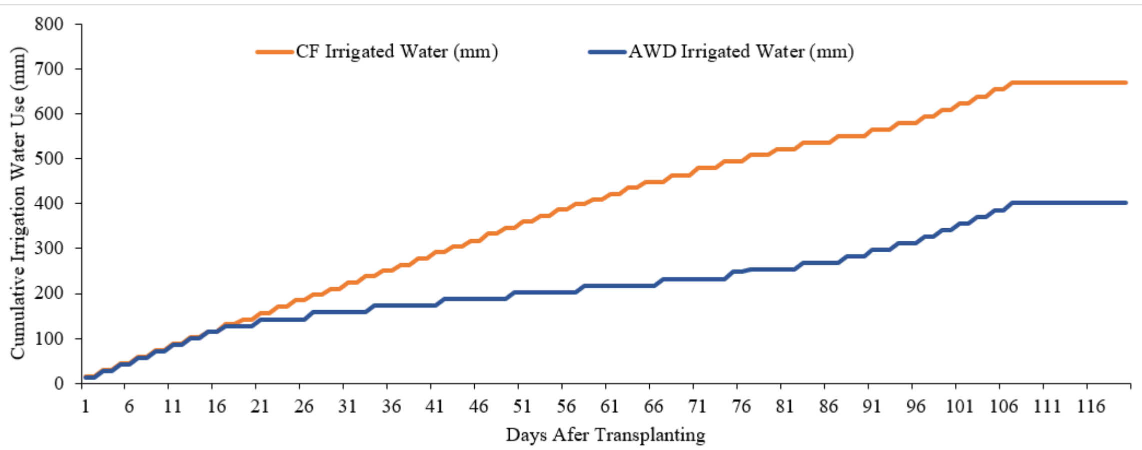


Figure 1.8 Conceptual framework of irrigation water use for AWD irrigated rice and the traditional CF irrigated rice.

1.3.2 Socio-economic benefit of AWD irrigation

The major cost of rice cultivation is irrigation cost (water fees and fuel used for pumping) in irrigated rice cultivation in Bangladesh (Alam *et al.*, 2010; Carrijo, Lundy, *et al.*, 2018). As AWD irrigation is a water saving technology and it is also reduced the irrigation cost. The AWD irrigation cost were $23-42$/ha less than the continuous flooded irrigated rice paddy(Alam *et al.*, 2010; Carrijo, Lundy, *et al.*, 2018). In Bangladesh, the AWD irrigation increased the farmers income up to 32% than the continuous flooded (CF) irrigated farmers (Lampayan, 2014) and decrease the production cost 4% (Carrijo, Lundy, *et al.*, 2018). Moreover, the AWD irrigated rice did not decreased the per unit yield. Some studies found that the AWD irrigation decreased water use without production lost (van der Hoek *et al.*, 2001). In CF irrigated rice yield 4.6-5.4 ton/ha and in AWD irrigated yield 5.1-6.2 ton/ha in Bangladesh and increased rice yield 10-15% compare with CF irrigated rice in Bangladesh (Basak, 2016a).

1.3.3 Environmental benefit of AWD irrigation

The environmental benefit of AWD irrigation in terms of water saving and low emission is the great advantage for climate change mitigation. The AWD irrigation technique save water is 20-40% in Bangladesh. Several studies found that the water savings from AWD to be 22–26%, representing 2,580–3,590 m3 of water saved per ha (Satar, M. A., Moniruzzam, M. Kashem, 2009; Kürschner *et al.*, 2010; Lampayan *et al.*, 2015). Ali et al. (2013) reported that conventional puddled rice caused emissions of 3.3 tCO2e/ha and that implementation of AWD reduced emissions to 2.5 tCO2e/ha. This is a reduction of 0.8 tCO2e/ha, a 24% decrease. However, the authors did not calculate the GHG emissions associated with diesel fuel used for pumping water. By using fuel savings results from other studies (A. S. A. Ferdous Alam, A. C. Er and

Halima Begum, 2015; Hasan *et al.*, 2016) it can be estimated that AWD may decrease emissions by 0.032–0.106 tCO_2e/ha via fuel savings alone. The overall AWD application benefit shows in **figure 1.9.**

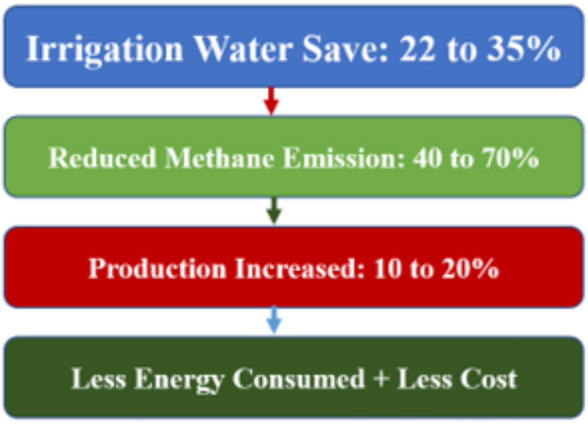


Figure 1.9 The environmental and socio-economic benefit of AWD irrigation technique compared to the CF irrigation technique.

1.3.4 Status of AWD irrigation in Bangladesh

AWD irrigation system was first introduced in Bangladesh in 2004 with the assist of International Rice Research Institute (IRRI). Initially, Bangladesh Rice Research Institute (BRRI) and Bangladesh Agriculture Research Council (BARC) applied AWD irrigation on their farm (Rahman and Sander, 2017). In 2008-09, the Department of Agriculture Extension (DAE) under ministry of agriculture (MoA) started a project on AWD irrigation. The AWD irrigation system started to implement in farmer level from 2012. Currently, BRRI, BARC, DAE, Rural Development Academy (RDA), Barrind Multipurpose Development Authority (BMDA), Rangpur Dinajpur Development Rural Service (RDRS) are working on accelerating the AWD implementation in field level. The government target to bring 20% of total rice area under AWD irrigation within 2025. But still now the AWD irrigation application rate in field level less than 8% of total rice area.

1.4 NECESSITY OF THE STUDY

The long time series rice area mapping is very important for crop water requirement assessment, food security, greenhouse gas estimation and sustainable rice paddy production for Bangladesh. To manage sustainable rice production, the proper information for rice paddy extension is very important. There are several studies on rice paddy mapping in Bangladesh with conventional and remote sensing application. The conventional rice area mapping depends on the direct field visit, farmer interviews and statistical analysis which missing the spatial information. The remote sensing application studies are based on different sensors and resolution data (Mosleh, Hassan and Chowdhury, 2015). The single sensors and the single year or shorter time series rice area mapping (Zhang *et al.*, no date; Gumma, 2011; Mosleh and Hassan, 2014a; Nguyen *et al.*, 2015; Shapla *et al.*, 2015) is very common approaches in remote sensing-based studies. Most of the studies conducted on a single year and season-based rice mapping but the long-term rice area mapping with seasonal extension is very important for rice CWR, Irrigation water management and methane emission assessment. In this study, is the first attempts to map seasonal rice area from 2001 to 2018 with multi-sensors remote sensing data. The output from the study (chapter 2) will be very helpful for the sustainable rice cultivation management for the upcoming decade.

AWD irrigation system is a proven tool to reduce water use and methane emission, but the technology does not adopt wide scale in the country. The practical feedback of a technology application depends on the widely and efficiently used of the technology. The AWD irrigation techniques introduced in Bangladesh from 2010 but still now the techniques not widely adopted in farmer level. Most of the previous study on AWD irrigation are socio-economics (van der Hoek *et al.*, 2001; Alam *et al.*, 2010) and environmental benefit (van der Hoek *et al.*, 2001; Oo *et al.*, 2018a; Runkle *et al.*, 2019). There is a huge gap between the AWD irrigation and advantages and AWD irrigation implementation way in the farmer level. The AWD irrigation implementation strategy development particularly the AWD suitability analysis of the rice paddy area in the country is very crucial. In this study the AWD suitability classes of rice paddy area on seasonal and regional perspective will be the first step to the academic research in Bangladesh (Chapter 3). The result from the AWD suitability analysis will be advantageous for suitable rice area and season selection for AWD irrigation application.

The rice crop water requirement assessment (CWR) is also very important for rice paddy irrigation water management and climate change mitigation. The most of the previous studies on the CWR assessment based on the FAO CROPWAT software, modelling and simulation based estimation of CWR (Gheewala *et al.*, 2014; Vasu *et al.*, 2018). The remote sensing based CWR requirement assessment is essential and efficient for rice paddy water management. Moreover, the CWR for AWD and non-AWD irrigated rice did not pay much attention in previous studies. In this study, the remote sensing based, and local climatic factors influenced CWR assessment for seasonal rice paddy in Bangladesh will be assessed which will be effective tools for long term irrigation water management and mitigate the water related environmental problems (chapter 4).

The irrigated rice area mapping another important part of this dissertation. The studies on irrigated and rainfed rice area mapping is mainly two types of studies found. The traditional way by using field data, national statistical source data, model based and representation with GIS or statistical techniques (Portmann, Siebert and Döll, 2010). The irrigated rice area mapping with remote sensing data derived depends on the existing Normalized Differentiate Vegetation condition (NDVI), soil moisture, land surface temperature parameters (Ambika, Wardlow and Mishra, 2016). The large scale and long-term irrigated area map with emphasis on the irrigation water supply sources very important for the sustainable water resource management. In this study used the crop water demand (CWR) and supply (Rainfall/irrigation) were investigated with remote sensing data and tools is very efficient for the irrigated rice paddy mapping. The information on irrigated, supplementary irrigated and rainfed rice area could be very helpful for seasonal rice-based irrigation management especially the green water application, methane emission assessment and mitigation of the environmental problem (chapter 4).

As a climate changes impacts vulnerable country, the policies are emphasis on climate change adaptation. There is a huge potential for the country to climate change mitigation within different sectors. The national climate change strategy is emphasis on the energy, transportation and industrial sector but did not pay attention on agricultural sector. Agriculture is the largest sources of greenhouse gas emission but there is less attention on mitigation. To mitigate climate change drivers from agriculture is very important for the country. The greenhouse gas emission from agriculture especially from the rice paddy cultivation is a potential sector for climate change mitigation in the country. The methane emission estimation with remote sensing (Jacob *et al.*, 2016; Peters, Bennartz and Hornberger, 2017; Arai *et al.*, 2018) and field data with model estimation(Of *et al.*, 2011; Khan and Saleh, 2015; Begum *et al.*, 2019) are the common trend of the previous study. There are some uncertainties of model based or satellite derived estimation without the emphasis of seasonal rice paddy as a source of emission. In this study (chapter 5), the IPCC model used for emission factors and scaling factors and satellite derived seasonal rice area map used for methane emission estimation over the country from 2001 to 2018.

Along with the environmental benefits and opportunity assessment of AWD irrigation, the performance analysis of AWD irrigation is important. The SWOT analysis of AWD irrigation system with comparative benefit assessment among the major rice growing countries also evaluate in this study (chapter 5). According to previous attempts, RS-based rice paddy cropping pattern with CWR, AWD suitability and methane emission assessment can provide subnational or field-level information (depending on sensors and spatial resolutions) which derived information ensures efficient and accountable policies as it enables policy makers to directly target specific objectives such as rice paddy cultivation with less water and low emission trajectory for the future decade.

1.5 OBJECTIVES OF THE STUDY

Therefore, taking the argument in section 1.4, with respect to the indispensable need for countrywide information on different components of climate smart rice paddy management, the objective of this study is to develop model and methodology to assess rice paddy distribution, CWR for AWD and non-AWD irrigated rice, irrigated rice paddy, AWD suitability and methane emission estimation leveraging publicly available RS data and platforms, considering the physio-climatic condition of environment and methane emission model for Bangladesh. Sub-objectives to fulfil this goal are:

1. Map rice paddy distribution from 2001 to 2018,
2. Evaluate the physio-climatic and socio-economic suitability of AWD irrigated rice area,
3. Estimate the crop water requirement for AWD and non-AWD irrigated rice,
4. Model water saving from AWD and non-AWD irrigated rice,
5. Map the irrigated, supplementary irrigated and rainfed rice area,
6. Methane emission estimation model for AWD and Non-AWD irrigated rice,
7. Evaluate the AWD irrigation status, constraint, and implementation strategies in Bangladesh.

1.6 ORGINALITY OF THE STUDY

1. Map time series of seasonal rice paddy extension in a consistent methodology combining ALOS-2 ScanSAR, MOD13A2 Kalman's filtered and MCD12Q1.
2. Countrywide potential socio-economic and physio climatic AWD suitable rice area map.
3. Entablements of CWR model for AWD and Non-AWD irrigated rice using local climate induced FAO CROPWAT model and MOD16A2 imageries.
4. Detecting irrigated, supplementary irrigated and rainfed rice area with GSMaP and MOD13A2 imageries.
5. Methane emission estimation with IPCC model and season and irrigation regime specific emission factors.

1.6.1 Novelty of the study

1. Irrigated, Supplementary irrigated and rainfed rice area mapping with climatic parameters,
2. CWR assessment for AWD and non-AWD irrigated rice with remote sensing data.
3. Socio-economic and physio-climatic suitability assessment of AWD irrigated rice, and
4. Evaluate the AWD irrigation status, constraint, and implementation strategies in Bangladesh.

1.7 THESIS OUTLINE

This thesis is divided into 6 chapters. Chapter 1 (current chapter) introduced rice paddy agriculture in Bangladesh followed by necessity, objectives, and originality of the research. The main body of the research is divided into four chapters (2-5). Each chapter covers backgrounds, literature review, the adopted methodology, results and discussion and conclusion. Chapter 2 covers part of research accessioned with mapping rice paddy distribution. Chapter 3 discusses the physio-climatic and socio-economic suitability of AWD irrigated rice. Chapter 4 describes detail about CWR for AWD and non-AWD irrigated rice and seasonal irrigated rice area mapping. Chapter 5 describes the methane emission estimation from the rice paddy. Finally, chapter 6 highlights the outcomes of this research, suggested implementations, limitation, and future works. **Figure 1.10** shows the general processing flow and order of chapters.

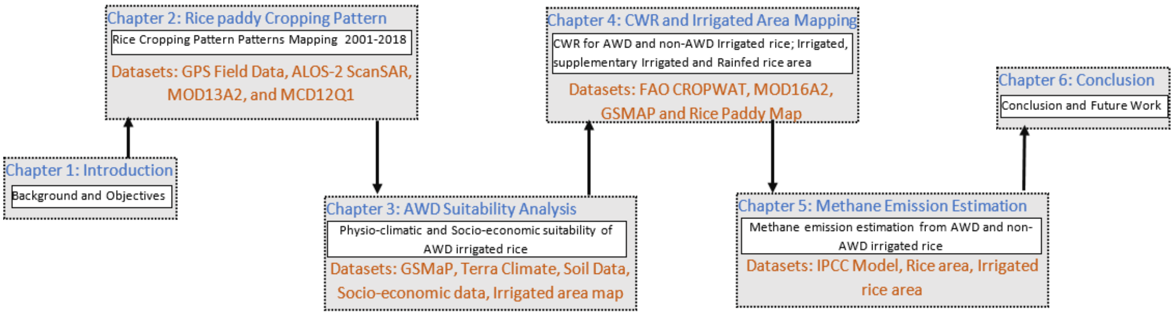


Figure 1.10 The overall flowchart of the chapter outline of this dissertation.

1.8 STUDY AREA

Bangladesh is one of the largest rice-growing countries in South Asia. It extends from 20º44´00″ to 26º37´51″ N latitude and from 88º00´14″ to 92º40´08″ E longitude and covered 148,450 km2 (**figure 1.11.a**). Physically the country is almost low altitude, relatively flat except the north-eastern and south-eastern hill tracts. Administratively, the country divided into major seven division: Dhaka, Rajshahi, Chittagong, Rangpur, Sylhet, Barisal, and Khulna. Climatically, average annual rainfall varies from 1,200 mm in the extreme west to over 4,000 mm in the northeast and temperature 4º C in January to 42º C in April (BMD, 2017). The country's mean annual lake evaporation is approximately 1040 mm, which is about 45% of the mean annual rainfall (Kirby *et al.*, 2014). The lowest average monthly precipitation is 4 mm in December to the highest 560 mm in July 2017. The minimum monthly average temperature is 11º in January and maximum in April 35º in the same year (BMD, 2017). There is a huge seasonal variation of the weather parameters especially the temperature and rainfall (**figure 1.11.b**). Based on the crop calendar of Bangladesh, there are three major rice-growing seasons in the country (Kirby *et al.*, 2014). The boro rice season (December/January to March/April) is the second largest by cultivated area and largest by production accounts for 50% (4.84 million hectares) of total rice production of the country. It is cultivated in dry winter and summer times with full irrigation and high fertilizer inputs. Aus rice (April/May to July) season is the smallest cultivated area, accounts for 9% (1.04 million hectares) of total production. The Aus is cultivated under almost rainfed condition but a great uncertainty due to the flood. Amon rice (July/August to November) is the largest (5.53 million hectares) rice-growing season by area and second largest by production, accounts for 41% of total rice production (BBS, 2018b). This rice season is a very critical growing period due to the flood in the early growing stage and frequent drought in the later growth stage. The detailed rice crop calendar showed in **figure 1.11.c**. The rice production in the country is seriously affected by climate change impacts.

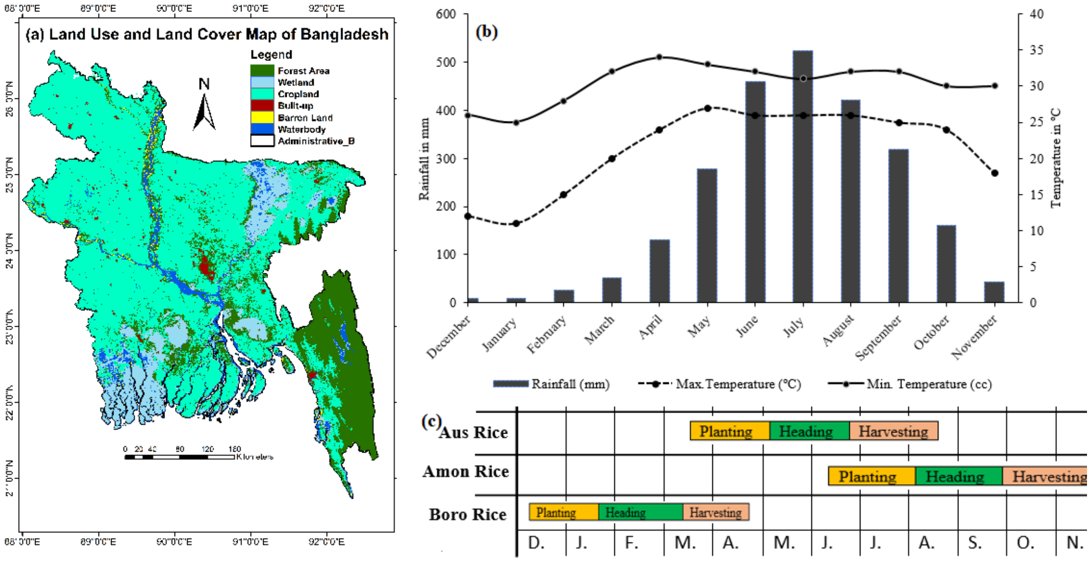


Figure 1.11 (a) Geographical location and generalized land use and land cover (LULC) map of the study area from MCD12Q1, (b) Monthly average minimum and maximum temperature, and rainfall over Bangladesh (BMD (Bangladesh Meterological Department), 2017), (c) Rice paddy crop calendar in the study area.

Chapter 2: Mapping rice paddy cropping pattern

2.1 CHAPTER OVERVIEW

In this chapter we first briefly discuss the background of the study, review previous attempts in mapping rice paddy distribution using different optical and SAR data in section 2.2. Then we describe the adopted methodology in detailed in section 2.3. In section 2.4 results and 2.5 is discussion followed by conclusion in 2.6.

2.2 INTRODUCTION

2.2.1 Background of the study

Rice is the staple food more than half of the global people and sources of 40% of total calorie intake (Mosleh, Hassan and Chowdhury, 2015). About 90% of total global rice production cultivated in Asia. Bangladesh is the 4th largest rice producer and top rice consumer (annual 172 kg per capita) country in the world (FAOSTAT, 2019). Agriculture contributes 19.2% of country's total GDP and 40% of the labour force engaged in this sector (BBS, 2018c). The 75% of the total arable land of the country used for rice cultivation and produce 56.8 million ton rice in 2018(BBS, 2018c). Due to the technological development (irrigation, high yield varieties, management) rice production increased drastically. But the country is still not self-sufficient to rice production and frequently import rice (4th importer)(RAHMAN and PARVIN, 2009). The country needs to produce 70% more food for extend 300 million people in 2050 (Government et al., 2018). To increase rice production, the country intensively using the arable land, irrigation water, chemical fertilizer, and pesticide. But, the rice production of the country facing several challenges likes; high demand of rice for drastic population growth (Mosleh and Hassan, 2014b) the arable land losses (Rai et al., 2017), climate change impacts(Kumar et al., 2017), water scarcity (Hasan et al., 2018), arsenic contamination (Carrijo, Akbar, et al., 2018) and disses transmissions (Gilbert et al., 2008), salinity intrusion in coastal area. At the end of 2025, 15 to 20 million hectares of irrigated rice will suffer extreme water scarcity (RAHMAN and PARVIN, 2009). Intergovernmental Panel on Climate Change (IPCC) predict that the country will possibly decline rice production 8% by 2050 (Cancelliere et al., 2007). To ensure the food security, the country needs to adapt policy for sustainable rice management. As a result, proper information on rice paddy especially the spatial distribution, seasonal extended, long term dynamic are very important for the country.

2.2.2 Objectives

The main objective of this study is rice paddy mapping with ALOS-2 ScanSAR and MODIS dataset over Bangladesh from 2001 to 2018. The dynamic changes of rice paddy cropping pattern, intensity, and area very important for the country. The long time series observation of rice paddy dynamics is also investigated in this study. The details objectives of this study have been set as follows.

01. To produce seasonal rice area map with ALOS-2 ScanSAR images and GPS field data over selected tiles in 2018,

02. To delineate the seasonal rice area with ALOS-2 and MO13A2 data from 2001 to 2018, and

03. To evaluate the result with field data, relevant studies, and national statistical data.

2.2.3 Literature Review

The conventional ways of rice mapping are field visit, farmer interviews, household survey, and expert opinion to collect data and represent with Geographic Information System (GIS) and statistical application at national or sub-national level. Although, it's provides historical trends of rice area but unable to provide the exact location of the rice paddy field. Moreover, the traditional method is time consuming, inconsistence and laborious. There is discrepancy between conventional rice area statistics and actual rice production and frequently unstable the country's rice market. As a result, sometimes country shows the enough rice production but at the end need to import rice. Accurate and timely spatio-temporal information on rice paddy field could overcome the problem. The remote sensing application is one of the most appropriate solution for rice area mapping.

Remote sensing application for rice area monitoring and mapping is already proven as an efficient and dependable tool for precise and timely information on rice phenology and vegetation development (Mosleh, Hassan and Chowdhury, 2015). The remote sensing-based rice mapping studies are mainly used optical sensor and Synthetic Aperture Radar (SAR) sensor data. The optical single sensor-based Landsat, AVHRR and MODIS data derived indices are the most common at global and regional scale (Abatzoglou, J.T., S.Z. Dobrowski, S.A. Parks, 2018). The mix pixel classification is one of the disadvantages for single sensor application. Multi temporal and high-resolution sensor data have been used to overcome such problem (Long et al., 2013).

Zhang et al., (2018) applied the multi-temporal Landsat 8 Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) data with Convolution Neural Network (CNN) algorithm used for mapping rice area in Dongting lake area, China. The MODIS and Landsat data blended by spatio-temporal adaptive reflectance fusion model (STARFM) to produced multitemporal Landsat like data and combinedly with LST, a simple patched-based deep learning CNN algorithm to extract the rice area. The result shows that the overall accuracy 97.06^ with kappa value .091 where 6.43% and 0.07 higher than the support vector machine model; and 7.68% and 0.09 higher that than the random forest model, respectively. Finally, they correlate their result with national statistical data and found strong correlation ($R^2 = 0.9945$). Similarly, the Landsat TM and OLI data from 1993 to 2016 with NDVI and Modified Normalized Difference Water Index (MNDWI) and masking method have been used for rice area mapping in Southern China region(Liao et al., 2018).

In another study Gumma et al., (2014) used the moderate resolution imaging spectrometer (MODIS) derived Normalized Difference Vegetation Index (NDVI) maximum value composite (MVC) data with 500 m spatial resolution and the intensive field plot data in Bangladesh, 2010. The multi-temporal spectral signature of rice phenology in pixel level matched with the field plot data to identified seasonal rice area. The result also compared with the national statistical sources data and found overall 90% accuracy, and in major district level also showed very strong agreement (R^2 value) 96%, 93% and 06% at boro, aus and amon rice season. Although, the global coverage, high temporal resolution and long-time series are advantages of using optical data for rice mapping. But the main challenge of the optical remote sensing data are cloud contamination and coarse spatial resolution especially for cloud prone country like as Bangladesh.

Synthetic Aperture Radar (SAR) data have been used to complement the cloud problems of optical sensor images because SAR data are not influenced by weather conditions (Zhu et al., 2012). Several studies used L-band SAR data for seasonal rice are mapping at national and subnational scale(Wang et al., 2009). The advantage of SAR data is its ability to penetrate canopies and sensitive to vegetation structure, water content in any weather condition. Zhang et al., (2009) investigated the synthetic aperture radar (SAR) ALOS/PALSAR data derived multidate variation of horizontal-horizontal polarization (HH) data with support vector machine (SVM) classifier have been used in rice and other land types distinguish in Zheijiang province in South East China. The three different stages of rice growing (transplanting, tillering and heading) data used and the result found the conditional kappa value 0.87 and, the producer's and user's accuracy 0.90 and 0.76, respectively.

In another study by Singha et al., (2019) of the operational near real time rice area mapping with Sentinel-1 data on google earth engine (GEE) platforms with random forest classifier in Bangladesh and India, 2017. The study used the 6 days temporal resolution and 10 m spatial resolution backscattered coefficient (HH and HV) time series data of Sentinel-1 to investigate the dB reflectance characteristics in different rice growing stage. The global georeferenced field photo data have been used for model training and testing, the result found 90% overall accuracy of rice classification in Bangladesh and Northeast India. High spatial resolution, less weather affects, and polarized data are the advantages of SAR sensors remote sensing. But, the wide area coverage, short time series, available data are the limitation for SAR dataset.

Combinedly, the optical and SAR sensors data used for rice paddy mapping is one of the most common research trends to better estimate the rice paddy. Torbick et al., (2011) used Phased Array L-band Synthetic Aperture Radar (PALSAR) fine beam single/dual beam (FBS/D) measurements with decision tree classifier for flooded paddy rice detection, integrated multitemporal wide beam 1 (WB1) ScanSAR backscattered coefficient (HH) for rice paddy flooded condition detection in Sacramento Valley, USA. Moreover, the PALSAR based rice paddy hydroperiod validated with the high temporal resolution MODIS derived enhanced vegetation index (EVI) and land surface water index (LSWI) used for paddy rice hydroperiod. The result shows that the PALSAR and MODIS hydroperiod very strong overall accuracy (95%) and in four different date agreement varied from 85% to 94% in the study area.

Guan et al., (2018) studied the multiple sensors; MODIS, Landsat and PALSAR-2 dataset for the rice paddy mapping and yield estimation in Thai Binh Providence, Vietnam in summer rice growing season in 2015. The study used the surface reflectance and vegetation indices (VI) by fusing the optical observations from the Landsat sensors and the Moderate Resolution Imaging Spectroradiometer (MODIS); and second, the L-band radar data from the PALSAR-2 sensor onboard the Advanced Land Observing Satellite 2. The result found that fusion datasets reduce observational gaps and allow us to better identify peak VI values and derive their empirical relationships with crop-cutting yield data (R2 = 0.4 for all the rice types, and R2 = 0.69 for the dominant rice type −58% of all the sampled fields.

Several studies found that the SAR backscattered amplitudes is very sensitive to the flooded rice even vegetative stage (Wang et al., 2009). This study takes advantage of both optical sensors long time series and L-band SAR radiometric sensitivity to rice bio geophysical properties. In Bangladesh, along with seasonal cloud contamination, the high cropping intensity, crop diversity and land fragmentation are the challenges to map rice area. Due to the favourable environment for rice cultivation through the year, fertile land and high market demand of rice, rice cultivated three times in a year as single, double and triple crops. The three main rice growing season in Bangladesh are December/January to April (Boro Season), April/May to June/July (Aus Season) and July/August to November/December (Amon Season). Moreover, the small farm size, high cropping intensity and frequently changes the rice cultivated field.

It is a dilemma between optical and SAR sensor-based rice mapping. Although, the optical remote sensing has long time series with high temporal resolution but the coarse spatial resolution and cloud contamination. On the other hand's SAR sensor has high spatial resolution and less cloud affects but short time series and data availability. Combinedly, SAR and optical sensor application for rice area mapping is potential solution. Multisensory; Landsat, MODIS and PALSAR data derived Vegetation Indices have been used for rice mapping in Thailand(Guan *et al.*, 2018). MODIS NDVI and AMSR-E Land Surface Water Coverage (LSWC) with Fast Fourier Transformation (FFT) techniques have been used for rice crop pattern and intensity recognition in global scale (Jonai and Takeuchi, 2012). As a result, to leverage the such spatial features continuous time series of remote sensing images covering same region is very important. In this study, we used Geographical Positioning System (GPS) field data, high spatial resolution Phased Array-type L-band SAR (PALSAR-2) sensor onboard the Advanced Land Observing Satellite (ALOS-2) data and MOD13A2 with Kalman's filtered data from 2001-2018 used to overcome the rice mapping challenges over Bangladesh.

2.3 METHODOLOGY

Regarding what was discussed in section 2.2, we aimed to combining optical and SAR RS data to map oil palm distribution. To find the best combination we tested the accuracy of map generated with two combinations of Landsat and MODIS with PALSAR/PALSAR2 yearly mosaic. In following sections, we describe detailed adopted methodology in each approach. This study consists of (1) field data collection; (2) ALOS-2/PALSAR-2 data processing and seasonal rice paddy detection; and (3) ALOS-2 ScanSAR data and MODIS data used rice mapping. The overall flowchart of this study is illustrated in **figure 2.1**.

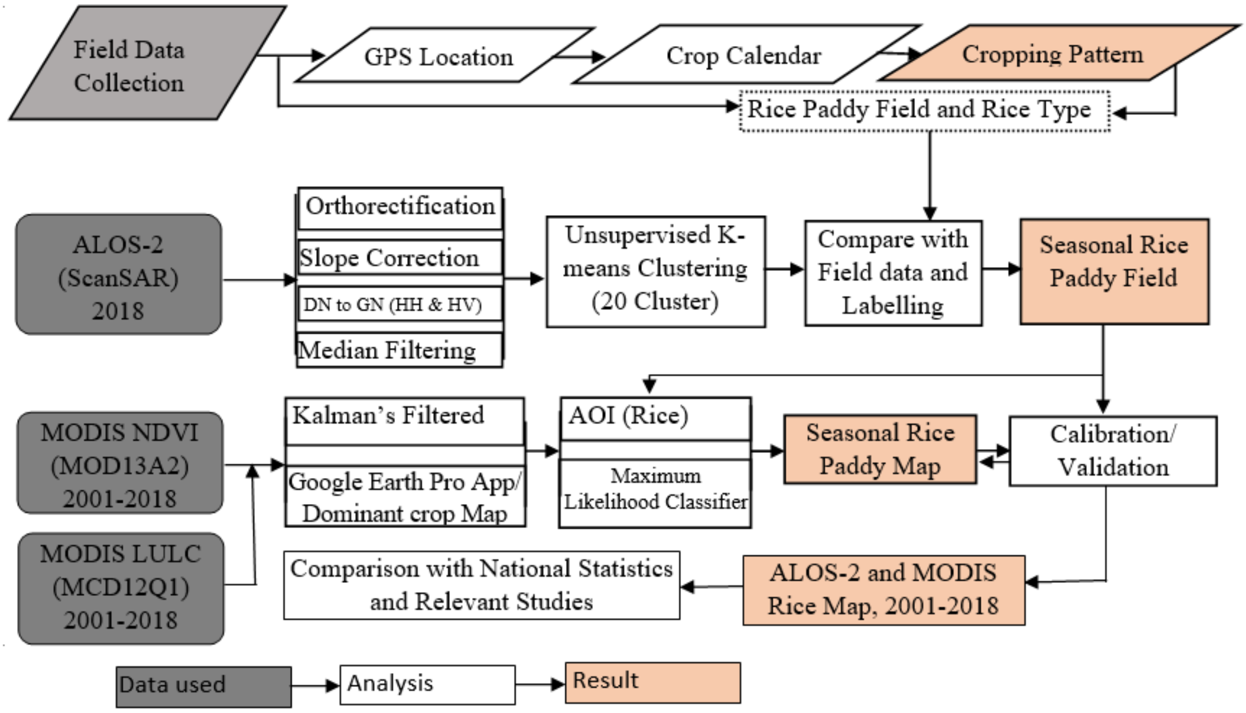


Figure 2.1 Overview of the rice paddy mapping framework. Geographical position system (GPS) location of rice paddy field with its cropping pattern, multi-dated PALSAR-2 HH and HV backscattering coefficient value with k-means clustering and rice area mapping with MCD12Q1 masked MOD13A2 Kalman's filtered NDVI data used maximum likelihood classification techniques over Bangladesh from 2001 to 2018. The flowchart illustrated the data, analysis, and result of this study.

2.3.1 Dataset Used

2.3.1.1 Field data collection

The Global Positioning System (GPS) location of sample field plots was collected from 267 locations during October to December 2018. The field data were collected by local agricultural officers, journalist, and local expert through social media (Facebook messenger, IMO, What's app, Viber) on request volunteer basis. The response person visited the field and gathered the GPS location with mobile GPS tracker, cropping pattern and crops season (Boro-Aus-Amon) information from the farmer's. Three basic questions provided to the volunteer, (i) What is the GPS location of the paddy field? (ii) How many times the rice paddy cultivated on this field in 2018? (iii) What are the plantated and harvested dates (tentative) of the cultivated rice paddy in 2018? We tried to select the large size field (> 3 hectares) for the better spatial resolution representation. They collected 48 GPS point on boro rice, 35 on amon rice, 32 on aus rice paddy field. The 71 points on the field where boro and amon rice cultivated as double rice crops, 21 points on the field where rice cultivated in boro and aus rice season, 25 on fields where aus and amon rice cultivated and 35 points on fields where boro rice, aus rice and amon rice cultivated as triple rice crops. The number of collected sample filed-plot data varied due to boro-amon rice cropping pattern is the most common cropping system and aus-amon, boro-aus rice cropping pattern is not so familiar rice cropping pattern in Bangladesh. The GPS field plot location with rice cropping pattern was used for seasonal rice paddy delineation with ALOS-2 ScanSAR data. The collected field data details shown in appendix-A.

2.3.1.2 ALOS-2 ScanSAR dataset

The ALOS-2/(PALSAR-2) was launched in 2014 and it's equipped with enhanced phased array L-band Synthetic Aperture Radar-2 sensor (PALSAR-2). The ALOS-2 ScanSAR used in this study were tiled ortho-slope corrected ALOS-2 Scan SAR data as an analysis ready data (ARD) provided by Japan Aerospace Exploration Agency (JAXA) and Japan International Cooperation Agency (JICA) in JICA-JAXA Forest Early Warning System in the Tropics (JJ-FAST). The dataset on selected tiles and date used for this study. In this study uses nine images of the ALOS-2 ScanSAR mode backscatter coefficient product of both HV and HH polarization (18 scenes) data at 50-m grid size. The L-bands ALOS-2 ScanSAR HH and HV backscattering value are very sensitive to the surface inundation condition even in vegetated stage(Arai *et al.*, 2018). The L-band backscattering characteristics are very helpful to detect rice paddy field (figure 3.d). The ALOS-2 ScanSAR revisit time is 14 days and this study covering the image on the following months January, February, March, May, June, July, September, October and November in 2018. Although, the dataset missing April, August and December month's image but based on the crop calendar, these months are harvesting season for boro, aus and amon rice, respectively. As a result, the missing dataset not affected this analysis. We used 7 tiles on the study area and rename the tiles as the major administrative coverage area. The used tiles are N26E090_RSP045 (Sherpur), N26E088_RSP046 (Dinajpur), N25E090_RSP045 (Mymensingh), N25E089_RSP045 (Rangpur), N24E090_RSP045 (Dhaka), N24E089_RSP045 (Rajbari) and N23E089_RSP045 (Satkhira). The geographical area coverage of the tiles along with the GPS field-plot location shown **figure-2.2**.

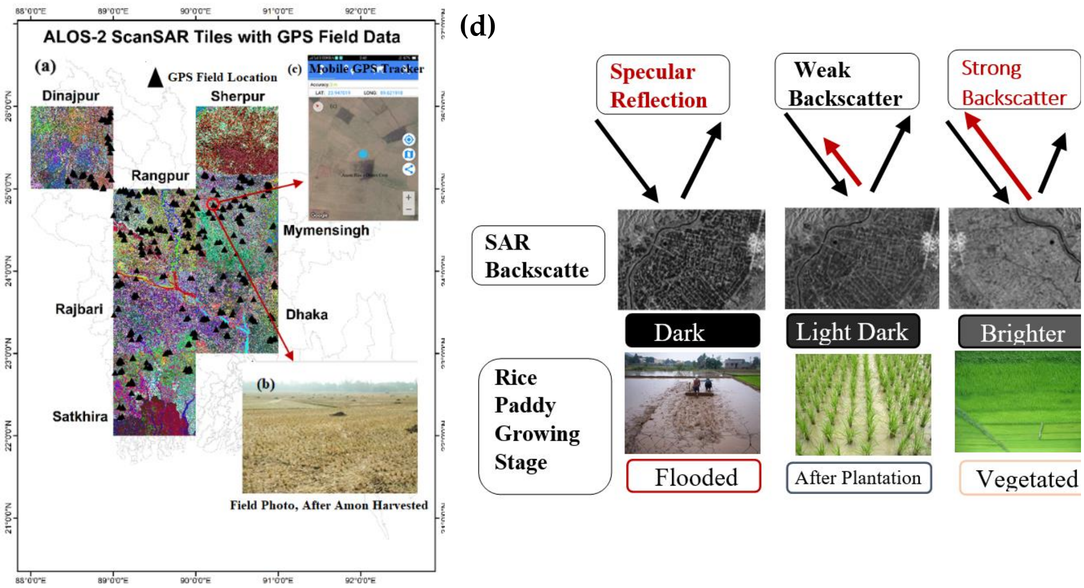


Figure 2.2 (a) Selected ALOS-2 ScanSAR tiles on the study area with the administrative coverage, (b) Field photo of a selected field after Amon rice harvested and preparing for the Boro rice plantation, (c) Mobile GPS tracker location of the field; (d) ALOS-2 ScanSAR backscattered characteristics in different rice growing stages.

2.3.1.3 MODIS dataset

Moderate-resolution imaging spectroradiometer (MODIS) imagery was downloaded from the Land Processes Distributed Active Archive Centre (LP DAAC) (https://lpdaac.usgs.gov/lpdaac/get_data/data_pool). The MOD13A2, which is referred to as the continuity index to the existing National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer (NOAA-AVHRR) derived NDVI (Didan, 2015). MOD13A2 version 6 products are derived by compositing two MOD09A1 8-day surface reflectance data in 16 days periods. The dataset already used atmospheric correction and cloud screening. Annual 23 scene and altogether 411 scenes for 18 years composite uses for analysis. We used MOD13A2 NDVI data with 1km spatial resolution and 16 days temporal resolution over the study area from 2001 to 2018. The MCD12Q1 LULC dataset provides a suite of science data sets (SDSs) at an annual time step for six different land cover legends (Friedl, MFriedl, M., Sulla-Menashe, D. ., Sulla-Menashe, 2019). This study used MCD12Q1 500-m spatial resolution data from 2001 to 2018 supplementary dataset.

2.3.1.4 National rice area statistics and other data

Bangladesh Bureau of Statistics (BBS) is a government organization under the Ministry of Planning (MoP) and responsible for data collection, analysis and published. The national and major administrative boundary level rice area statistics were obtained from BBS. The BBS collected data from the field level by household survey and reports the annual rice area and estimated the production. This study uses the annual statistical report from 2001 to 2018 on rice cultivated area in Bangladesh. The dominant crop calendar map produced by the Bangladesh Agriculture Research Council (BARC, 1998) and Very High Resolution (VHR) images visualization of Google earth pro app (Google earth V 7.3., 2010) used to extract the seasonal rice area. Moreover, the remote sensing based relevant studies result also use for comparing the result of this study.

2.3.2 Rice cropping pattern mapping with ALOS-2 ScanSAR and field data 2018

The rice crop cultivation is a unique physical environment which distinguishable from other crops. Before plantation, the cultivated land plough with water and makes muddy and flooded for a few days. This flooding period for one week or more, ALOS-2 backscattered shows a specular reflection, after plantation and growing stage showed weak backscattered. In the well growing vegetated period, the strong backscatter appears in the rice paddy field. After harvesting, the fallow straw field also demonstrates distinguish backscatter value. The multi-dated ALOS-2 ScanSAR dual- polarized (HH and HV) images use for the rice paddy identification. In image pre-processing, orthorectified and slope corrected by Sigma SAR (Shimada, 2010). The digital number (DN) value of the images converted into backscattered coefficient (Gamma-nought). The median filtering (3×3 window) applied for HH and HV gamma naught. The unsupervised classification (K-means++) run with 20 categories and 100 iterations for image clustering. The rice paddy growing condition is the difference from other crop condition. The flooded condition of rice paddy field shows the homogenic backscattering signal and almost similar cluster classes into a K-means class. We trial different K-means number classes and found 20 cluster classes are the satisfactory result. By using the GPS field information of rice paddy field, the K-means classes are compared with the field data. Initially, we distinguish the rice and non-rice class. Within the rice class, the K-means cluster value extracts for confusion matrix. With the confusion matrix, we select which K-means classes are matches with the field cropping pattern (boro, aus, and amon and others pattern of rice). Then, we labelled the K-means class according to the seasonal rice cropping pattern. Finally, we prepared the boro, aus and amon season rice map over the selected ALOS-2 ScanSAR tiles. This rice paddy map further used for MODIS based rice area mapping. We compared our result with field data and national statistical data.

2.3.3 Rice paddy mapping with ALOS-2 ScanSAR and MODIS data from 2001 to 2018

In Bangladesh, the most challenging to use optical data is seasonal uncertainty especially cloud contamination, missing values and atmospheric noise. The cloud contamination is a severe problem especially during the aus rice-growing season (June to August). To overcome the problem, we used local maximizing fit Kalman filter (KF), is a recursive extrapolation algorithm that integrates observations and their respective uncertainties to estimate the state of a process minimizing the mean of the squared errors [37]. The maximum and minimum NDVI values used for Kalman's filtering and smoothing. The Kalman filters make the NDVI time series smooth and continuous time series of NDVI values from 2001 to 2018. The 16 days Kalman's filtered MOD13A2 NDVI dataset composed as annual image.

The MCD12Q1 land use and land cover (LULC) data resampled and reclassified as the agricultural and non-agricultural land class. The agricultural land area masked out from annual MOD_NDVI annual data to reduce the data volume and prepared annual agricultural land MOD_NDVI data layer from 2001 to 2018. The NDVI temporal signature of annual Kalman filtered NDVI values shows various patterns. We used the annual rice crop calendar of Bangladesh fixed out the rice planting, development, and harvested period. At the land preparation and plantation season, the NDVI spectra for rice paddy is very low. During the growing and development stage, the NDVI value increased and reached to the peak. After the peak, the temporal value decreased at harvesting season. The entire growing period rice spectra demonstrated as a fold. In double and triple rice case, it is illustrated double and triple fold, respectively. Based on these NDVI temporal signature similarity characteristics (Gumma *et al.*, 2014; Mosleh and Hassan, 2014b), the annual Kalman's filtered MODIS data used for the rice spectral signature extraction.

Based on the distinguish rice phenology development temporal extend, we selected various location for rice paddy temporal signature extraction. In this stage, ALOS-2 ScanSAR based seasonal rice area map of 2018 used as the base map for the different rice paddy pattern temporal signature extraction. Moreover, the very high resolution google earth pro app and dominant cropping pattern map used to select the area of interest (AOI). Based on ALOS-2 ScanSAR rice paddy map and spectral similarity technique (SMT) (Sakamoto *et al.*, 2009), we extracted the standard NDVI signature of various rice pattern in 2018. The temporal signature of a rice paddy in 2018 used as a standard spectrum for rice pattern recognition for other years. The 2018 ALOS-2 based MODIS rice area map used as based map and applied for the rest of the year rice area mapping. The temporal signature has been collected as; Boro rice-other crops, Amon rice-other crops, Boro-Amon rice, Aus rice-others crop, Aus-amon rice, and Boro-aus-amon rice. At least 100 AOI has been selected for each cropping pattern and set a threshold value for each class. More than 700 AOIs for each year selected for temporal signature extraction. Among the various classification, the maximum likelihood classification (MLC) is commonly used for rice crop mapping with good performance (Defries and Townshend, 1994; Hubert-Moy *et al.*, 2001). The MLC presumes that signatures class of the pixels are normally distributed and evaluated the probabilities of a given pixel belong to each class. The pixel is assigned to the class with the highest probability (Zhang *et al.*, 2014). In this study used the supervised classification with maximum likelihood classifier (MLC) for rice area identification. The three major rice-growing seasons (Boro, Aus and Amon) rice area map prepared from the various rice cropping pattern. Then, we estimated the rice area statistics in the major seven administrative division level in the study area. Finally, the rice area is extracted and prepared the annual seasonal rice area map of each year and seasons from 2001 to 2018. The overall research flowchart is shown in figure 2.1.

2.3.4 Accuracy assessment and area validation

The field data, the government reported national statistics and relevant data used for accuracy assessment and validation the result from this study. Firstly, the GPS filed data used for ALOS-2 ScanSAR seasonal rice area maps accuracy assessment. The government reported annual rice area statistics have been used for the ALOS-2 ScanSAR rice area validation. Secondly, the ALOS-2 ScanSAR rice area data used for the MODIS based rice map validation and accuracy assessment. Finally, the published report from the Bangladesh Bureau of Statistics (BBS) annual reported rice area from 2001 to 2018 used for MODIS based rice area map comparison. Moreover, the result of this study was compared with relevant studies on remote sensing-based rice area mapping of Bangladesh.

2.4 RESULTS

2.4.1 ALOS-2 ScanSAR rice paddy map-2018

The ALOS-2 ScanSAR rice area map over the selected tiles in the study area was compared with the GPS field data and statistically reported rice area. The boro rice area is the dominant rice area in the selected tiles 10,28,036 ha (47.14% of total rice area), followed by amon rice 10,17,983 ha (46.64%) and aus rice area 135543 ha (6.21%), respectively. In major district boundary coverage of the selected tiles on the study area are estimated the seasonal rice area statistics shown in table 2. The Mymensingh and Gazipur districts are the prominent boro rice cultivated area in the study area. In percentage of the total rice cultivated area, Gazipur (54.80%), Munshigonj (54.81%), Tangail (53.59%), Sirajgonj (53.63%) of the total rice area estimated as boro rice area. The Faridpur (32.22%), Rajbari (33.70%) and Pabna (38.50%) districts are the lowest boro rice cultivating area in the study area. The estimated amon rice is the second largest rice cultivated area followed by the boro rice area in the study sites. The Mymensingh and Tangail districts are the leading estimated amon rice-producing area is 2,57,157 ha (45.13%) and 1,22,680 ha (42.92%), respectively. Faridpur (60.50%), Rajbari (58.00%) and Magura (53.85%) districts are the top amon rice production area by the percentage of the total rice cultivated area. The aus rice area is the lowest estimated rice planted season in the study area. The Mymensingh (41,233 ha) and Pabna (24,759 ha) districts are the major aus rice cultivated area. The details seasonal rice distribution map shown in **figure 2.3**.

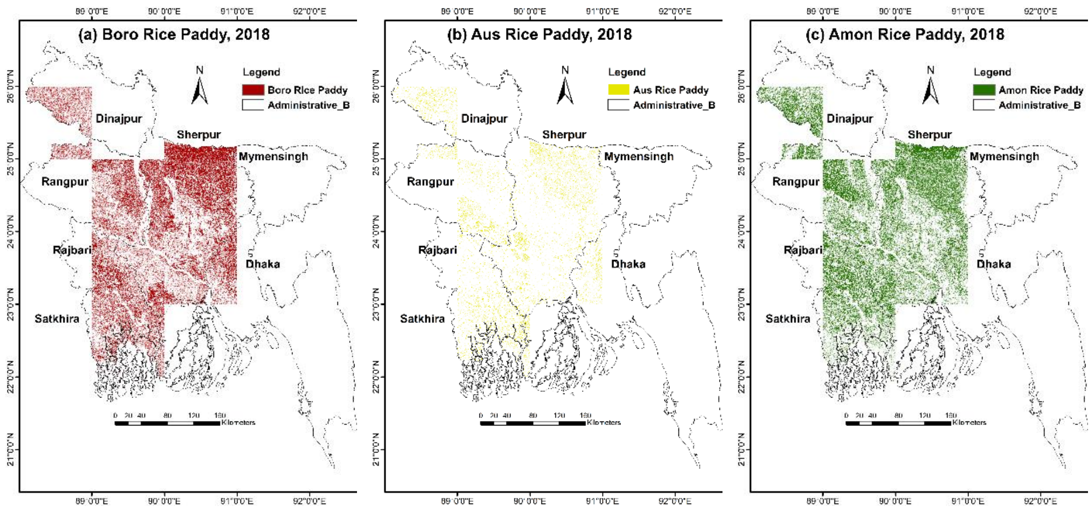


Figure 2.3 ALOS-2 ScanSAR backscattered coefficient unsupervised k-means class and GPS field data used seasonal rice area map over selected tiles on Bangladesh in 2018, (a) Seasonal boro rice area distribution map, (b) aus rice paddy field distribution map and (c) Amon rice paddy field map.

2.4.1.1 ALOS-2 ScanSAR rice area map validation with field data and national statistics

The ALOS-2 ScanSAR derived seasonal rice area map of selected seven tiles validated with the collected GPS filed data. The field data point compared with the ALOS-2 ScanSAR based rice area map. Among the 35 GPS points of amon rice field data, 27 points classified amon rice paddy field, 2 fields are misclassified as boro and amon rice, 3 fields as aus rice and 3 fields as aus and amon rice crop field in ALOS-2 ScanSAR rice map. The probable misclassification between amon and aus rice class is late amon and early aus planted rice paddy field. The single amon to double boro and amon rice paddy fields and aus and amon rice field misclassified is mainly due to the field size change in the different season. Among the total 48 points of boro rice paddy field data, 38 GPS points on boro rice identified as boro and 2 points misclassified as boro and amon rice field, 3 points as aus rice field, 4 points as boro and aus rice and 1 point as amon rice paddy field. Among the 32 GPS point on aus rice field data, 24 points classified as aus rice field and other points are misclassified as amon rice, boro rice, and boro and amon rice field in ALOS-2 ScanSAR rice paddy map. Among the 71 points on boro and amon rice paddy field, 61 points identified as amon and misclassified 3 of them as boro rice, 2 as amon rice, 3 as boro, amon and aus rice paddy field. The higher user's and producer's accuracy found at boro-amon rice pattern are 84.72% and 85.91% respectively. The more GPS point, the most common rice cropping pattern are the probable causes of higher accuracy. The lower producer's and user's accuracy in the boro-aus rice cropping pattern and the probable causes are the rarely cultivated pattern and fragmented small field size. The aus rice paddy also shows lower accuracy (70.59%) as the fluctuated planting date in between boro and amon rice-growing season and misclassified as boro and amon rice paddy field. The double and triple rice cropping pattern also illustrated comparatively lower accuracy mostly due to the changing field size from one season to another. The overall accuracy between the GPS field data and ALOS-2 ScanSAR rice paddy map is 78.65% with the kappa value 0.76. **Table 2.1** demonstrated the detail error matrix.

Table 2.1 Accuracy assessment of GPS field plot data and ALOS-2 ScanSAR based seasonal rice paddy map over the study area, 2018.

Classified Data	Reference Data								
	Amon	Boro	B-A	Aus	A-A	B-A	B-A-A	Classified Total	User's Accuracy
Amon	27	1	2	2	0	2	0	34	79.41
Boro	0	38	3	2	0	2	0	45	84.44
B-A	2	2	61	2	3	1	1	72	84.72
Aus	3	3		24	1	3	0	34	70.59
A-A	3	0	1	0	16		2	22	72.73
B-A	0	4	1	2	1	13	1	22	59.09
B-A-A	0	0	3	0	4	0	31	38	81.57
Reference Total	35	48	71	32	25	21	35	267	
Producer's Accuracy	77.14	79.17	85.91	75.00	64.00	61.90	88.57	Overall Accuracy=.7865, Kappa=.7622	

(Here, B-A= Boro-Amon Rice, A-A= Aus-Amon Rice, B-A= Boro-Aus Rice, B-A-A= Boro-Aus-Amon Rice)

Moreover, the ALOS-2 ScanSAR seasonal rice area in major administrative boundary level compared with the Bangladesh Bureau of Statistics (BBS) reported rice area statistics (BBS, 2018c). Among the administrative boundary, the Mymensingh district is the top rice-producing area. The estimated amon rice area and reported amon and boro rice area are almost same, whereas the estimated aus rice area is overestimated in the district. Similarly, in the case of other districts, the estimated and reported amon and boro rice area showed higher agreement. But, the estimated and reported aus rice area demonstrated overvalued and higher discrepancy. The ALOS-2 ScanSAR amon rice area and the BBS reported rice area is shown very good agreement (R^2= 0.98) followed by boro (R^2= 0.94) and aus (R^2= 0.71) in the selected administrative district level. The total estimated and reported amon rice area is 10,17,983 ha and 9,95,505 ha, respectively in the study area. The boro area also showed good agreement whereas reported area is 11,01,538 ha and estimated area 10,29,036 ha. The aus rice area shows higher discrepancy between the reported and estimated area (**table 2.2**).

Table 2.2 Comparision of seasonal ALOS-2 ScanSAR estinmated rice area with national statistics by administrative districs.

District	ALOS-2 Estimated rice area (ha)				BBS Reported rice area (ha)			
	Boro Rice	Aus Rice	Amon Rice	Total	Boro Rice	Aus Rice	Amon Rice	Total
Dhaka	35361	5448	32986	73795	47156	747	16716	64619
Faridpur	44309	9997	83172	137478	27804	6580	82090	116474
Gazipur	48218	2796	36963	87977	54316	1356	42502	98174
Madaripur	26218	2813	31631	60662	33677	1525	26511	61713
Manikgonj	36481	1752	43652	81885	46533	142	38891	85566
Munshigonj	36377	845	29138	66360	26450	940	20745	48135
Narayangonj	25106	4578	20361	50045	26018	690	10883	37591
Narshingdi	43892	6127	42720	92739	50213	331	41483	92027
Mymensingh	271349	41233	257157	569739	266243	16626	259040	541909
Rajbari	22488	5539	38712	66739	12664	1310	46256	60230
Shariatpur	34911	4634	26610	66155	21172	9180	17689	48041
Tangail	153148	9931	122680	285759	191878	837	116482	309197
Magura	40850	3075	51254	95179	42696	3310	58715	104721
Narail	43826	5561	37737	87124	59063	5459	39975	104497
Pabna	68888	24759	85268	178915	56317	16974	94727	168018
Sirajgonj	97614	6455	77942	182011	139338	4725	82800	226863
Total	1029036	135543	1017983	2182562	1101538	70732	995505	2167775

2.4.1.2 MODIS based rice map calibration with ALOS-2 ScanSAR rice data

The ALOS-2 ScanSAR seasonal rice area map was used for calibrating the MODIS derived seasonal rice area map in 2018. The higher spatial resolution and field data validated ALOS-2 rice area map used as the base map for the MODIS rice area mapping. The region of interest (ROI) have been selected from ALOS-2 ScanSAR rice area map and the MODIS NDVI spectral singnatures of that ROI extracted (**figure**

2.4). The ALOS-2 ScanSAR derived ROI's temporal signatures of MODIS NDVI value observed and adjusted over the study area for seasonal rice area mapping.

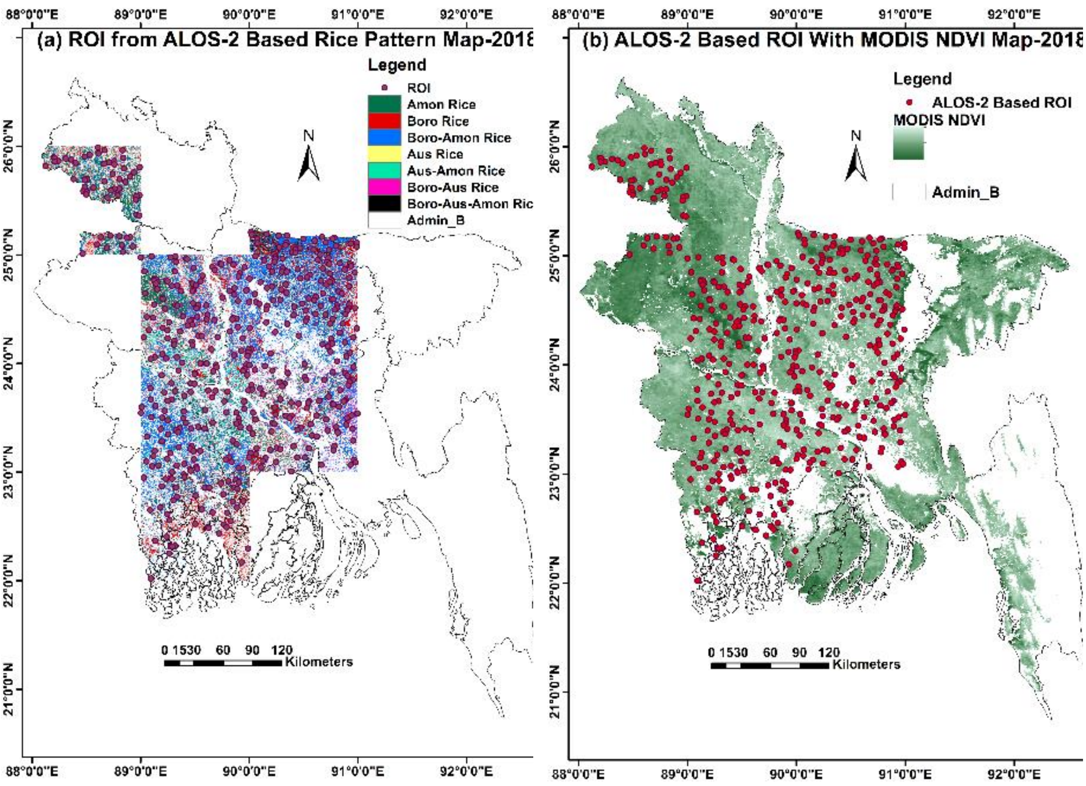


Figure 2.4 (a) ALOS-2 ScanSAR seasonal rice area map used region of interest (ROI) selection over the selected tiles, (b) ALOS-2 ScanSAR derived ROI used to extract the MODIS NDVI spectral value over the selected region in 2018.

Due to the high spatial resolution and atmospheric noise-free ALOS-ScanSAR data, even the smaller rice area could detect efficiently. In pixel level, the low spatial resolution MODIS NDVI one pixel represent almost twenty (20) pixel of ALOS-2 ScanSAR data. As a result, the ALOS-2 SacanSAR derived and MODIS adjusted NDVI ROI value represent better classification result for the seasonal rice area map. The ALOS-2 ScanSAR and MODIS data used maximum likelihood classified seasonal rice area map compared over the study area. Randomly, 600 points selected in ALOS-2 ScanSAR rice map and extracted the raster value from the MODIS seasonal rice area map. The result is compared to the confusion matrix of ALOS-2 and MODIS map (table 3). The amon rice area demonstrated 84.08% user's and 84.50% producer's accuracy. There are 30 points classified as aus rice and 2 points as boro rice. The commission and omission error also lower (16%) in ALOS-2 and MODIS amon class. The boro rice paddy illustrated the higher produce's accuracy (90%) and user's accuracy (86.54%) with lest commission (6.98%) and omission (13.5%) error. The boro planting date is distinguishably different than amon rice planting date but late boro and early aus plantation date in some region are very close. As a result, there is some misclassification between boro and aus rice class. The aus rice is the lowest user's and producer's accuracy of 76.00% and 79.58%, respectively. The commission (23.83%) and omission (18.5%) error are also higher in aus rice class. The probable causes of this discrepancy are – i) difference between ALOS-2 ScanSAR (50-m) and MODIS (1000-m) spatial resolution, ii) smaller cultivated area (almost 10%), and iii) fluctuation of planting date of aus rice area. Moreover, the data acquisition process of ALOS-2 ScanSAR and MODIS are also different. The error matrix of ALOS-2 ScanSAR and MODIS seasonal rice area map showed in **table 2.3**. This calibrated MODIS rice area map used for updated the rice area map from 2001 to 2017 and finally produced the MODIS seasonal rice area map from 2001 to 2018 over Bangladesh.

Table 2.3 Confusion matrix between ALOS-2 ScanSAR based seasonal rice and MODIS based seasonal rice paddy map in 2018.

MODIS/ Classified Data	PALSAR-2/Reference Data				
	Amon Rice	Boro Rice	Aus Rice	Classified Total	User's Accuracy
Amon Rice	169	2	30	201	84.08
Boro Rice	10	180	18	208	86.54
Aus Rice	21	18	152	191	79.58
Reference Total	200	200	200	600	
Producer's Accuracy	84.5	90.00	76.00		Kappa .77

2.4.2 MODIS rice area map 2001-2018

The MOD16A2 NDVI time-series data demonstrated uncertainty and missing value over the year especially during the rainy season. The aus and amon rice planting season (June to August) the cloud affects are optimum and there is huge missing data. The most challenging part of using optical data is to solve cloud contamination problem. The Kalman's filtered recursion methods filled the missing data to smooth the NDVI spectral signature. The smoothed spectral signature of NDVI indices used for the rice crop pattern identification. In **figure 2.5** showed the MOD13A2 NDVI spectral signature with and without Kalman filter.

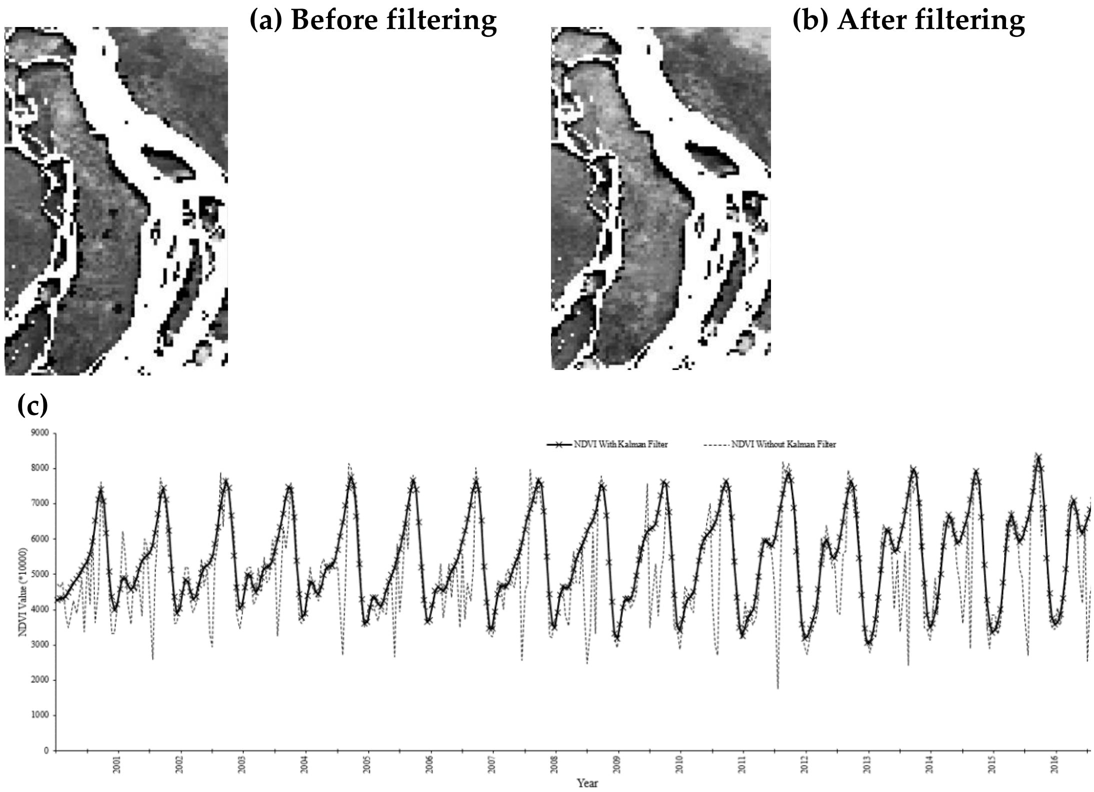


Figure 2.5 (a) MOD13A2 NDVI data from 2001 to 2018 before Kalman's filtered, (b) the images after filtering and (c) the spectral signature of a selected point in the study area with Kalman's filtered and without Kalman's filtered data.

The temporal variation of NDVI signature in different rice growing stage evaluate for the distinguish rice paddy field from the non-rice field as well as the seasonal rice. The rice paddy NDVI signature shows very low value in the transplanting season (0-20 days after transplanting) and start to increase up to the peak (80-100 days) in growing and maximum greenness stage. After the peak, the rice greenness value, as well as the spectral signature values, start to decrease and become very low in harvesting (110-120) and fallow season. The boro, aus and amon single rice crop pattern shows the single fold in their growing period. In case of double and triple rice paddy, the spectral signature value starts to increase followed the fallow season to transplanting season. The value again shows a similar pattern as the previous cycle. The boro-amon, boro-aus and aus-amon double rice cropping pattern demonstrated the double fold and the boro-aus-amon triple rice paddy showed the triple-fold in a single year. The single or double rice along with the non-rice cropping pattern shows single rice or double rice fold and others pattern. In **figure 2.6** illustrated the selected ROI for various rice cropping pattern and ideal NDVI temporal signature for the rice cropping pattern over the study area.

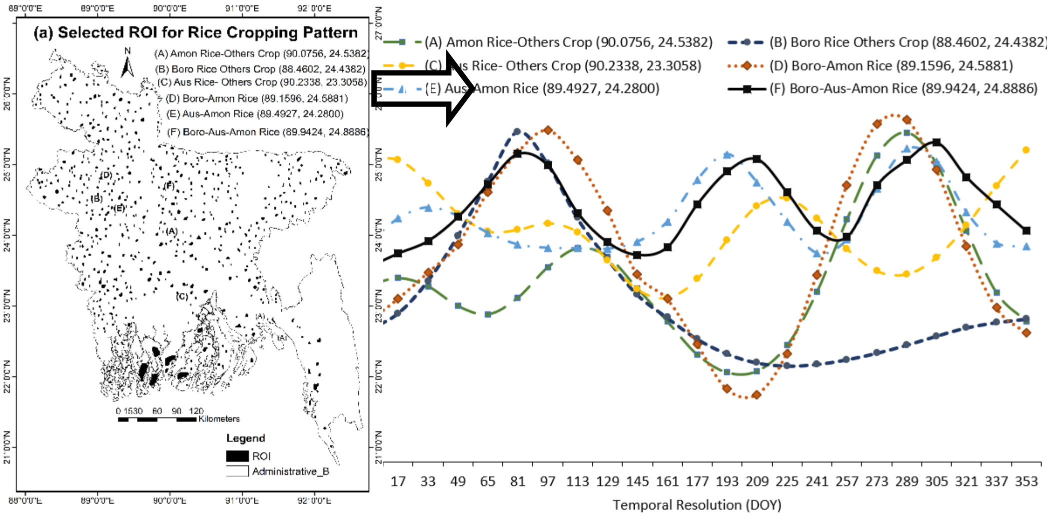


Figure 2.6 (a) ALOS-2 ScanSAR, dominant rice crop map and Very high resolution google earth pro used selected rice paddy field area of interest (AOI); (b) the ideal spectral signature for the different rice cropping pattern over the study area, (A) Amon single rice and others crop, (B) Boro-Amon double rice paddy field, (C) Boro single rice paddy and other crop field, (D) Aus single rice paddy and others crop, (E) Aus-Amon double crop rice paddy field, and (F) Boro-Aus-Amon triple rice paddy field spectral signature.

2.4.2.1 Boro rice paddy mapping result

The estimated boro rice area of the country gradually increased from 35,64,900 ha (32.95%) in 2001 to 47,87,200 ha (42.94%) in 2018. The boro rice area enlarged 34.28% within the time. Although, the boro rice cultivated under the fully irrigated condition and required more input as a result the production cost is comparatively high. But the cultivated area increased due to the higher per unit yield (4.42 tone/ha) and less disaster-prone (BBS, 2018a). The boro rice area started to increase drastically from 2010 with the availability of deep and shallow irrigation pump (Kirby *et al.*, 2014). The boro rice area increased up to 2015 and reached its peak as 49,63,800 ha figure 8 (s). The area becomes almost saturated and there is no further increased. The central-northern part of the country especially Mymensingh and Rangpur districts are the major boro rice cultivating region in the country. The southern coastal zone and north-western driest part of the country are the less boro rice farming regions. The detail boro rice distribution map is shown in **figure 2.7**.

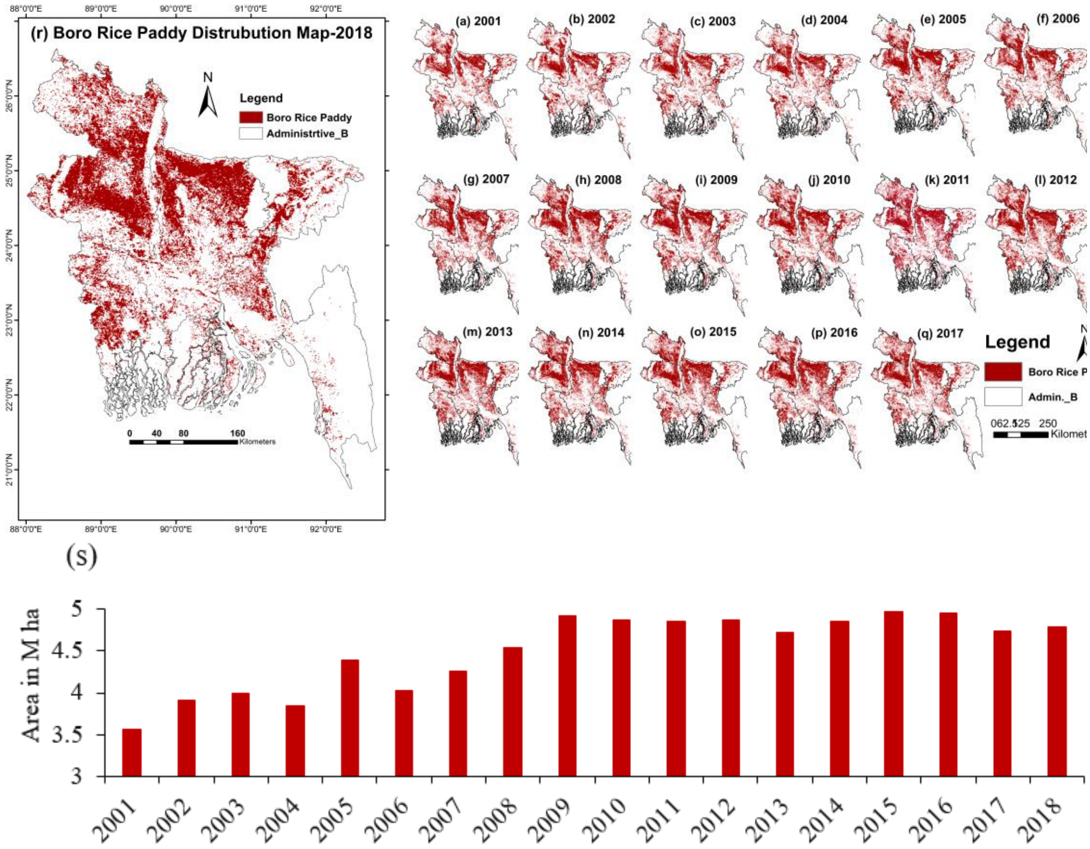


Figure 2.7 MODIS Kalman's filtered NDVI with maximum likelihood classifier used and ALOS-2 ScanSAR updated seasonal boro rice distribution map over the study area, (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, (j) 2010, (k) 2011, (l) 2012, (m) 2013, (n) 2014, (o) 2015, (p) 2016, (q) 2017 and (r) 2018; and (s) boro rice area statistics from 2001 to 2018.

2.4.2.2 *Aus rice paddy mapping result*

The aus rice area is the smallest amount of cultivated rice season in the country. The aus rice cultivated under almost rainfed condition over the country. Although, the production cost is low but the area decreasing over the time (17.05%). Due to the monsoon condition the aus rice growing season frequently experienced flood disaster. Moreover, the low per-unit yield (2.27 tone/ha) makes it rarely cultivated among the farmers (BBS, 2018b). In 2001, the estimated aus rice area was 15,33,000 ha (14.17%) and becomes 12,71,600 ha (11.40%) in 2018. The area gradually decreasing over time with some fluctuation. The lowest cultivated area observed in 2007 and it was 11,07,300 ha. The comparatively higher altitude central and south-central part of the country is the major aus rice-farming area in the country. The details distribution and statistics of aus cultivated rice area over the study area shown in **figure 2.8.**

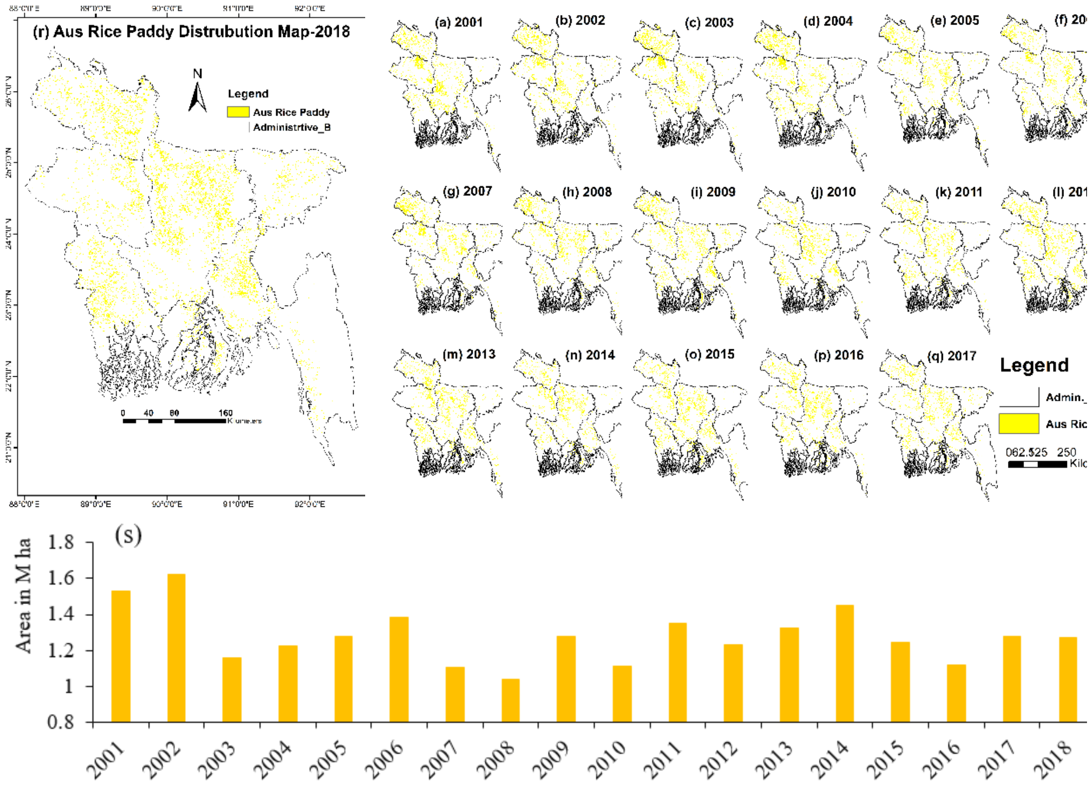


Figure 2.8 MODIS Kalman's filtered NDVI with maximum likelihood classifier used and ALOS-2 ScanSAR updated seasonal aus rice distribution map over the study area, (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, (j) 2010, (k) 2011, (l) 2012, (m) 2013, (n) 2014, (o) 2015, (p) 2016, (q) 2017, (r) 2018; and (s) aus rice area statistics from 2001 to 2018.

2.4.2.3 *Amon rice paddy mapping result*

The amon rice cultivated area decreasing over time but, still it's the dominant rice-growing season in the country. The amon rice cultivated from July to November/December, which is the monsoon and post-monsoon season with plenty of rainfall. As a result, the amon rice area is mostly rainfed and supplementary irrigated and popular rice-growing season in the study area. The estimated amon rice cultivated area were 57,18,800 ha (52.87%) in 2001 and becomes 50,87,200 ha (45.64%) in 2018. The area decreased 11.04% from 2001 to 2018. The lowest estimated amon rice area was 48,47,200 ha in 2007. The probable case of this low estimation was the devastating impacts of tropical cyclone "Sidr" (Moni *et al.*, 2015). Comparatively lower per unit yield (2.46 tone/ha), and disaster risk in the harvested season are the probable cause of such declination. The central north and north western part of the county especially, Mymensingh, Rajshahi and Rangpur division is the major amon rice-growing zone in the country. Moreover, the boro-amon double rice cropping pattern is the most common cropping pattern in the study area. The details distribution of amon rice cultivated rice area shown in **figure 2.9**.

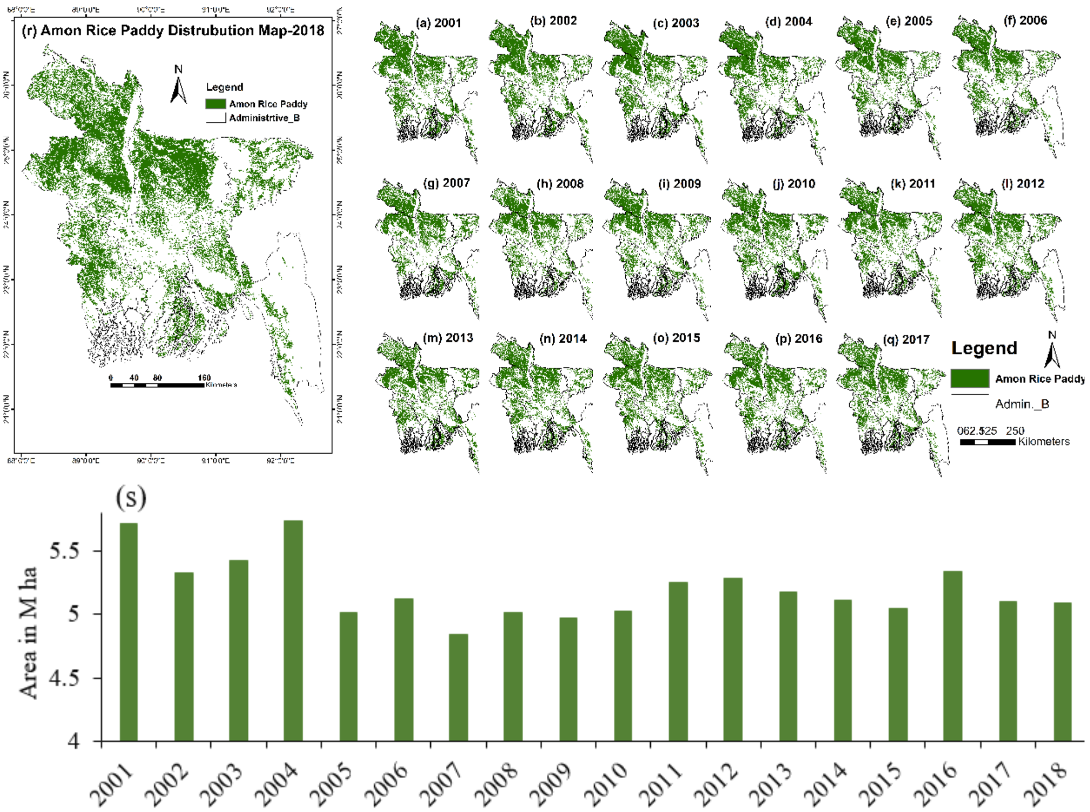


Figure 2.9 MODIS Kalman's filtered NDVI with maximum likelihood classifier used and ALOS-2 ScanSAR updated seasonal amon rice distribution map over the study area, (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, (j) 2010, (k) 2011, (l) 2012, (m) 2013, (n) 2014, (o) 2015, (p) 2016, (q) 2017 and (r) 2018; and (s) amon rice area statistics from 2001 to 2018.

2.4.2.4 MODIS rice area in major administrative division level

The MODIS derived rice area in greater seven (7) administrative divisional scale were estimated from 2001 to 2018. The greater Dhaka division is the largest rice cultivated division as it's also greater by area. The amon (45.48%) and boro (45.73%) rice as single and double cropping pattern is the dominant crop. Currently, Dhaka division divided as Dhaka and Mymensingh division and especially the Mymensingh division is the major rice-growing region in the country. The aus rice is cultivated in a very small area (8.78%) in this division. The flat physiographic condition, fertile land, better agricultural infrastructure, and less disaster driving the rice crop expansion in this region. The second largest division Chittagong is dominant by amon rice (47.92%) and followed by boro (37.44%) and aus rice (14.63%). Although the coastal and mountainous physiography and blooming of non-agricultural economic leading declined of the rice area in this division. The Khulna division is another coastal region and recently aquaculture practice increased, and saline intrusion is the major constraint for rice cultivation. But the development of salinity tolerates rice verities and mix cultivation practices of fish and rice becoming popular in this region(Chowdhury *et al.*, 2011). The leading rice crop is amon (50.40%) and trailed by boro (35.40%) and aus (14.65%) rice. The riverine Barishal division's major rice crop is amon (65.55%), boro (20.70%) and aus (14.14%). The less rainfall and higher temperature leading drought prone Rajshahi division's leading estimated rice crop area amon (46.54%), boro (45.60%) and aus rice (7.84%). The Rangpur division also showed similar rice cropping pattern as the amon (54.25%), boro (40.82%) and aus rice (4.85%). All over the country, Amon is the main rice crop (48.67%) followed by boro rice (42.09%) and aus rice (9.24%). In **figure 2.10** shows, the division wise estimated different types of the rice area in Bangladesh from 2001 to 2018.

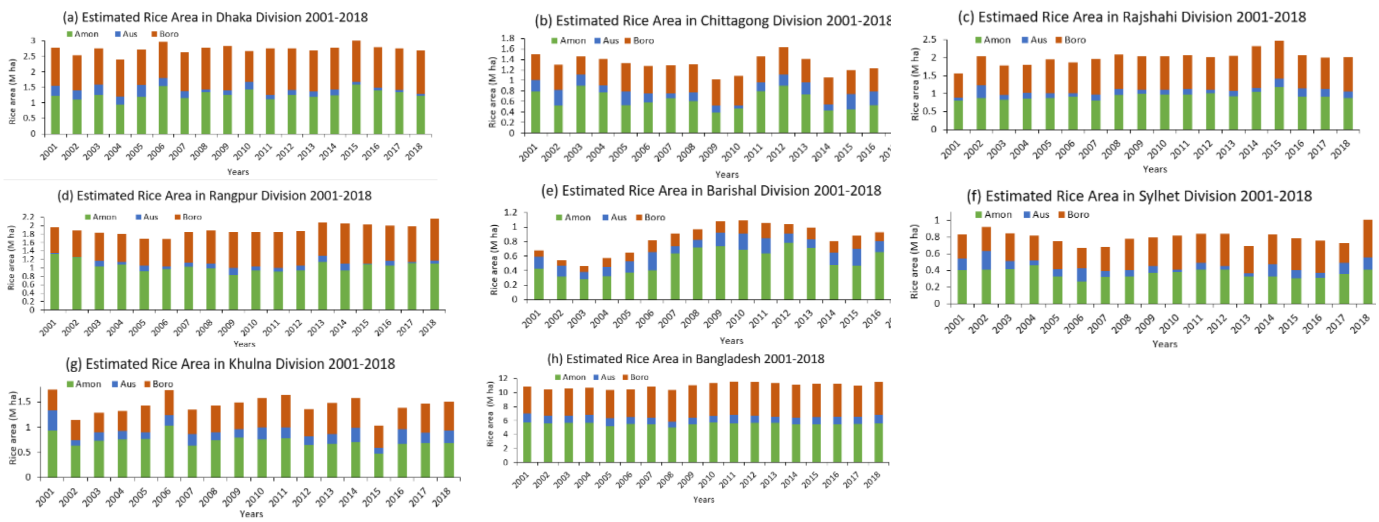


Figure 2.10 Boro, Aus and Amon rice area in seven division in Bangladesh (a) Dhaka division, (b) Rajshahi division, (c) Rangpur division, (d) Chittagong division, (e) Barisal division, (f) Sylhet division, (g) Khulna division and (h) over Bangladesh from 2001 to 2018.

2.4.2.5 Comparisopn of ALOS-2 ScanSAR rice area and MODIS rice area-2018

The ALOS-2 ScanSAR seasonal rice area and ALOS-2 ScanSAR derived MODIS seasonal rice area in 2018 compared. Among the administrative 16 district coverage of ALOS-2 ScanSAR rice area statistics and the MODIS estimated rice area show very good agreement (**figure 2.11**). The ALOS-2 boro rice area and MODIS estimated boro rice area demonstrated the highest agreement (R2 value 0.97). In Dhaka, Mymensingh, Manikgonj, Rajbari, Tangail, Pabna and Sirajgonj district MODIS derived boro rice area is a bit of over-estimated from ALOS-2 rice area and the rest of the case are underestimated. In amon rice area case also showed very good agreement in MODIS and ALOS-2 estimated rice area (R2 value 0.93). In Dhaka, Gazipur, Mymensingh, Manikgonj, Tangail and Sirajgonj district MODIS derived amon rice area is comparatively over-estimated from ALOS-2 rice area and rest of the case are slightly underestimated. The probable cause of this discrepancy is the variation of MODIS and ALOS-2 SacanSAR spatial resolution. As the larger cultivated rice area are leading the overestimation. The higher disagreement shown in between the ALOS-2 and MODIS estimated aus cultivated rice area (R2 value 0.72). As the comparison of ALOS-2 ScanSAR rice area and national statistics reported aus rice area also showed the similar lowest agreement. In the study area, most of the district case the result showed fluctuation. The overall result of ALOS-2 ScanSAR and MODIS rice area showed very agreement.

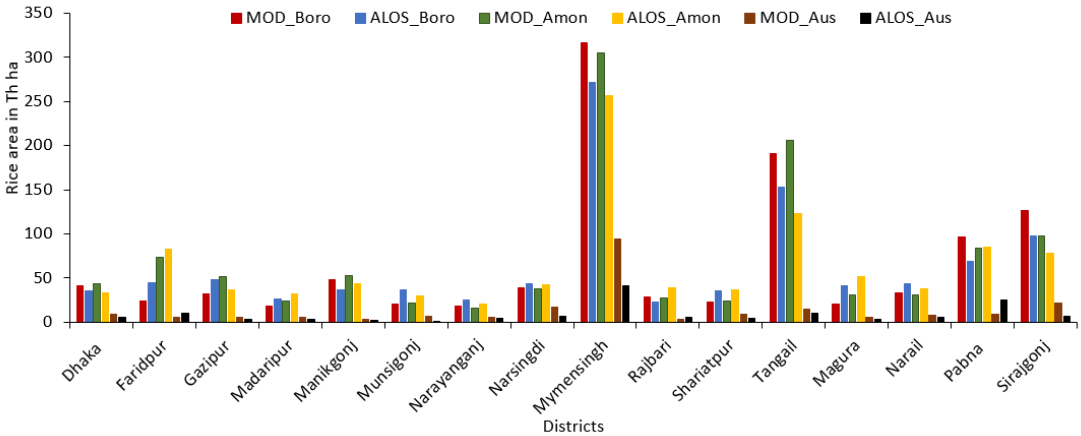


Figure 2.11 The ALOS-2 ScanSAR seasonal rice area statistics and MODIS rice area staistices on Boro, aus and amon rice season over the seleected 16 administrative districts in 2018.

2.4.2.6 MODIS rice area comparision with relavent studies

International rice research institute (IRRI) produced and published seasonal rice area map on Bangladesh, 2010(Gumma *et al.*, 2014). The study used MODIS 500m spatial resolution, 8-days composite and spectral matching techniques with intensive field data. The IRRI seasonal rice area map compared with this result of this analysis. The result illustrated the higher user's accuracy in the boro rice class (85.89%) similar to ALOS-2 MODIS comparison. The overall accuracy is 0.70 and kappa value 0.664 (**table 2.4**) . The highest commission error occurs in boro-amon (46.15) rice pattern and lowest in case of boro-aus-amon (8.06) rice pattern. The higher commission error of boro and amon double rice cropping patterns most probable cause is the boro-aus and aus-amon rice pattern misclassification. The early aus rice sometimes classified as boro rice and late planted aus misclassified as amon rice. The maximum omission error in aus-amon rice (45) cropping pattern and minimum in boro rice (15) case. The aus rice and amon rice plantation seasons are mostly overlapped in some regions. Especially, the single aus rice cropping pattern planted in early and aus as double or triple rice cropping pattern planted in comparatively late season, which are the probable causes of higher omission error. The boro rice as single crop mostly cultivated in low land of the study area and there are no other rice or crop cultivated in the cropping year is the causes of minimum omission error.

Table 2.4 Confusion matrix between MODIS analysis rice map of this study with the IRRI produced seasonal rice area map on Bangladesh, 2010.

Classified/PALSA R-2 Data	Reference/IRRI Data							
	Amon	Boro	B-A	Aus	A-A	B-A-A	Classified Total	User's Accuracy
Amon	82	1	8	24	8	5	128	80.00
Boro	1	85	7	16	7	4	120	85.89
B-A	9	4	83		27	32	155	70.37
Aus	5	10	0	60	0	0	75	70.58
A-A	3				55	2	60	61.29
B-A-A	0	0	2	0	3	57	62	82.35
Reference Total	100	100	100	100	100	100	600	
Producer's Accuracy	82.0	85.0	83.0	60.00	50.0	57.00	Overall Accuracy=.7033, Kappa=.644	

(Here, B-A= Boro-Amon Rice, A-A= Aus-Amon Rice, B-A-A= Boro-Aus-Amon Rice)

We compared the result from this study with sentinel-1 images, field photo and random forest classifier use seasonal paddy rice mapping in Bangladesh with 90% overall accuracy in 2017 (Mohite *et al.*, 2018). Although, there is spatial resolution difference between the ALOS-2 ScanSAR and MODIS dataset with the sentinel-1 (10-m) data but the result shows overall accuracy 76% and kappa value 0.70. A significant number of the random point were selected as no data value in MODIS rice map especially in aus, boro-aus and aus-amon rice cropping pattern due to the spatial resolution differences. With higher spatial resolution data it's possible to identify even small size field but in low spatial resolution, it's challenging.

2.5 DISCUSSION

2.5.1 MODIS rice area comparison with reported government statistical data

The annual rice area estimated from this study compared with the reported statistics of Bangladesh Bureau of Statistics (BBS) published "Yearbook of Agricultural Statistics" from 2001 to 2018 (BBS, 2018c). Although, the BBS data collection methodology is quite different from the remote sensing technology. The BBS data were collected by the household survey, field visit, and expert opinion on rice cultivated area and estimated the annual production. But the comparison with the statistical data could be a viable source of validation of remote sensing data. The comparison was conducted at two stages- i) at the national level estimated seasonal boro, aus and amon over the study area from 2001-2018 with the BBS reported statistics, ii) major administrative division level within the same period. The estimated boro rice area in 2001 to 2004 shows slightly underestimated (2 to 3%) from the reported data and 2010 demonstrated the best agreement between two datasets and after that boro rice area somewhat (3 to 5%) overestimated compare to the statistical data. The estimated amon rice area and reported area shows some variation (2 to 5%) during some year. The estimated aus rice area and reported rice area show poor accuracy among the seasonal rice with 3-10%. The estimated and reported seasonal rice area (boro, aus and amon) and reported rice area from 2001 to 2018 illustrated in figure 11 with R^2 value 0.97 (boro rice), 0.76 (amon) and 0.27 (aus) rice. The comparison between remote sensing based estimation and statistical data similar relationship found in others studies, R^2 value 0.42 and 0.87 in South and Southeast Asia (Xiao, Xiangming & Boles, Stephen & Frolking, Steve & Li, Changsheng & Yeluripati, Jagadeesh & Salas, William & Moore, 2006), 0.97 in Asian countries (Gumma, 2011) and 0.84 to 0.91 (Mosleh and Hassan, 2014b) in Bangladesh.

The estimated rice area competes with the division level reported rice area over the study area from 2001 to 2018 (**figure 2.12**). In Dhaka division, the 18 years average estimated amon rice (45.48%) area is slightly overestimated than the reported amon rice (43.19%), boro rice area also underestimated (5%) and aus rice area over estimated (2%). The estimated amon rice area in Chittagong division underrated (3%) than the reported amon area, boro rice area overestimated by 2% and aus rice area almost comparable the reported aus rice area (14.05%) of total rice. In Rajshahi division, the estimated boro (45.60%), amon (45.49%) and aus rice (7.84) almost like the reported rice area of this district. In Rangpur, estimated boro and amon rice area slightly underestimated, and aus rice area overestimated compare to the reported rice area in this division. In Barishal division, also show the similar result as like the Rangpur division. In Sylhet division, the estimated boro (45.57%) and reported boro (44.84%), estimated amon (42.11%) and aus (12.33%) almost like the reported area. In individual year basis division wise boro, amon and aus rice area show some fluctuation. In figure 2.12.d, shows the division wise estimated and reported boro, amon and aus rice correlation from 2001 to 2018.

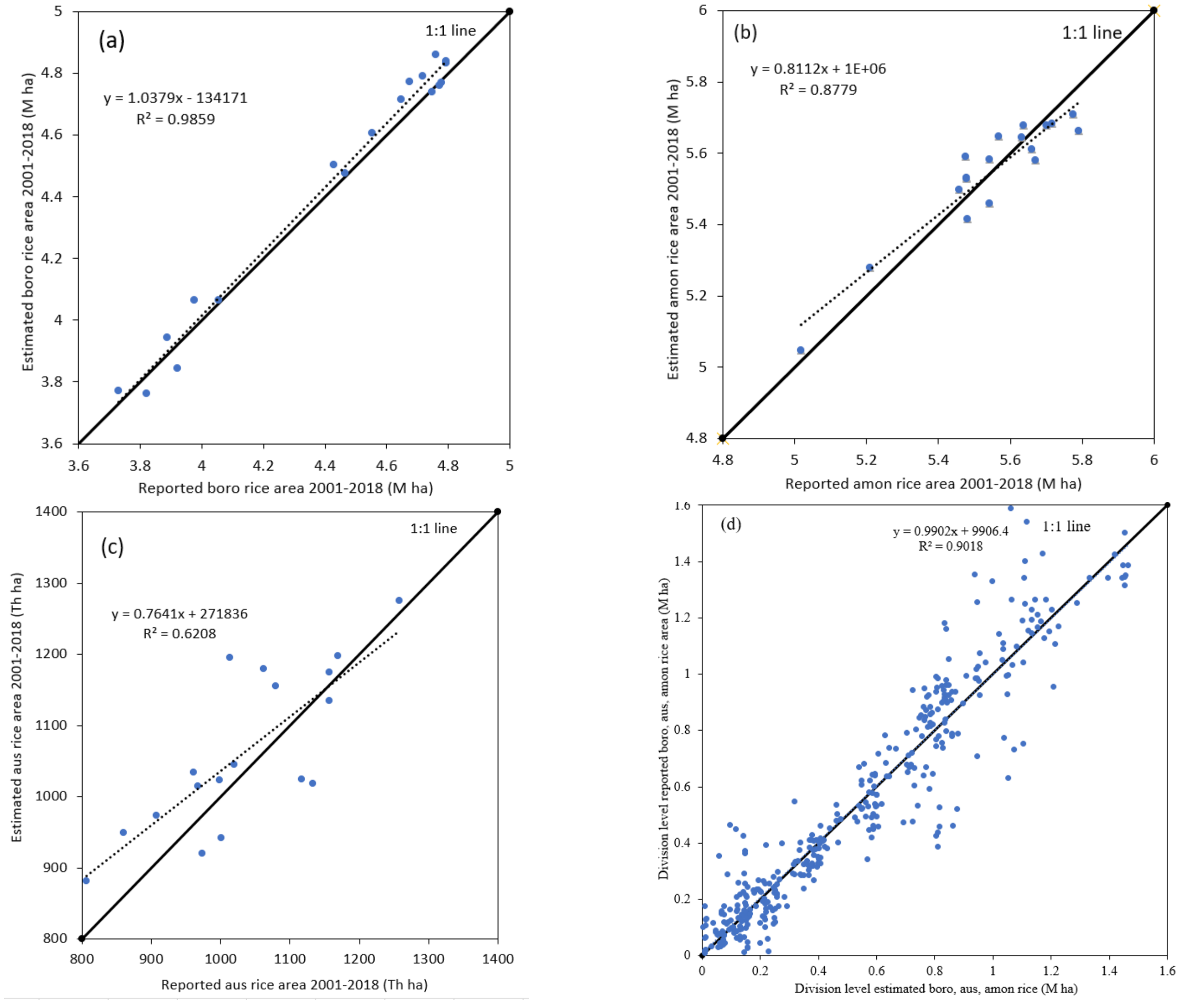


Figure 2.12 MODIS based rice area statistics comparison with national statistical rice area data; (a) MODIS estimated boro rice area vs national statistics reported boro rice area 2001 to 2018, (b) MODIS estimated amon rice area compare with reported statistical amon rice area 2001 to 2018, (c) estimated aus rice area vs reported aus rice area from 2001 to 2018, and (d) estimated boro, Aus and amon rice area comparison with reported boro, aus and amon rice area by division from 2001 to 2018.

We also compared our result with the United State Department of Agriculture (USDA) Foreign Agriculture Service (FAS) data and found very good agreement with our estimation (USDA, 2019). As rice is the staple food, the country's staple market price of rice is a very important indicator for socio-economic stability. The government always try to keep the balance of rice market price and frequently import rice in case of insufficiency. The country still fighting to achieved self-sufficient to produce rice and there is no export of rice. The rice import statistics is an important indicator of rice production of the country. The result of this study compared with the rice import data (**figure 2.13**) of Bangladesh. The comparison found that the MODIS based estimated rice area in 2007 (103,83,000 ha), 2010 (110,17,200 ha) and

2017 (111,24,200 ha) was comparatively lower and the reported imported rice amount are higher than usual years. The imported rice was 2,04,700 tone in 2007, 1,30,800 tone in 2010 and 3,20,000 tone in 2017 which comparatively higher imported amount than the other years. There are a severe flood and devastating tropical cyclone "SIDR" in 2007 (Moni *et al.*, 2015), another acute flood and drought in 2010 ((BBC, 2010; Afrin, Hossain and Mamun, 2019) and also severe flood in 2017 (CNN, 2017; GIEES, 2017) hits on the country. These flood, drought and cyclone are leads huge damaged of the rice paddy in Bangladesh. Which strongly support to the result of this analysis. But the statistical data shows similar trends as the earlier and previous year. Although the rice cultivated area not increasing that much but the overall rice production is increasing over Bangladesh due to the high yielded varieties, intensive agriculture input (fertilizer, pesticide, irrigation) but the rice area slightly decreased over the time(Kirby *et al.*, 2014).

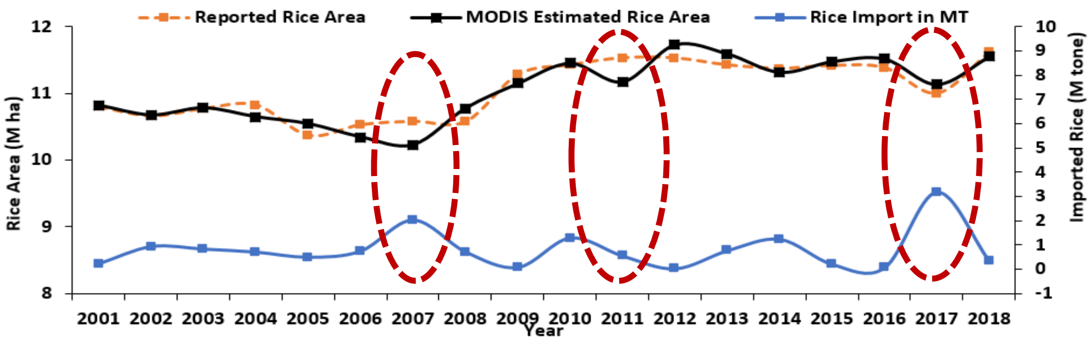


Figure 2.13 ALOS ScanSAR-MODIS estimated rice area compared with annual national imported rice statistics (USDA) reported from 2001 to 2018.

2.5.2 Uncertainties

Rice paddy mapping with remote sensing is challenging and there are some potential sources of uncertainties. The uncertainties sources could affect the result of the rice paddy map. All the stages from field data collection, image processing, classification and calculation could be possible sources of potential error. Although we try to collect field data in larger crop extend (>3 ha) but the co-exists of others vegetation and waterbody could be a potential source of uncertainty. The monthly temporal resolution of ALOS-2 ScanSAR data used for this study, but the rice planting season especially in aus and amon season varied region to region more than one month and lead to misclassifying of paddy rice. The ScanSAR backscattered coefficient data very sensitive to the surface water condition and during the rainy season the non-rice field also exist inundated condition. As a result, aus rice paddy detection shows a higher discrepancy. The MODIS data with 16 days temporal and 1 km spatial resolution and some paddy field area extends less than the spatial extends and influence the result. Although, the higher resolution ALOS-2 ScanSAR data for 2018 used to update the problem. The result compares with remote sensing-based study, but the spatio-temporal resolution and methodologies are the difference and potential error source of discrepancy. Moreover, the national statistics source data used for statistical comparison. The national statistical data collection and estimation process itself has some discrepancy and not always provides accurate measurement. In BBS rice paddy statistical data case, it's mentioned that the data avoided the fraction number and represent as the round figure. Moreover, it's very common that the national statistical data sometimes influenced by the government for political and socio-economic reason in the developing countries. So, the sources of uncertainties could occur on both resultant and compared parameters.

2.6 CONCLUSION

This study demonstrated the remote sensed based seasonal rice paddy mapping over Bangladesh from 2001 to 2018. The multi dated ALOS-2 ScanSAR data with unsupervised classification and supervised labeling used for seasonal rice paddy. The methodology shows very good accuracy (59% to 84%) to identify even the complex rice cropping pattern. Along with the high spatial resolution ALOS-2 ScanSAR, the low-resolution MODIS Kalman's filtered NDVI data with spectral similarity matching and maximum likelihood classifier used seasonal rice map with very good agreement. The comparison results between ALOS-2 ScanSAR rice map and MODIS rice area map shows very good agreement with overall accuracy 84.04%, and kappa value 0.77. The MODIS rice map result compared with the national statistics and shows R2 value 0.97 for boro, 0.77 for amon and 0.28 for aus rice in national scale from 2001-2018. The compared result in major divisional level shows r2 value 0.90 from 2001-2018. The combinedly, high spatial resolution SAR sensor data and high spatial resolution of long time series optical sensor data could be potential tools for seasonal rice area mapping. The long time series spatial data on seasonal rice paddy area could be very important for the policy maker to ensure the food security and climate change mitigation.

The output from this chapter, the seasonal rice area map will be used for input dataset for the chapter 3 (AWD irrigation suitability analysis), chapter 4 (CWR and Irrigated rice area mapping) and for chapter 5 (methane emission estimation from rice paddy).

Chapter 3: AWD irrigated rice area suitability analysis

3.1 CHAPTER OVERVIEW

In this chapter we first discuss about the background of the chapter 3, review previous attempts assessing the AWD suitability of environment and socio-economic for different rice paddy in section 3.2. Then we describe the adopted methodology in detailed section 3.3. In section 3.4 results are discussed followed by conclusion in section 3.5.

3.2 NTRODUCTION

3.2.1 Background of the chapter

Rice is the staple food and the widely cultivated crop in Bangladesh. Due to the huge demand of rice, the country trying to increase the rice production in future decade to ensure the food security. But the rice production of the country facing several challenges likes as: the arable land losses, Climate change impacts, irrigation water scarcity, greenhouse gas emission, and diseases transmission. Traditional flooded condition rice cultivation is one of the largest GHG's producer, 13% of country's total GHG's emission (WRI, 2017). Moreover, the country withdraws 31.34 km3 water for irrigation and 79% of the water source is ground water (FAOSTAT, 2019). The country irrigation practices development leads green revolution and increased food production drastically. The Irrigation developments and yield improvement have been sustained by the construction of surface water use and shallow and deep tube-well irrigation pump also increased from 0.2 million to 10 million from 1985 to 2012. Due to the excessive ground water pumping, the ground water table decreasing 2-3 feet/year over the country (Hasan *et al.*, 2018).

The rice cultivation has great socio-economic impacts for the country. But the rice production of the country is under great socio-economic and environmental threat. The more rice production means use more precious ground water and produce more GHG's methane, which accelerating the global warming. The country is committed to reduce GHG's as part of the global agreement on climate change adopted by the United Nations Framework Convention on Climate Change (UNFCCC). With the conclusion of COP 22, the "COP of Action", country is now seeking practical innovations and solutions to meet both their mitigation commitments and food security goals (Nash, 2016).

Alternate Wetting and Drying (AWD) irrigation system are one of the sustainable solutions for rice cultivation. AWD, is a management practice in irrigated rice characterized by periodic drying and flooding of fields. Submergence of soil and organic residual material in rice paddies leads to anaerobic decomposition of organic matter that releases methane. Periodic drying events interrupt the duration of this process and reduce methane emissions up to a 70% compared to continuous flooding (Carrijo, Lundy, *et al.*, 2018). In addition, AWD can reduce water use by up to 30% without any production loss, thus also resulting in water conservation and reduced fuel consumption required for water pumping (Basak, 2016b; Carrijo, Lundy, *et al.*, 2018).

In Bangladesh, AWD irrigation system has been introduced in 2010 by international rice research institute (IRRI). Although the national and international organization working on dissimilation of AWD irrigation system, but the AWD irrigation system has not been widely applied by farmers in the field level. The widespread uptake of AWD will need support from a range of different stakeholders, namely irrigation authorities, extension services and local government units, to demonstrate the benefits and viability to farmers and to adapt the way in which water is provided, managed and valued. The AWD suitability analysis has not paid much attention to adopt and upscaled AWD irrigation system. To adopt the AWD irrigation system at field level, the proper information on AWD irrigation is very important. In this study, we used an empirical method to assess the suitable area for AWD irrigation application based on physical and climatic parameters.

3.2.2 Objectives

The alternate wetting and drying irrigated suitable rice area assessment with remote sensing, statistical and geospatial dataset is the main objective of this chapter. The AWD irrigation depends on physio-climatic and socio-economic parameter especially the season specific environmental condition. In this study we asses AWD irrigated suitable rice area region with the physical, climatic, social, and economic characteristics of the country. The overall objectives of this chapter fixed as follows.

- Physically suitability of AWD irrigated rice,

-Climatically suitable area for AWD irrigated rice,

- Socio-economic suitable of AWD irrigated rice area,

-Validation and comparison of model result with relevant sources of data.

3.2.3 Literature review

Alternate wetting and drying (AWD) irrigation system are a proven way to reduce water use and methane emission. The suitable area for AWD irrigation means the condition under the maximum water saving and emission reduction without production los. The condition of an environment for a given crop, is evaluated by biophysical suitability assessment methods (Ir.C.sys, Ranst and Ir.I.Debaveye, 1991; Vasu et al., 2018). This assessment, for AWD irrigated rice cultivation proposes, considers physical, climatic, and socio-economic characteristics of a location associated with crop requirements. In these approaches the locations where the environmental conditions are well matched with the crop requirements will be identified as "Suitable". Thus, suitability assessment consists of analysis of soil properties, topography, and meteorological data with the aim of comparison with crop requirements. For quantitative assessment of environment suitability, Food and Agriculture Organization of United Nations (FAO) land suitability evaluation, in particular, parametric methods (FAO, 1976; Ir.C.sys, Ranst and Ir.I.Debaveye, 1991) such as stories (Equation 4.1) and square root methods (Equation 4.2) are the most commonly used approaches. In these methods after selection of influencing factors based on a given crop's requirements according to (Ir.C.sys, Ranst and Ir.I.Debaveye, 1991) and experts' knowledge, rating and scoring is conducted according to optimal level of requirement provided by (Ir.C.sys, Ranst and Ir.I.Debaveye, 1991).

$$\mathbf{S\_i = [(A/100) * (B/100) * (C/100) * \dots]} \qquad \text{Equation 3.1}$$

$$\mathbf{S\_i = \ 〚[R]〛\_min * \sqrt{}(B/100 * C/100 * \dots)]} \qquad \text{Equation 3.2}$$

Where Si is the suitability index, R min is the rated value of the most limiting criterion, and A, B, C are the remaining rated values for rest of factors. In these methods, geomorphological suitability, and metrological suitability, are evaluated separately. Integrating geomorphological suitability and metrological suitability, the final biophysical suitability is calculated (Equation 3.3).

$$\mathbf{SI = S\_M * S\_G} \qquad \text{Equation 3.3}$$

Where *SI* is final suitability index. S_M and S_G respectively are metrological and geomorphological suitability indices.

In more recent approaches such as multi-criteria approaches, factors are rated based on experts' suggestions. In a comparison study on different suitability assessment methods conducting by Vasu et al., (2018), multi-criteria method performed better than parametric and stories index methods in land suitability assessment for major cultivated crops in a region with 2.15 km^2 in Mahabubnagar district, Telangana, India. However, performance of multi-criteria method highly dependences on expert knowledge and experience which makes this model not suitable for regional studies with heterogenous environment.

So far, a significant number of studies assessed biophysical suitability of different crops but a very few attempts on AWD suitability assessment. Most of the study conducted on the socio-economic benefit (Alam et al., 2010; Education et al., 2016; Carrijo, Lundy and Linquist, 2017) and environmental advantages (Minamikawa, 2014; Carrijo, Akbar, et al., 2018; Runkle et al., 2019) of the AWD irrigation.

In a study conducted by Megaran et al., (2017) the capacity of Iran's land for sustainable crop production has been evaluated based on very high-resolution spatial data sets of soil properties, topography, and climate. They first evaluated the suitability of the land regarding numbers of soil attributes and geomorphological parameters and then in the next step climate limitation incorporated. Once the suitability index for a grid cell was calculated, the overall suitability of that cell was calculated based on the Liebig's law of the minimum. In this approach the most limiting factor control the crop's growth. The suitability index was then classified into very good, good, medium, poor, very poor and unsuitable classes. Accordingly, about 50% of the existing croplands were identified being in low-quality lands which represents unsustainable practices. In this study a general set of crop requirements have been set which affect the productivity in range of crops, however the authors discussed that there might be some adaptive traits that can grow under not suitable conditions. Also, they raised this point that the results should be interpreted corresponding with the reliability and quality of the data which is source of debit.

Bradford et al., (2017) discussed that future soil moisture and temperature extremes may expand suitable area for rainfed agriculture in drylands. In this study first drylands have been identified based on the mean annual temperature. Then they considered seven variables that represent specific hypotheses about environmental consist of (1) mean annual precipitation; (2) mean annual temperature; (3) mean winter precipitation; (4) weather extremes; (5) water availability when conditions are warm; (6) mean seasonal potential evapotranspiration; and (7) access to economic markets. In the next step authors discussed the chosen statistical model to predict the future distribution of rainfed agriculture. Then considering geomorphology of the area, crop requirements were compared with future precipitation and temperature projections derived from NCEP/CFSR data. Based on their assessment soils' moisture increases with warm conditions which improves the suitability while extreme high temperatures decrease suitability. The regional exception to this trend was is European area, where suitability in temperate dryland portions declines substantially.

Nelson et al., (2015) evaluate the seasonally suitable rice area with the remote sensing and field data in Philippine. The study used seasonal rice area, rainfall, potential evapotranspiration, and soil percolation as the suitability determination factors and conducted intensive field study for sensitivity assessment. The dry season rice area found fully suitable for AWD irrigation and the 60% of the wet season rice area are suitable.

Sander et al., (2017) discuss the country scale AWD suitable rice area in Philippine with remote sensing and climatic data. Based on water supply and loss of paddy rice field principles, the study estimated the water supply as effective precipitation and the field water loss calculated with soil percolation loss and evapotranspiration in the study area. The dry season rice area was fully suitable for AWD application whereas the 30% of wet season rice area of the country is suitable for AWD irrigation implementation.

(Pearson *et al.*, 2018) discus on the socio-economic barrier to adoption AWD irrigation in Bangladesh. The study reviews existing published article on AWD irrigation management in Bangladesh and explore the socio-economic barrier to widely adopt the technology in field level. They mention several barriers like as farm size, farm ownership, water rental system, yield decreasing, farmer education level etc. as the barrier to adopt AWD irrigation in Bangladesh.

The physical environment as well as climatic parameter and socio-economic parameters have a great influence o AWD suitability but somehow there is huge research gap. In this study, we used physio-climatic parameter for AWD suitability analysis over Bangladesh. However, the local climatic condition, physical features determined the suitable area for AWD irrigation. The physical, climatic, and socio-economic parameter with geospatial techniques for AWD irrigation suitable rice area makes this study noble.

3.3 METHODOLOGY

The methodology of the chapter consists of physical, climatic, and socio-economic parameter selection, valuation, sensitivity and collinearity analysis and model building. The outcome of the model will be validated and compared with relevant data and studies. The flowchart of the chapter shows in **figure 3.1**.

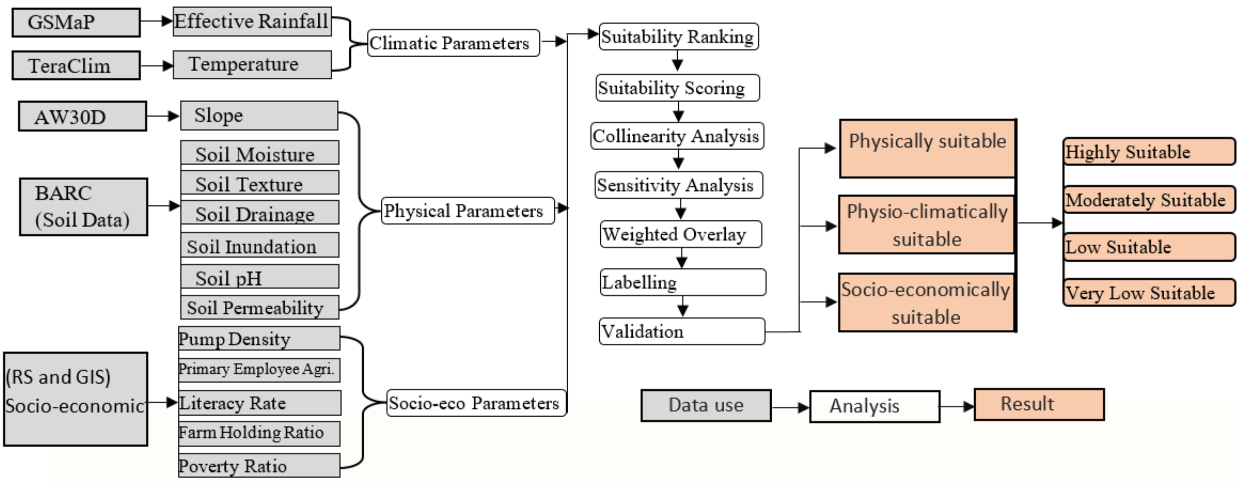


Figure 3.1 Research flowchart for the AWD suitability assessment.

3.3.1 Dataset used

Several data set have been used for this study. Moderate resolution imaging spectroradiometer (MODIS) MOD16A2 derived seasonal rice area map (chapter 2), Global satellite mapping of precipitation (GSMaP) data for effective precipitation estimation (chapter 4), monthly temperature from Terra Climate, and ALOS-AW3D30m data for slope analysis has been used for this study. The remote sensing and associated data derived poverty dataset (Steele et al., 2017) and population density data (Stevens et al., 2015) also used in this study. Besides the remote sensing data, GIS based shapefile data of soil properties like texture; soil drainage, soil inundation, soil pH, soil permeability, soil moisture data from Bangladesh Agriculture Research Council (BARC) have been used (BARC, 1998). The AWD irrigation application field location and water saving data from Rural Development Academy (Bogura) used as model validation. The socio-economic data on irrigation pump density, poverty, literacy rate an others relevant data from Bangladesh Agricultural Research Council (BARC), Bangladesh Meteorological Department (BMD), Bangladesh Bureau of Statistics (BBS), Bangladesh Rice Research Institute (BRRI), CSIRO, FAOSTAT, and relevant literature review from the journal and publications. The data types, spatial and temporal resolution, purposed of the data are shown in **table 3.1**.

Table 3.1 Remote sensing and geo-spatial dataset used this study from different sources, spatial and temporal resolution.

Dataset	Product	Spatial Resolution	Temporal Resolution	Purpose
Rice area	Rice area	1000m	seasonal (2001-2018)	Rice Mapping
Poverty	Wealth Index	1000m	Annual	Poverty
Population	Gridded	1000m	Annual	Population density
GSMaP	Precipitation	0.1 degree	Monthly (2001-2018)	Precipitation
Terr Climate	Temperature	1km	Monthly (2001-2018)	Temperature

ALOS	AW3D30	30m	-	Slope
Soil Properties	Texture, Moisture, Drainage, p^H, Permeability, Inundation	1km	1998	Physical suitability
Pump density	Pump density	-	2015	Irrigation facility
Literacy Rate	Education level	-	2011	Awareness
Primary employment	PEA	1km	2015	Adaptability

3.3.2 Suitability parameters selection

3.3.2.1 Physical parameters

The parameters for AWD suitability assessment are considered based on the (i) favourable condition and (ii) barrier or constraint to favourable condition. The rice paddy cultivated in flooded condition and the slope is an important factor for irrigation facility as well as paddy field water holding capacity.

Slope: The slope is less than 2% is highly suitable for rice cultivation as well as AWD implementation (Rabia et al., 2013). The higher percentage of slope is less suitable for rice cultivation.

Soil texture: Soil texture is the particles size of the relevant content of soil. The particles like sand, silt, clay amount in the soil, whose are influence water and air holding capacity. The silty clay soil is less percolation rate and highly capable to holding water in rice paddy and high suitable for the rice paddy cultivation (Sander et al., 2017).

Soil Moisture: Soil moisture is very important component of microclimate that both directly affects water availability and indirectly influences the temperature and humidity. The high soil moisture is good for rice cultivation (SYS, Ir. C, RANST, E V, DEBVEYE, J and BEERNAERT, 1993).On the other hands with increasing soil moisture, the CH4 uptake decreased (Luo *et al.*, 2013).

Soil pH: Soil pH is the indicators of soil alkalinity or acidity. The soil pH influences the soil nutrient content and methane emission. Methane emission increased with the methane emission (Wang et al., 2010). But the standard pH level is also important for the rice growth and yield maintenance. The pH level less than 4 and more than 8 is very low suitable for AWD irrigation.

Soil drainage: Soil drainage is a natural process which determine the water movement across, through and out of soil the soil as the gravity force. It’s determined the land suitability of a particular crop. The poorly drainage and very well drainage soil is responsible for water logging and dry soil, which are not good for rice cultivation as well as AWD irrigation (Ir.C.sys, Ranst and Ir.I.Debaveye, 1991).

Soil Permeability: Soil permeability is the quality of soil responsible for water and air transmission. It's directly influences the soil percolation loss and seepage loss and effects the irrigation management. Rapid permeability rate response for faster field irrigation water loss (Fields, 2009). The slow permeability is slow percolation rate and good for the AWD irrigation.

Inundation: Land inundation refer the land area by brought water through natural cause as river overflow, heavy rainfall, or artificial causes like dam construction. Bangladesh is a low land area and inundation play very important for rice cultivation. The very low inundated area is not suitable for rice cultivation and as well as for AWD irrigation (SYS, Ir. C, RANST, E V, DEBVEYE, J and BEERNAERT, 1993). Similarly, very high land also not suitable for AWD irrigated rice cultivation.

3.3.2.2 Climatic parameters

Precipitation: The AWD irrigation techniques is a control irrigation system and the irrigation schedule managed as per the necessity of CWR. The irrigation scheduling and water cycle managed with the surface water level and soil moisture observation. As precipitation is a natural phenomenon and interrupt the AWD irrigation schedule. The high precipitation rate area is low suitable for AWD irrigation application (Nelson *et al.*, 2015).

Temperature: The surface temperature is another important factor for AWD irrigation. The soil temperature both directly and indirectly influences the soil pH, evapotranspiration, and methane emission. Moreover, the low temperature and very high temperature is not good for rice production. The soil temperature more than 36º c and less than 16º is not good for rice late tillering to panicle and gap filling stage(Fields, 2009). The soil temperature more than 33 increased the methane emission rate and 26-29 is best suitable for AWD irrigated rice (Arunrat and Pumijumnong, 2017).

3.3.2.3 Socio-economic parameter

Irrigation pump density: Irrigation or water controlling is the key component for AWD irrigation. The benefit of AWD irrigation in terms of water saving and production cost reducing fully depend on irrigation system. In Bangladesh, the irrigation facilities mostly owned by rich farmer and the poor farmers are rent water from the pump owner and pay a fixed amount to the irrigation pump owner whatever, the farmer apply AWD or CF irrigation (Adnan, 2007). Moreover, the government financial subsidise for irrigation enjoyed by the pump owner. As a result, the AWD saving beneficiary are the pump owner. But the instalment of low-cost shallow pump owned by farmer help to control the irrigation facilities (Hussain, 2009). The pump density is considered as socio-economic parameter as the more irrigation pump means the higher suitable for AWD irrigation.

Land holding size: The average farm holding size in Bangladesh by household is 3.67 ha and it's differed from divisional variation 2.76 to 4.92 ha (Mottaleb, Krupnik and Erenstein, 2016). Farm holding size is also strongly related to the farm ownership. In Bangladesh, only 37% of cultivating their own land, 34% pure tenants and 29% cultivating their own plus rented land (Ahmed *et al.*, 2013). The farm size and land ownership are one of the socio-economic barriers to adopt AWD irrigation as it's decreases the farmer technical efficiency (Majumder *et al.*, 2016). In this study, we consider the higher land ownership percentage is better for AWD irrigation application.

Poverty: Poverty means lack of resources or access to the facilities. Most of the farmer are poor and annual income is very low. It's very difficult for them to adopt or experiment new facilities. Due to the poverty, the farmer used microcredit loan from the NGO's during cultivation period (Pearson *et al.*, 2018). The poor farmers have no land ownership and pump ownership as a result the high poverty porn region has less potential to adopt AWD irrigation.

Literacy Rate: Literacy rate or farmer level of education is an important factor to adopt AWD irrigation. The benefit of AWD irrigation depend on the proper application of AWD irrigation. Several studies reported the yield decreased due to the improper application of AWD ((Pearson *et al.*, 2018)). Moreover, the AWD is not only benefited for water saving but also benefited for greenhouse gas emission reduction. To understand the proper implantation and advantage of AWD irrigation, farmers awareness in term of education level asses for this study.

Primary Employment and Population Density Ratio (PEA/PPP): The small farm holding size, landless farmer and poverty are the major constraint for widely application of AWD irrigation. To overcome the problem, community level adaptation and co-operational farming is very effective for AWD adaptation (Rahman and Sander, 2017). As a result, the primary employment in agriculture and the population density is indicator to large community level adaptation of AWD irrigation.

3.3.3 Suitability assessment

This research used suitability assessment framework proposed by FAO (Ir.C.sys, Ranst and Ir.I.Debaveye, 1991). Figure 3.1 shows the flowchart of biophysical suitability assessment. In this context, suitability can be summarized in a generic model of equation 4.4:

$$S = f\ (x\_1,\ 〖x〗\_2, x\_(3, \dots,)\ x\_n) \qquad \textbf{Equation 3.4}$$

Where S is defined as suitability index and x_1, x_2, …, x_n are the factors affecting the overall suitability, such as soil, topology, and climate parameters. To assess the biophysical suitability of a given crop, geomorphological suitability, metrological suitability, and socio-economic suitability are usually evaluated separately. In this study we considered 6 physical factors, 2 climatic factors and 5 socio-economic factors effecting suitability of AWD irrigated rice, considering geomorphological, metrological, and socio-economic characteristics of environment based on detailed literatures review discussed in section 3.2. We find out the best value of the parameters for AWD irrigation. Based on the most suitable value and the physio-climatic condition, we set the relative suitability value. The factors we considered and assign the suitability value range from very low suitable (0) to highly suitable (9). In **table 3.2** shows the parameters and their suitability scored. We estimated three different types of suitability: (i)Physically suitable, Physio-climatic suitable, and (iii) socio-economic suitable.

3.3.3.1 Physically suitability assessment

Although the study area is a small low land, flat physiographic country with very few variations from except the south-eastern and north eastern hilly region. In this study, the ALOS Global Digital Surface Model, ALOS World 3D-30M model (AW3D30) dataset used for the slope analysis (Takaku *et al.*, 2016). The slope properties converted into percentage and reclassified and rescaled according to the suitability. The soil properties; drainage, texture, pH, permeability, and inundation data produced by Bangladesh Agriculture Research Council (BARC) as GIS shapefile format with FAO soil standard(BARC, 1998). The data set reclassifies, resample, and rasterized for the suitability analysis. Then, we assign the weighted value for the physical parameter and analysis the sensitivity for the suitable weighted. Furthermore, the investigated the interrelationship among the physical parameter, we analysis the multicollinearity of the physical parameters and used it for suitability model. **Table 3.2** shows the detail dataset with suitability classes value of the physical parameters.

Table 3.2 Physical parameters- slope ad inundation; and soil properties- texture, permeability, drainage, soil pH data from different sources and scored according to the importance of suitability for AWD irrigation.

Parameters & Scored	Highly Suitable (9)	Moderately Suitable (7)	Low Suitable (5)	Very Low Suitable (3)	Not Suitable (1)
Soil Texture	Silt Clay	Fine Sandy loam	Silt loam	Sandy Loam	Fine Sand
Soil Permeability	Slow	Slow-moderate	Moderate	Mixed	Rapid
Soil Moisture	200-300mm	300-400 mm	100-200mm	>400mm	<100 mm
Drainage	Imperfectly drain	Poor drained	M. well drain	Well drained	Very Poor drain
Soil Inundation	Medium lowland	Medium highland	Low land	Highland	Very highland
Slope	0 – 2%	2-4%	4– 8%	8-25%	>25%
Soil pH	5.5-7.3	7.3-7.8	7.8-8.4	4.0-5.0	<4.0 and >8.4

3.3.3.2 Physio-climatic suitability

The physical parameters are used as a single parameter with the climatic parameter to analysis the physio-climatic suitability. This study used TerraClimate dataset for all temperature related parameters with 2.5 arc minutes spatial resolution (Abatzoglou *et al.*, 2018) and Global Satellite Mapping of Precipitation (GSMaP) with 10 km^2 spatial resolution for two precipitation related parameters (Kubota *et al.*, 2006). All meteorological parameters were rescaled into 1000 m spatial resolution. The physical parameters are annual, but the climatic parameters are monthly averaged. To keep the harmony between the physical and climatic parameter, we prepared the decadal (2008-2017) monthly averaged climatic dataset. The monthly climatic data prepared the seasonal composite based on the seasonal rice calendar of the study area. Next, the physical and climatic parameters and overlay as seasonal composite. Finally, the weighted value assign for the physio-climatic parameter based on the sensitivity analysis. **Table 3.3** shows the physio-climatic parameter and their suitable range with three different set of weighted value for sensitivity analysis.

Table 3.3 Climatic parameters- effective precipitation and temperature data and scored according to the importance of suitability for AWD irrigation.

Parameters & Scored	Highly Suitable (9)	Moderately Suitable (7)	Low Suitable (5)	Very Low Suitable (3)	Not Suitable (1)
Effective Precipitation	200-300mm	300-400mm	400-500mm	500-800mm	>800mm
Temperature	27-29 ºC	29-31 ºC	31-33 ºC	<27 ºC	>33 ºC

The physical parameters and climatic parameters are combinedly used for physio-climatic suitability analysis. To fix the weighted value for the suitability model, we analysis the sensitivity of the parameters. We used different set of weighted value and found significant result from the set A, B, and C value rang (**table 3.4**).

Table 3.4 The physio-climatic parameter weighted values for the sensitivity analysis of AWD suitability classes.

Case	Effective Precipitation	Temperature	Physical Parameters
A	50	20	30
B	40	20	40
C	50	30	20

3.3.3.3 Socio-economic suitability assessment

The socio-economic parameters are selected and collected from different sources of data. The poverty dataset is collected from world bank report published per head income count poverty situation in Bangladesh. The poverty dataset used the remote sensing, statistical and mobile detail call record (CDR) dataset to estimate the poverty in 1 km spatial resolution based on the income level in 2015 (Steele *et al.*, 2017). The per pixel population (PPP) dataset also used remote sensing data and associated dataset to produce population density in 1 km grid scale (Stevens *et al.*, 2015). The primary employment in agriculture (PEA) data collected from Bangladesh Bureau of Statistics (BBS) national household survey dataset. The statistical dataset in smallest administrative level (Upazilla) and converted it into 1km spatial resolution geospatial data. The PPP and PEA dataset blended it, to prepared PPP and PEA ration dataset to use for the people engagement in agriculture density assessment. The irrigation pump density dataset from minor irrigation survey data from BBS, 2015 and the literacy dataset also collect from BBS census report. The irrigation pump density and literacy rate estimated in Upazilla level with geospatial techniques and produced 1 m spatial resolution dataset for socio-economic suitability assessment. All the parameters assign appropriate suitability score based on literature review, expert opinion, and prior knowledge (**Table 3.5**). The weighted value assign after sensitivity and multi-collinearity analysis. Furthermore, the FAO land evaluation for rice crop is modified for the AWD irrigation suitability (SYS, Ir. C, RANST, E V, DEBVEYE, J and BEERNAERT, 1993). In this study we analysis AWD suitability with physio-climatic parameters as four suitable classes; High Suitable, Moderately Suitable, Low Suitable and Very Low Suitable. Finally, the seasonal rice area map (Chapter 2) used for suitable rice area extraction.

Table 3.5 Selected socio-economic and the assign scored according to the importance of suitability for AWD irrigation.

Parameters & Scored	Highly Suitable (9)	Moderately Suitable (7)	Low Suitable (5)	Very Low Suitable (3)	Not Suitable (1)
Pump density	>40	30-40	20-30	5-20	0-5
Farm holding size	>1.30	1.20-1.30	1.15-1.20	1.10-1.15	<1.15
Literacy rate	66-84	55-66	45-55	34-44	24-34
Poverty	0-120	120-150	150-180	180-210	>210
PPP/PEA	>10	2-10	0.15-2	0.08-0.15	<0.08

3.3.4 AWD suitability validation with field data

The result from the AWD suitability analysis compared with the field data. The AWD irrigation implemented 87 rice paddy site data over the study area collect from Rural Development Academy (RDA) reported data. The field location and the water use data set used for site specific water saving dataset. The AWD field location with water save data extract from the AWD suitable class map. The AWD water saving and suitable class are compared to assess the model performance.

3.4 RESULTS AND DISCUSSION

3.4.1 Physical suitable rice area

The physical parameters sensitivity analysis and assign the score according to the influence on the model result. The physical suitable parameters collinearity shows that the parameters are individual and negligibly correlated with each other. The highest correlation between soil inundation and permeability and other parameters are almost independent (**table 3.6**). The variance influence factors (VIF) analysis shows that the VIF value is less than 2. The VIF value of less than 4 is a very good independent variable for predicted variables (Murray *et al.*, 2012). Furthermore, the sensitivity result of the physical parameter illustrates the less sensitive to the suitable classes and equal influence have been selected.

Table 3.6 The multicollinearity matrix for the physical parameters with the variance inflation factor (VIF).

Varriables	S_Texture	S_Slope	S_ pH	Permiabili	S_Moisture	_Inundatio	S_Drainage	VIF
S_Texture	1							1.143126
S_Slope	-0.01615	1						1.189225
S_ pH	0.168982	0.250132	1					1.203106
S_Permiab	0.224727	-0.12993	-0.20068	1				1.243601
S_Moistur	-0.04852	0.100988	-0.09427	-0.05218	1			1.100462
S_Inundati	-0.08564	-0.29971	-0.28334	0.300281	0.215257	1		1.343375
S_Drainag	0.100604	0.108664	0.096933	-0.03871	-0.04342	-0.09162	1	1.029754

The physically suitable 7 factors used for this study. The sensitivity analysis result shows that the equally weighted value determined very high suitable area

50.56% whereas, the 70% weight-imposed parameters determined highly suitable area fluctuated **figure 3.2.** The soil slope and drainage parameters are higher sensitive for highly suitable area, 50.48% and 49.63% respectively. Soil inundation and soil permeability exposed the less sensitive in highly suitable area case, 40.02% and 47.38%, respectively.

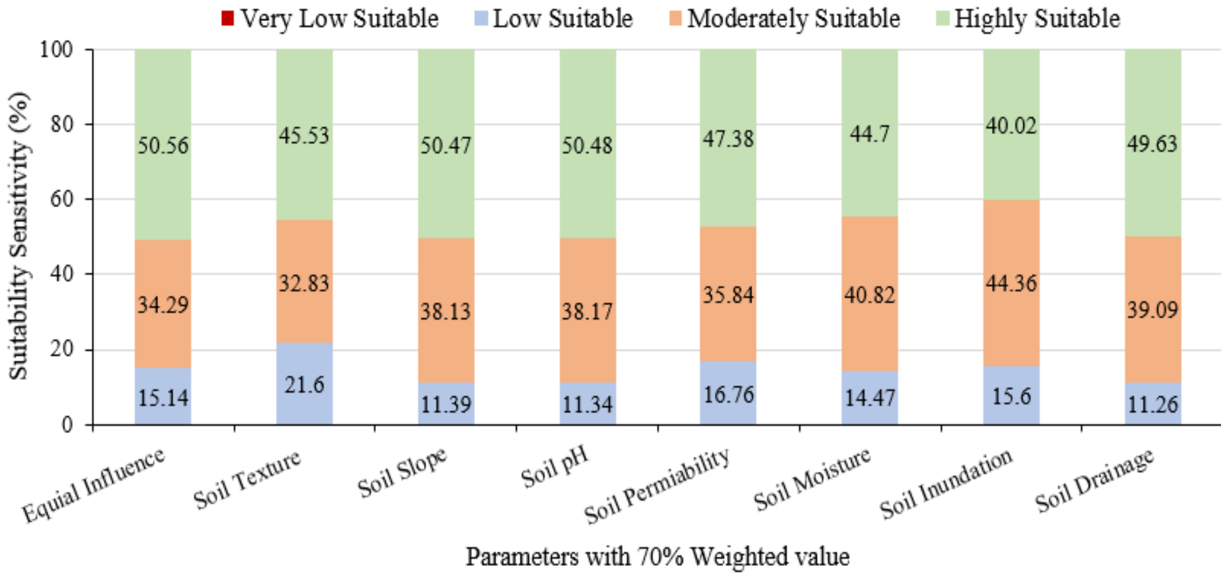


Figure 3.2 Sensitivity analysis result of the physical factors for AWD suitability assessment.

The physically suitable AWD irrigated result shows that the central northern and central western part of the country are the highly suitable AWD irrigated rice area. The comparatively high elevation, dominant silty clay soil, imperfectly drainage soil and comparatively lower moisture induced the region as physically high suitable AWD irrigated rice area. The southern part and the eastern part of the country are low suitable rice area. The southern coastal area are very low inundation and fine sandy soil types influenced the suitability. The south western part of the country is the mountain region is mountain region with highly drainage soil, and soil texture makes the region low suitable rice area (**figure 3.3.a**). The overall highly suitable rice area in the study area is 39% of the total rice area. The 60% of total rice area is moderately suitable area for the AWD irrigated rice and only 1% area is low suitable (**figure 3.3.b**). In conclusion, physically the stud area is suitable for the AWD irrigation implementation.

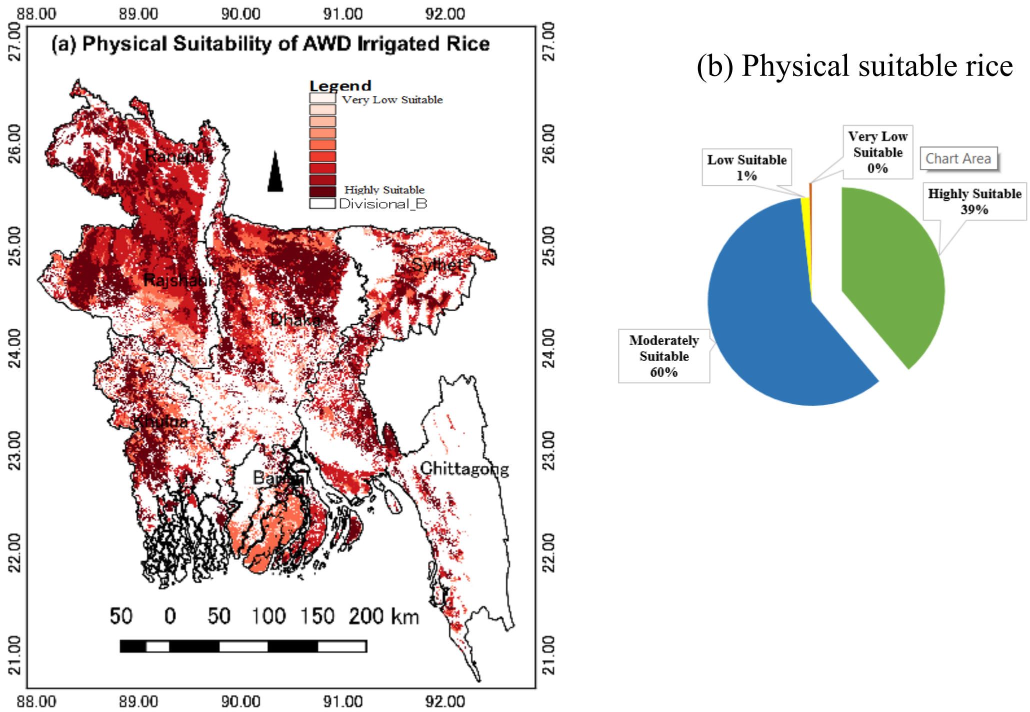


Figure 3.3 (a) Physical alternative wetting and drying (AWD) suitable rice area distribution based on the physical properties over Bangladesh; (b) AWD suitable rice area statistics based on the physical parameter.

3.4.2 Physio-climatic suitable rice area

The sensitivity of the three different parameters for physio-climatic suitability shows that the precipitation is the most influenced parameter for the physio-climatic suitability (**table 3.7**). In the set A and C case the precipitation weighted value is constant and case B the value decreased, and the suitability class also changed in B case. The physical parameter is the moderately sensitive and temperature is the less sensitive for the physio-climatic suitability. As a result, we use the set A value for the physio-climatic suitability determination for this study.

Table 3.7 Physio-climatic parameters sensitivity result of three different set weighted value and suitability of Boro, Aus, and Amon rice growing season

Rice Season	Boro Rice Area (%)			Aus Rice Area (%)			Amon Rice Area (%)		
Suitability/Cases	A	B	C	A	B	C	A	B	C
Highly Suitable	79.312	69.069	87.375	0.327	8.471	0.218	0.997	0.966	0.023
Moderately Suitable	20.625	30.723	12.443	15.571	23.680	8.300	50.444	62.040	38.882
Low Suitable	0.061	0.206	0.181	71.465	55.457	64.407	47.364	35.407	56.420
Very Low Suitable	0	0	0	12.635	12.389	27.073	1.193	1.585	4.674

The physical and climatically suitability parameters are overlay and prepared the physio-climatically suitable area. As the country is physically suitable for AWD irrigation from this model. But the seasonal weather condition changed the suitability classes over the area. The seasonal suitability in case of boro rice shows that the highly suitable in terms of physio-climatic suitability. The central-north and western part of the country are highly suitable. Some part of this region exposed comparatively low suitable as the region is dominant wet land (Chalan beel) in the country. In case of amon rice shows the moderately suitable and the distribution demonstrated the same as boro rice season. The aus rice season exposed as the lower suitable AWD irrigated rice area. **Figure 3.4** shows the physio-climatically suitable rice area distribution over the country.

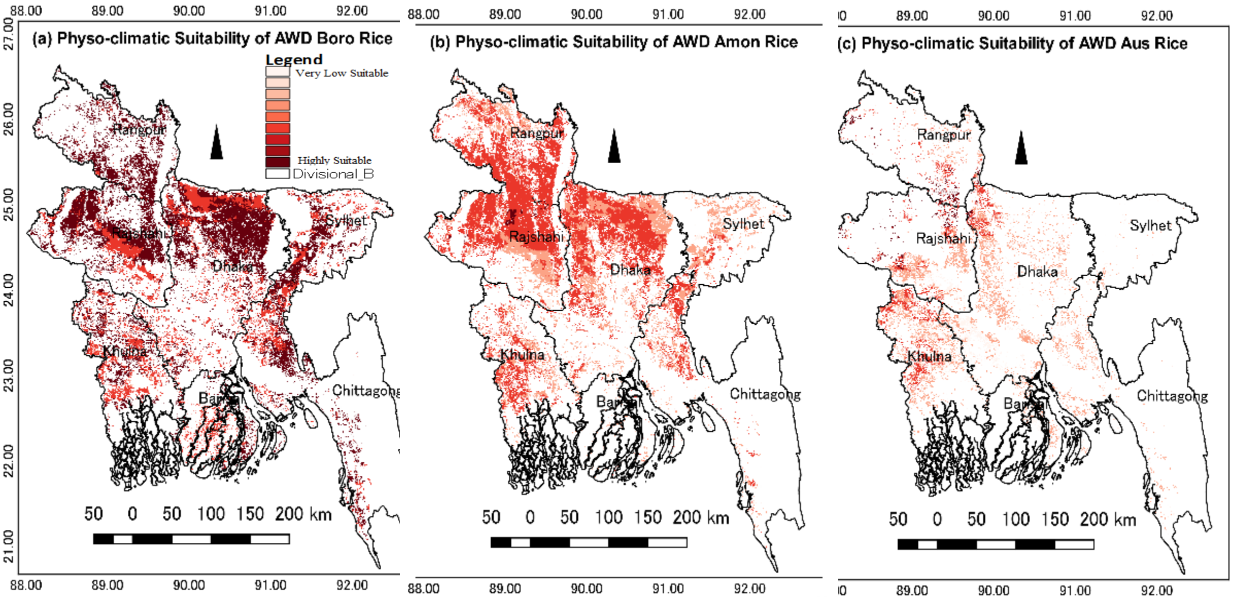


Figure 3.4 The physio-climatic suitability classes of AWD irrigated (a) boro, (b) amon and (c) aus rice paddy.

Statistically, 80% of total boro rice growing are is highly suitable for the AWD irrigation in terms of physio-climatic suitability, whereas 20% of the area moderately suitable and there is no low and very low suitable area. The dry season with less rainfall and totally irrigated condition makes this season as highly suitable. The 7% of total amon cultivated area is highly suitable and, 33%, 38% and 22% area are moderately, low and very low suitable area, respectively. The amon rice season is higher rainfall season with dominant supplementary irrigated area are the probable causes of this suitability. The aus rice season is the least suitable season for the AWD irrigation application. There are only 1% area is highly suitable and 11%, 56% and 32% of the area are moderately, low and very low physio-climatic suitable area. The details suitable area results for boro, amon and aus rice area shown in **figure 3.5**.

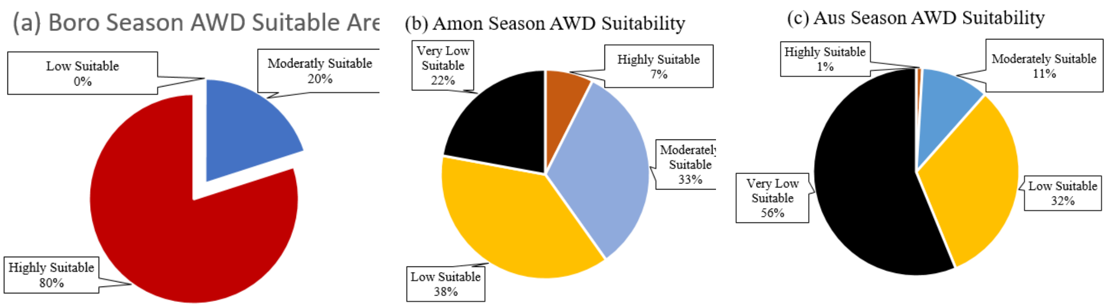


Figure 3.5 The physio-climatic suitability class statistics of AWD irrigated (a) boro, (b) amon and (c) aus rice paddy.

3.4.3 Socio-economically suitable area

The socio-economic parameters sensitivity result shows the various influenced result on the suitability classes. The suitable class influence illustrated 4.76% to 8.72% on the highly suitable class. The farm holding size, PPP/PEA ratio and the irrigation density showed the higher influenced on the highly suitable class (**figure 3.6**). The equally weighted parameter demonstrated the sensitivity on highly, moderately, and low suitable classes are 9.21%, 47.64% and 43.1%, respectively. In this study we used the equally weighted parameters for this study for suitability analysis.

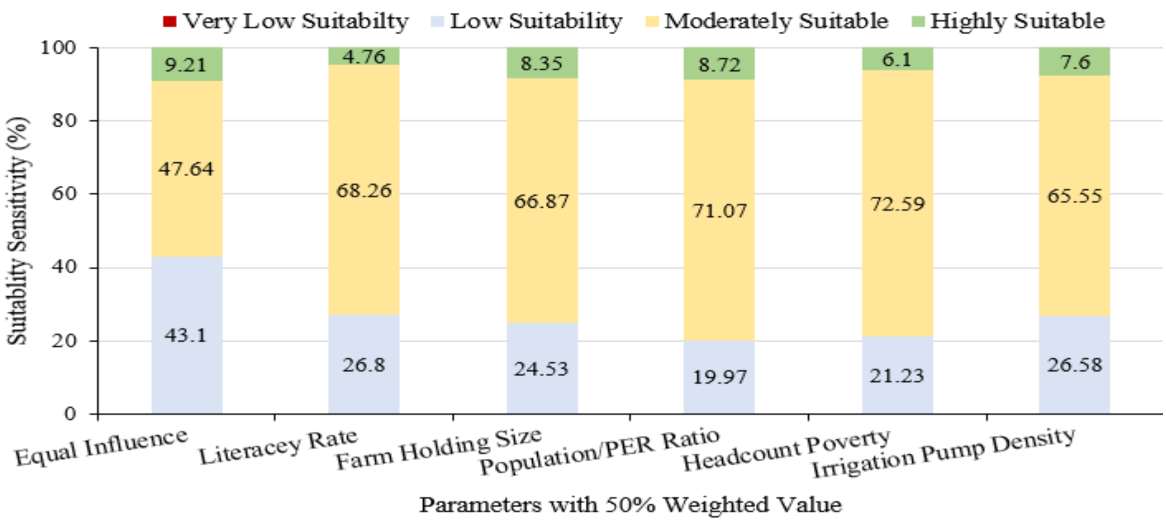


Figure 3.6 Sensitivity of the socio-economic parameters on the AWD suitable classes.

The socio-economic suitable parameters collinearity shows that the parameters are individual and negligibly correlated with each other. The highest correlation between irrigation pump density and farm holding size, and between PPP/PEA ratio and poverty among the parameters, and other parameters are almost independent. The variance influence factors (VIF) analysis shows that the VIF value is less than 2 (**table 3.8**). The VIF value of less than 4 is a very good independent variable for predicted variables (Murray *et al.*, 2012). Furthermore, the sensitivity result of the physical parameter illustrates the less sensitive to the suitable classes and equal influence have been selected.

Table 3.8 The multicollinearity analysis result of the socio-economic parameter for sensitivity analysis.

Varriables	IPD	FHS	terarcy Rat	Poverty	PPP/PEA	VIF
IPD	1					1.111081
FHS	0.236082	1				1.082068
Literarcy R	0.089173	0.11066	1			1.056362
Poverty	-0.16322	-0.13103	0.142715	1		1.138826
PPP/PEA	-0.11076	-0.00778	-0.14016	-0.2435	1	1.099614

The socio-economic parameter determined suitable area foe AWD irrigation in Bangladesh showed variation from physical and physio-climatic suitable rice area. Only 2.43% of total rice area is highly suitable, whereas the moderately, low and very low suitable area are 55.19%, 28.43% and 13.95%, respectively (**figure 3.7**). But physically the country shows 80% rice area is highly suitable for AWD irrigation application.

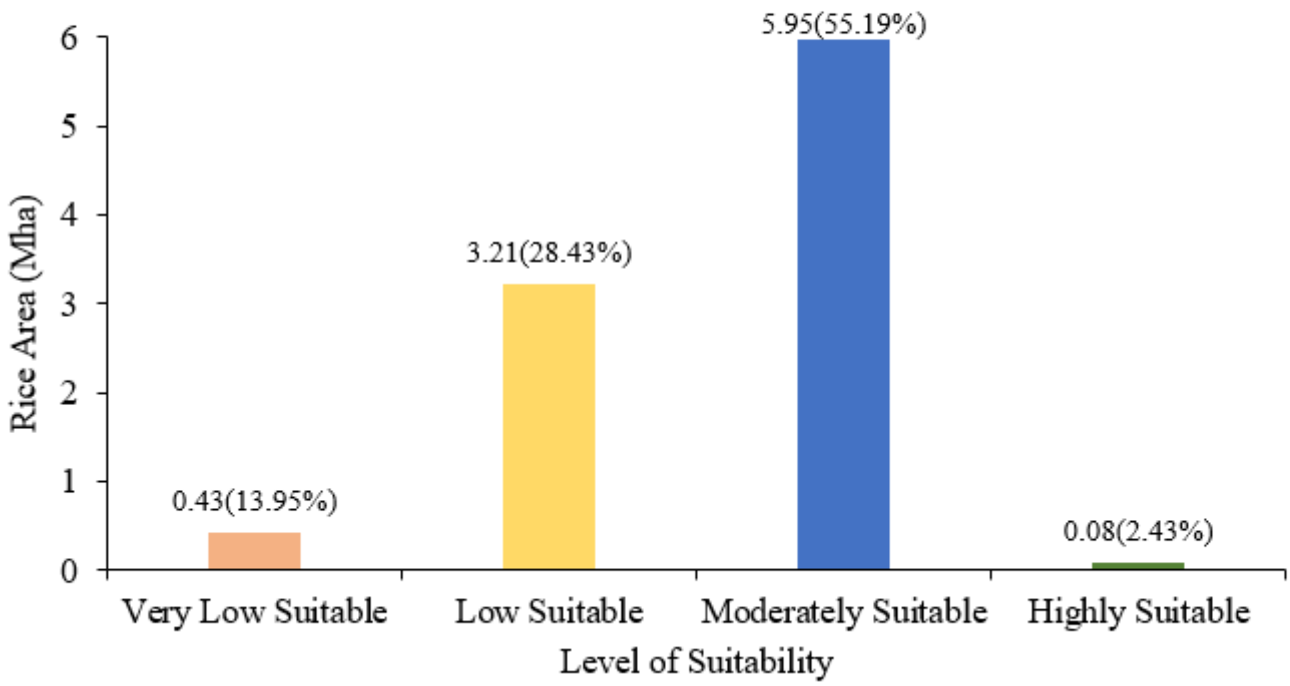


Figure 3.7 Socio-economically highly suitable, moderately suitable, low suitable and very low suitable AWD irrigated rice area in Bangladesh.

The central north-western and central-northern part of the country exposed comparatively higher suitability. The area as boro-amon double rice pattern is the dominant rice cropping pattern. A very small area in central northern part is highly suitable for AWD irrigation. The probable causes of the suitability area-comparatively rice farmer, literacy rate, and the irrigation facilities. The others part of this region exposed comparatively moderate suitability. Although the similar cases but the poverty rate is higher in this region makes as comparatively moderate suitable area for AWD application. The most northern art and the south-eastern part is the comparatively low suitable for the AWD irrigation implementation. The low irrigation facility, PPP/PEA ratio induced the region as such suitability rate. In **figure 3.8** shows the socio-economically AWD irrigation suitable area distribution over the country.

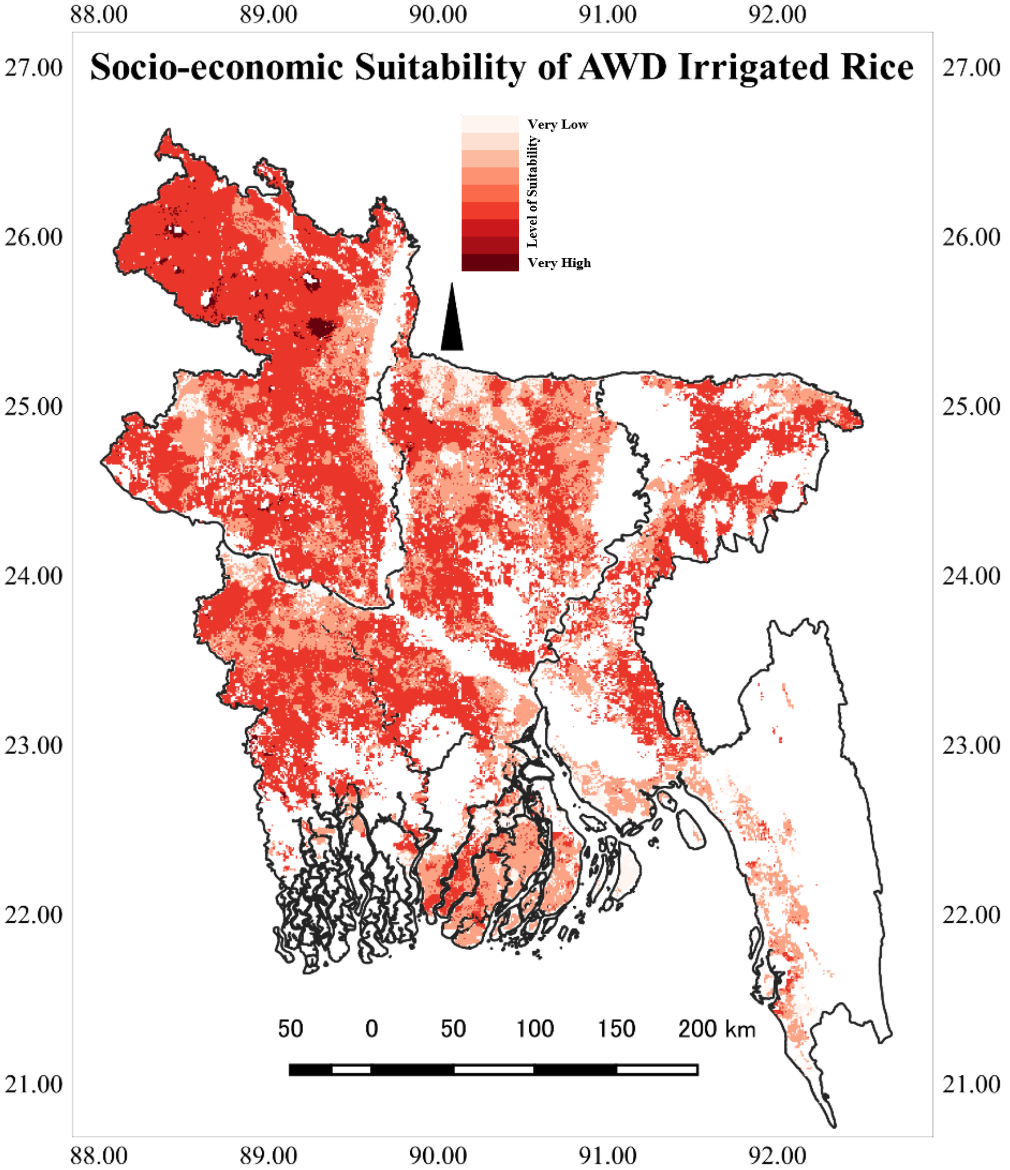
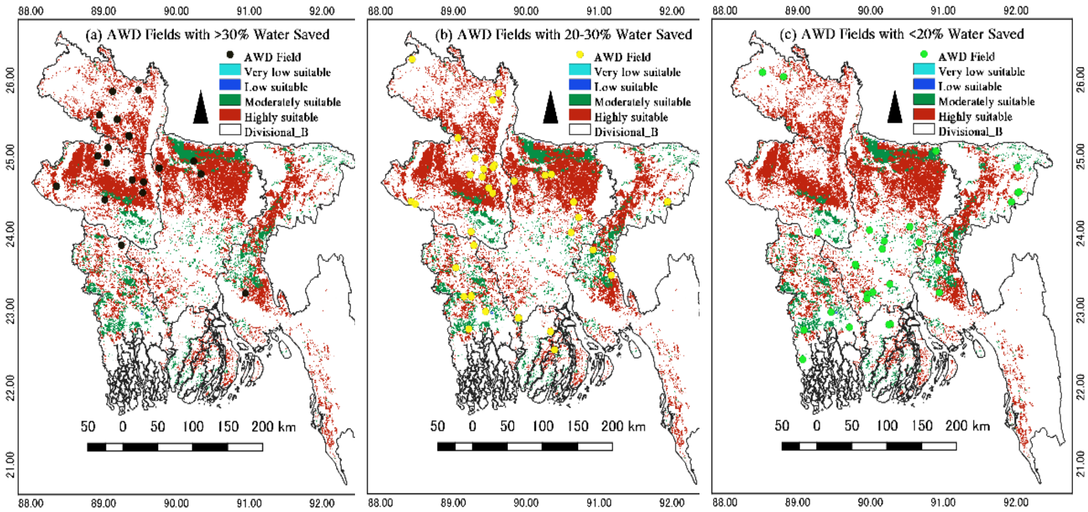


Figure 3.8 Socio-economical suitability of AWD irrigated rice area classes in the study area.

3.4.4 Suitability classes validation

This study determinate AWD suitable area has been compared with the field data. The AWD irrigated rice data on water use, crop height, and yield have been collected from Rural Development Academy (RDA). All together 86 field all over the country have been applied AWD irrigation under RDA supervision. In Bangladesh, the AWD irrigation applied only in the Boro rice season and this data are collected in 2018, Boro rice cultivation season. The data are collected from the AWD and non-AWD irrigated rice field. The water used in AWD field and non-AWD irrigated filed compared and calculated the water saving from the AWD irrigation application. Most of the AWD field with higher water saving rate are shows in the central and northern part of the country (**figure 3.9**). The water saving result distribution shows the harmonic trend with physio-climatic and socio-economic suitable are classes from this study.



Water Saved	Highly Suitable	Moderately Suitable	Low Suitable	Very Low Suitable	Total Field
WS> 30%	19	1	0	0	20
WS= 20%- 30%	53	5	0	0	58
WS < 20%	22	3	2	0	27

Figure 3.9 AWD irrigated suitable rice area model validation with field data, the water saving amount and AWD irrigated site in study area; (a) AWD field with >30% water saving, (b) AWD field with 20-30% water saving, (c) AWD field with <20% water saving in the study area.

Among the 86 field, the 20 filed save more than 30% water, 58 field save 30-20% water and 8 field save less than 20% water compared with non-AWD irrigated rice filed. Amon the >30% water saving field (20), 19 field area within the highly suitable AWD irrigated area and 1 field in moderately suitable area. The 20-30% water saving field (58) are also follow the suitability pattern, only 5 field are in moderately suitable area and rest of them are in highly suitable area. There are 8 less water saving (<20%) filed, 6 field are in moderately suitable area and 2 field in highly suitable area. In figure 3.10 illustrated the AWD water saving field with the AWD suitable classes all over the country. The highly suitable and water saving field are mostly located in the north-wester part of the country. The less water saving filed are mostly located in moderately suitable area and south-eastern part of the country. Although, the AWD irrigation water saving depends on the intellectual irrigation management, but our methodology applied suitable classes and the field data shows a very good agreement.

3.5 CONCLUSION

In this chapter we aimed:

1. Physically suitability of AWD irrigated rice,
2. Physio-climatically suitable area for AWD irrigated rice,
3. Socio-economic suitable of AWD irrigated rice area,
4. Validation and comparison of model result with relevant sources of data.

To achieve the objective 1, the physically suitability analysis with the slope and soil properties data and weighted overlay model. The result demonstrated the highly suitable area is 39% and moderately suitable area 39% whereas only 1% of total rice area is low suitable and there is no very low suitable rice area.

In case of objective 2, the physio climatic AWD suitable rice area fluctuated among the season in the study area. The boro rice season is the most suitable for AWD irrigation application, where 79% of total boro area is highly suitable. The amon rice area conditionally suitable for AWD irrigation implantation as the highly suitable area is 1% but the moderately suitable area is 62% of total amon rice cultivated area. The aus rice season is low suitable for AWD irrigation application as there are no highly suitable area, only 16% area moderately suitable and dominant low suitable are 79% of total aus rice area.

The socio-economic suitability analysis in objective 3, the 2.43% of total rice growing area is highly suitable, 55.19% moderately suitable, 28.43% low suitable and 13.95% of total rice growing area is very low suitable.

The AWD suitability classes compared with the AWD water saving field data. With the estimated suitability level, the AWD water saving rate observed very good agreement. Among the 30 sites with water save more than 30%, 29 field plots are located inside the highly suitable area and 58 plot water saving with 20-30% and 53 plots are inside the estimated moderately suitable rice area.

As remark, (i) although the physically and physio-climatically suitable area for AWD irrigation implementation is very high but the socio-economically suitable area is very low. There is huge potential to increases the socio-economic suitable area through the policy making and implementation. (ii) The physio-climatically suitable rice area varied and boro rice area is highly suitable for AWD irrigation and amon rice area is conditionally suitable for AWD irrigation, The boro rice area is already under AWD application but there is also potential to apply in amon rice area as the amon season is the largest rice producing season in Bangladesh.

The output from this chapter will be used for chapter 4 and 5. The physical suitable, physio-climatic suitable and socio-economically suitable rice area varied from each other and among the rice growing season. As a result, we proposed a scenario based on the different percentage of total rice area under AWD irrigation like- (i) Total rice growing area under CF irrigation, (ii) Total rice growing area under AWD irrigation, (iii) 70% of total rice growing area under AWD irrigation, (iv) 50% of total rice growing area under AWD irrigation, and (v) 30% of total rice growing area under AWD irrigation. Based on the scenario, we proposed CWR save (chapter 4) and methane emission reduction (chapter 5) scenario under AWD irrigation.

Chapter 4: Crop Water Requirement Assessment for AWD and CF Irrigation and Irrigated Rice Area Mapping

4.1 CHAPTER OVERVIEW

In this chapter we first discuss the background of the study and previous attempts estimating the CWR for AWD and Non-AWD irrigated rice paddy and irrigated rice area map using different RS data in section 4.2. Then we describe the adopted methodology in detailed section 4.3. In section 4.4 results and section 4.5 is discussion followed by conclusion in section 4.6.

4.2 INTRODUCTION

4.2.1 Background of the chapter

Actual CWR assessment is the most important part of the irrigation water management. CWR is the depth of water (mm) needed to meet the water demand of a particular crop consumed through evapotranspiration (ET) in a disease free, non-restricted soil and water condition to achieve the full potential production under the given growing environment (L.S.Pereira, 2013). The CWR term is applied for define the irrigated or rainfed crop. CWR differs from crop to crop as well as season to season. The rice paddy is one of the higher waters consumed crop and cultivated under fully watered condition. The amount of water uses for fulfilment of crops CWR as irrigation or rainfed. The irrigated rice paddy area in Bangladesh increasing over the time. In irrigated rice case the CWR differ from AWD irrigation to CF irrigated rice paddy field. It is already proven that the AWD irrigated rice require less water than the continuous flooded irrigation. To CSA rice paddy cultivation, the CWR assessment for irrigated rice is very important.

Irrigation management for rice paddy cultivation is very crucial for socio-economic and environmental perspective. Irrigated agriculture, which currently shares ~40% of the global crop production, is an important contributor to augment world food production, especially in semi-arid and arid regions (Prasad S Thenkabail *et al.*, 2009; Ambika, Wardlow and Mishra, 2016; Meier, Zabel and Mauser, 2018). In Bangladesh, almost 60% of total agricultural land is equipped for irrigation and 80%

of irrigated water source is groundwater pumping. The irrigation practices development leads green revolution and increased food production drastically. The Irrigation developments and yield improvement have been sustained by the construction of surface water use and shallow and deep tube-well irrigation pump also increased from 0.2 million to 10 million from 1985 to 2012. Currently, agriculture consumes more than 84% of the withdrawal groundwater (Siebert *et al.*, 2015). Annually, the amount of groundwater pumped for irrigation is increasing and the freshwater availability decreasing for others water use. As a result, the sustainable rice production with less water is a key concern for CSA. To investigate the irrigation water demand and management, the CWR assessment for different types of irrigated rice is the key content of the following chapter.

4.2.2 Objectives

CWR for AWD and CF irrigated rice and irrigated rice area mapping with CWR is the main objectives of this chapter. The water saving from AWD irrigated rice paddy also will be investigated in term of irrigated rice area. Moreover, the details objectives of this study are-

(i) To estimate the rice CWR for AWD and CF irrigated rice with MOD16A2 ET data and local climate adjusted crop co-efficient value from 2001- 2018,

(ii) To evaluate the benefits of AWD irrigation in terms of water saving,

(iii)To mapping the seasonal irrigated rice area with MOD16A2 and GSMaP data from 2001-2018, and

(iv) validation and comparison the result with relevant sources of data and studies.

4.2.3 Literature review

There has been significant number research attempt to estimate the rice CWR. The food and agricultural organization of United Nation (FAO)-56 manual is one of the most common approaches to estimate CWR in different crop(Allen *et al.*, 1998a). Following the FAO guideline, CROPAWT model is one of the most applied application for crop water requirement calculation, irrigation water requirement, irrigation scheduling of different crop (Luo, Xia and Yang, 2015). Several studies calculated the CWR for irrigated rice by using crop evapotranspiration and different Kc values as a function of local climatic condition and management practices of the study area (Ewaid and Abed, 2019). The FAO CROPWAT model incorporates methods for reference crop evapotranspiration and crop water requirements and allow the simulation of crop water use under various climate, crop, and soil condition. In CROPWAT model the penman-Monteith model have been used for crop evapotranspiration (Luo, Xia and Yang, 2015), lysimeter and filed data, surface energy balance algorithm for land (SEBAL), surface energy balance system (SEBS), METRIC, ALEXI are common methods to crop evapotranspiration estimation (Calera *et al.*, 2015).

Hossain *et al.*, (2017) evaluate the crop water requirement with historical climate data and FAO-CROWAT model for amon and boro rice paddy in western part of Bangladesh. The study used FAO Penman-Monteith method for reference ET and USDA method for effective precipitation estimation. The result found that the crop water requirement for boro 473-558 mm and irrigation water requirement 1212 mm. The CWR and IWR varied based on transplanting date, soil type, effective precipitation, and management practices.

Gautam and Sarkar, (2018) studied used the FAO model and monthly precipitation data and irrigation pipe network for crop water requirement and irrigation cost estimation for rice paddy in Jaharkhand and Bihar in India. The crop water requirement in the study area amounted to 7.22 lakh m3, of which Phase I is 6.12 lakh m3 and Phase II is 1.2 lakh m3 and the cost of annual surplus irrigated water for rice is 4.32 lakhs for an irrigation area of 1.284 km2 (phase I), and the same is INR 0.84 lakh for 0.252 km2 (phase II).

Besides this, the remote sensing techniques have been used as successfully and fruitfully for ET and Kc estimation. The Landsat-5 and DEIMES-1 data and leaf area index (LAI), surface albedo, weighted differentiated vegetation index (NDVI) have been used for crop ET and Kc estimation and reported CWR 2.13 mm/day (Neugebauer, 2013), remote sensing data with Penmen-Monteith equation (Neugebauer, 2013) have been used.

Kumari, Patel and Khayruloevich, (2013) investigates remote sensing-based approach of large-area crop water requirement using vegetation indices as proxy indicator of crop coefficient (Kc) in low land rice and Wheat double cropping pattern using multitemporal IRS P6-AWiFS data integrated with meteorological data following FAO-56 approach. Monthly biophysical parameters viz., fractional canopy cover (fc) and water scalar factor (Ws) were derived from spectral indices to adjust Kc for the different growth stages in rice- wheat system. The results showed that after including Ws with fc for rice, degree of fit (R2) has been significantly improved from 0.72 to 0.94 for Kc estimation of rice. Satellite derived Kc has captured the effect of phenology and management practices in study area. The estimated crop water requirement was 241.66, 531.34, 440.86 and 192.63 M ha for rice and 127.43, 135.77, 305.55, 262.84 and 204.5 M ha wheat at various growth stages.

Sakti and Takeuchi, (2018) evaluate the global crop water requirement integrated the various remote sensing data and CROPWAT model. The study used MOD13A2 based crop intensity and crop calendar for estimated Kc with CROPWT; and the MOD16A2 for ET to estimate the crop water requirement. The study investigated the long term (2001-2005, 2006-2010, 2011-2015) crop water requirement for global rice paddy.

The Crop coefficient is the fractional value of actual and reference evapotranspiration and whereas the is the reference evapotranspiration crop is well irrigated grass, 12 cm height, fully shading on the ground, and disease-free environment. The CWR have been reported as 400 to 500 mm (wet season) and 600 to 700 mm (dry season) for the Philippines (Tabbal *et al.*, 2002), 540 to 730 mm in the Punjab (India) (Chahal *et al.*, 2007). Several publications have reported crop coefficients (Kc) for rice as the following values for permanently flooded rice: 1.05, 1.20 and 0.9 to 0.6, during the initial, mid-season, and late-season stages, respectively (Allen *et al.*, 1998a) and 0.78 and 1.58 during the mid-season stage for transplanted paddy rice in nine regions of Korea with total growing season lengths of 100 to 110 days after transplanting (Yoo, Choi and Jang, 2011). Most of the study for CWR used remote sensing data and consider the local climate condition, soil parameters and crop types but management or cultivation practices have not been considered. The FAO also reported that due to the frequency of wetting and irrigation the crop Kc values varied from 1 to 1.10-1.30 (Allen, 1998). In this study, we used remote sensing derived ET data and CROPWAT based Kc values with considering the management practices in terms of AWD irrigation practices for the rice crop water requirement estimation. The main objective set for this study is CWR for rice with AWD irrigation practices and without AWD irrigated rice in Bangladesh.

Irrigated area mapping with remote sensing data is challenging due to the almost similar spectral reflectance from irrigated and non-irrigated rice phenology. Most of the case the irrigated area mapped based on the annual questionnaires survey, filed observation, interviews, expert opinion and statistical data. The statistical department of United Nations Food and Agriculture organization (FAOSTAT), country wise national census report used similar traditional method for irrigated and rainfed rice area mapping. The global map of irrigated area (GIMA5) used census based statistical data and produce irrigation equipped area with 5 arc-minutes resolution from 2000-2000.

Portmann, Siebert and Döll, (2010) evaluate the monthly global irrigated rainfed crop area (MIRCA2000) with national and sub-national level reported statistical data set for 26 crop classes in 2000. The result found that the rice paddy is the crop with largest harvested irrigated area, 33% of global crop production and 44% of total cereal production comes from irrigated agriculture. Similar types of dataset showed irrigated area increased 1990-2005 (Siebert *et al.*, 2015). But the statistical data, the crop types, growing season, local weather condition dynamic, existing crop condition are pay less attention. The satellite images based remote sensing application is one of the efficient tools for irrigated rice area mapping. There is a significant number of researchers have been conducted and still going on for irrigated rice area mapping with remotes sensing data over the globe. The long-term phenology analysis, soil moisture and temperature analysis, and the remote sensing based various indices analysis becoming popular for irrigated area mapping.

Salmon *et al.*, (2015) estimated the global Rainfed, irrigated, and paddy croplands (GRIPC) with integrating the statistical surveys, gridded climatic and remote sensing dataset. The study used MODIS and associated dataset with supervised classification and found 66 M ha irrigated paddy rice area.

Another study by Thenkabail *et al.*, (2009) applied multiple remote sensing data AVHRR, MODIS NDVI, JERS SAR associated with climatic data, google earth, and intensive field information to estimate the Global irrigated area map (GIAM). With the phenology indices and ground truth data they used spectral matching techniques (SMTs) to estimate the irrigated area in terms of annual irrigated area and equipped for irrigated area. The result shows overall accuracy 79-91% with the omission error does not exceed 21% and commission error less than 23%.

Ambika, Wardlow and Mishra, (2016) mapped high resolution irrigated area map from 2000 to 2015 over India with remotely sensed data. The study used 250 m spatial resolution MODIS Normalized Difference Vegetation Index (NDVI) dataset with the 56-land use land cover data for all agro-ecological zone in the study area. The result compared with the national statistical and ground survey data and found satisfactory accuracy with R^2 value 0.95.

In regional scale Gumma *et al.*, (2014) estimate the irrigated and rainfed irrigated rice area with satellite data and intensive field data in Bangladesh. The study used MODIS 500-m and 8 days composite NDVI dataset with spectral matching techniques. The result compared with national and sub-national and statistical data and found very good agreement. Similarly, the AQUACROP model, MODIS data, Landsat data with filed data and statistical data have been used for annual irrigated rice area mapping (Mosleh, Hassan and Chowdhury, 2015). Most of the study have been conducted on the existing field condition, it's didn't consider the sources of irrigation and climatic conditions. In this study, we consider the vegetation condition, crop water requirement and sources of irrigation water.

4.3 METHODOLOGY

This study consist of (1) Evapotranspiration estimation from MOD16A2; (2) Crop coefficient calculation with local climate adjusted parameters, (3) Effective precipitation estimation from GSMaP; (4) CWR estimation for AWD and Non-AWD irrigated rice cultivation; and (5) Irrigated rice area mapping with CWR and Effective precipitation. A flowchart of this study is illustrated in **figure 4.1**.

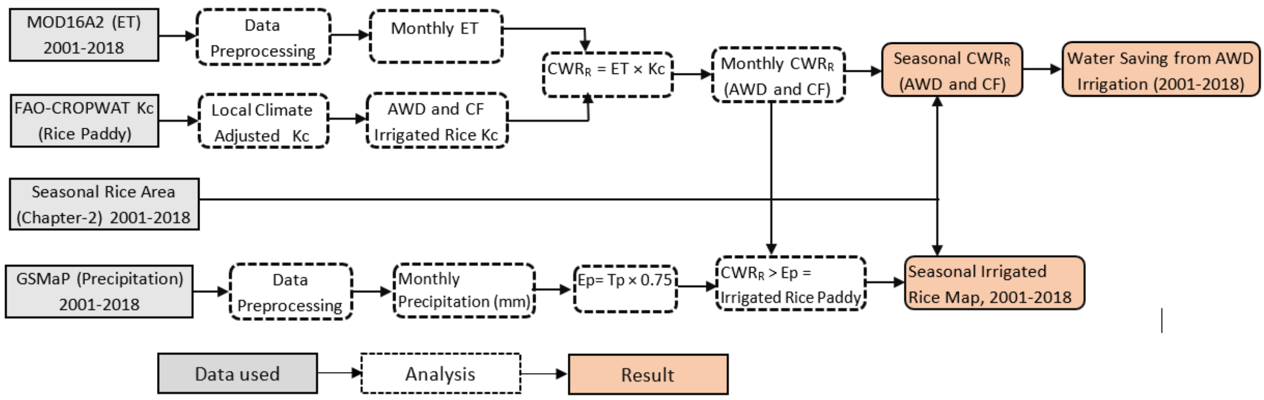


Figure 4.1 The overall research flowchart for the CWR estimation and irrigated rice area mapping over the study area.

4.3.1 Dataset used

4.3.1.1 Remote sensing dataset

The Moderate Resolution Imaging Spectroradiometer (MODIS) MOD16A2 data at 500 m spatial resolution, 8-day temporal resolution an atmospheric corrected data obtained from the United States Geological Survey database used for potential evapotranspiration estimation. The h26v06, h25v05 and h226v07 tiles covered the study area data from 2001-2018. The data originally recorded using sinusoidal projection in the hierarchical data format (HDF) were mosaicked, resized to the study area, and re-projected and resample into 1Km resolution on the geographical coordinate system using the Modis reprojection tool (MRT) algorithm. The monthly potential evapotranspiration (PET) extracted from the MOD16A2 8-day time composite data. The Global Satellite Mapping of Precipitation microwave (GSMaP) monthly data on 10 km Spatial resolution data used for monthly precipitation analysis (https://gportal.jaxa.jp/gpr/.). The precipitation data over the study area from 2001 to 2018 used to analysis the effective precipitation.

4.3.1.2 Climatic, Model, and statistical dataset

The FAO CROPWAT software used for the crop water requirement estimation. The historical climatic data on precipitation, temperature, evapotranspiration data from CLIMWAT and Bangladesh Meteorological Department (BMD) have been used for this study. The statistical data on irrigated seasonal rice area were collected from Bangladesh Bureau of Statistics (BBS), FAOSTAT, and other reliable source reported data. Moreover, the literature review, published and unpublished data source from research organization, newspaper was used for the comparison and validation the result of this study.

4.3.2 CWR assessment for AWD and CF irrigated rice

The crop water requirement (CWR) refers the depth of water need for rice to meet the water loss through evapotranspiration (ET) of a disses free, available soil water and fertility condition in the growing environment and fully potential production. Generally, rice crop water requirement (RCWR) considered as continuously flooded (CF) rice RCWR. According to the FAO-56 guidelines followed for rice CWR of traditional cultivation (L.S.Pereira, 2013), whereas

$$CWR = ET \times Kc \qquad 4.1$$

Where, R_{CWR} is the rice crop water requirement (mm), ET is monthly evapotranspiration (mm) and K_c is crop coefficient.

We used the equation 4.1 for monthly CWR assessment and the seasonal rice paddy map from chapter 2 for CWR assessment. The CWR for AWD and CF irrigated rice estimated on seasonal rice growing based and the annual CWR estimated with the seasonal CWR use.

4.3.2.1 Evapotranspiration (ET) estimation

The potential evapotranspiration calculated from MOD16A2 8 days composite 500m spatial resolution data. The reference evapotranspiration and potential evapotranspiration are different term but in rice cultivation condition without any water stress potential evapotranspiration is almost similar to reference evapotranspiration (Parvez and Inayathulla, 2019). In this chapter we used potential evapotranspiration as reference evapotranspiration for flooded rice cultivation. The Moderate Resolution Imaging Spectrometer MOD16A2 version 6 Evapotranspiration with 8 days temporal and 500m spatial resolution data have been used for this study. The Penman-Monteith equation, which include inputs of daily meteorological reanalysis data along with MODIS vegetation properties dynamics, albedo, and land cover have been used in MOD16A2 algorithm (Mu, Zhao and Running, 2013). The pixel values of MOD_ET layer is the sum of all eight days within the composite period. The data resampled and re-composite in monthly ET of each year from 2001-2018.

4.3.2.2 Crop coefficient (Kc) estimation

The crop coefficient (Kc) is the most important part of a crop water requirement assessment. The Kc is the ratio of potential evapotranspiration (ETc) of a crop and the reference evapotranspiration (ETo) in a disses free, water stress free, and fully potential growth condition of that crop. Generally, the crop coefficient estimated as follows

$$Kc = ETc/ETo \qquad 4.2$$

Where, Kc = Crop co-efficient for rice, ETc is the potential evapotranspiration (ET) and ETo is the reference crop evapotranspiration.

The crop Kc value for the rice is depends on the growing period, water availability, climatic condition, and cultivation practices. The crop growing stages is very important for Kc estimation and it's varied in different stage. In this study, the rice growing stages considered as (i) initial stage- 0 to 30 days after transplanting, (ii) midseason stage – 30 to 90 days after transplanting and (iii) late season stage – 90 to harvested days after transplanting. The FAO standard kc value for the initial, midseason and late season stage are 1.05, 1.20 and 0.95 respectively, in sub-tropical region (Allen, 1998). But the kc value for rice crop varied for climatic condition differ from region to region. In this study, the local climatic condition evaluates with the meteorological data and used the following equation for local climate adjusted Kc value.

$$Kc_{(ini)} = Kc_{(FAO)} + \frac{(I-40)}{(40-10)}[\, Kc_{(ini)} - Kc_{(inifig)}] \qquad 4.3$$

$$Kc_{(mid)} = Kc_{(FAO)} + [0.04(\mu - 2) - 0.004(RH - 45)]\left(\frac{hc}{3}\right)^{0\dot{}03} \qquad 4.4$$

$$Kc_{(late)} = Kc_{(FAO)} + [0.04(\mu - 2) - 0.004(RH - 45)]\left(\frac{hc}{3}\right)^{0\dot{}03} \qquad 4.5$$

Where,

$K_{c\,FAO}$ value for K(ini) $Kc_{(mid)}$ and $Kc_{(late)}$ taken from FAO chart (1.05, 1.20 and 0.95 respectively),

u_2 mean value for daily wind speed at 2 m height over grass during the late season growth stage (ms^{-1})

RH mean value for daily minimum relative humidity during the late season stage (%),

h is the mean plant height during the respective season stage (m)

The rice cultivation practices are also another important factor for the Kc estimation. In this study the rice management practice in terms of irrigation scheduling maintain is evaluate as AWD and CF irrigation practice. The Kc value also changed based on the irrigation practice variation, especially the wetting frequency refers as AWD irrigation affected the rice Kc values. The AWD irrigation cycle generally began from the midseason stage as a result the AWD irrigated rice Kc value in initial and mid-season period of rice based on the FAO equation(Allen *et al.*, 1998b).

$$Kc_{(AWD)} = Kc_{(Clim)} + [0.04(\mu - 2) - 0.004(RH - 45)]\left(\frac{hc}{3}\right)^{0.03} \times WE \qquad 4.6$$

Where, Kc (AWD) is the Kc value for AWD irrigated rice, Kc (clim) is the climate adjusted Kc value, and the wetting and drying event in midseason stages, which could reduce Kc value from 1.10-1.30 to 1.00 reduced almost 30% of Kc value (Allen, 1998). We considered W_E = 0.70 for AWD Irrigated Rice during mid-season in Bangladesh.

Finally, based on the equitation 4.1, the monthly and rice season basis (boro, aus and amon) CWR estimated from 2001 to 2018 over the Bangladesh (figure 4.1).

4.3.2.3 *Water use saving from AWD irrigation*

The crop water requirement for rice paddy is estimated from the previous section. The CWR for AWD irrigation and CF irrigation investigated. The water use difference from CF to AWD irrigation considered as water saving from AWD irrigation. RCWR for AWD and CF irrigated rice varied from 20% to 40%. We also reviewed some literature and report on AWD irrigation in Bangladesh and set 30% water saving from AWD irrigation practiced. We prepared final annual RCWR map for AWD and CF irrigation. In study area, the AWD irrigation techniques is not widely adopted in field level. We prepared a scenario-based crop water saving scheme based on AWD suitable rice area (Chapter 3). The different level of AWD irrigated area implementation is considered as, (i) CWR for total rice area under CF irrigation, (ii) CWR for total rice area under AWD irrigation, (iii) CWR saved by physically AWD suitable rice area under AWD irrigation, (iv) CWR save by physio-climatically AWD suitable rice area under AWD, (v) CWR saved by socio-economically AWD suitable rice area under AWD irrigation application in Bangladesh.

4.3.3 Irrigated rice area mapping

Irrigation is the water supply from other than natural sources to meet up the crop water requirement for the crop growth and production fulfilment. The irrigated rice area is calculated by using the rice crop water demand as CWR and the supply of water for meet up the demand as irrigation. The rice crop cultivated under flooded condition and it's need to continuous supply of water. The amount of water required for the rice growing season is refers as rice crop water requirement (R_{CWR}).

This water comes from generally from two ways; i) natural means rainfall, ii) Artificial means irrigation. We considered that, if the rainfall is not enough for rice growing condition then it's need alternative sources of water which refers as irrigated. We considered CWR and sources of supply as effective precipitation, and potential irrigated or rainfed rice area determined as follows.

$$\text{Irrigated} = CWR > Ep \; and \; \text{Rainfed} = CWR \leq Ep \quad 4.7$$

Where, CWR is the Rice crop water requirement (mm), E_P is the effective precipitation (mm).

If the crop water requirement is higher than the effective precipitation, the pixel considered as the irrigated area and lower means the rainfed area. On the base of Eq. (4.7), the irrigated and rainfed area mapped. In between the irrigated and rainfed area, we considered the rice crop stress tolerate and uncertainty of estimation. Then, we set a range of value and considered as supplementary irrigated area. We conduct the sensitivity analysis for the irrigated, supplementary irrigated and rainfed rice area. Three different set of value assigned for the sensitiveness of the result and compared with the available data source to fix the value for the irrigation type fixation. This irrigated and rainfed area map overlay with the rice area map and finally calculated the irrigated, supplementary irrigated and rainfed rice area. The three different seasons (boro, aus and amon) irrigated and rainfed rice area are calculated and mapped from 2001 to 2018.

4.3.4 Effective precipitation estimation

Effective precipitation is the portion of water from total precipitation used for rice crop water requirement. The total amount of precipitation could not be used for rice crop water requirement because of seepage loss, percolation loss, and run off loss. Global Satellite Mapping of Precipitation (GSMaP) monthly precipitation data with a 0.1 x 0.1-degree resolution have been used for effective precipitation estimation. GSMaP precipitation values are estimated using multi-band passive microwave and infrared radiometers from the GPM Core Observatory satellite and with the assistance of a constellation of other satellites (Shige et al., 2009). The monthly GSMaP data resampled into 1km and calculated the monthly effective precipitation for rice. There are several methods for effective precipitation estimation. In this study, we investigated FAO/AGLU, USDA S.C and FAO fixed ratio with 70%, 75% and 80% of total rainfall (Surendran et al., 2017). Based on the literature review, expert opinion, local climatic condition the fixed ratio method used for this study (Ali and Mubarak, 2017). Moreover, we use sensitivity analysis for three different fixed (70%, 75% and 80%) case and fixed 75% for the effective precipitation estimation. The equation used as follows.

$$\text{Effective precipitation (Ep)} = Tp \times 0.75 \quad 4.8$$

Where, Tp is the total precipitation in mm and 0.75 used as fixed ratio for rice paddy in Bangladesh.

4.3.5 Comparison and Validation

The result from this chapter is compared with the national government, International organization reported data and relevant studies. The effective precipitation estimation result compared with the FAO, USDA, and Indian method estimation. The Kc and CWR result compare with the FAO CROPWAT estimation result and relevant studies. The estimate irrigated, supplementary irrigated and rainfed rice area result compare with the governmental reported statistical data, FAO AGUASTAT data and relevant reported studies.

4.4 RESULTS

4.4.1 CWR for AWD and CF irrigated rice result

4.4.1.1 Crop coefficient for AWD and CF irrigated rice

The crop coefficient (*Kc*) value for the rice depends on the growing period, water availability, climatic condition, and cultivation practices. The standard Kc values for rice varied from 1.05 in initial, 1.25 mid-season to 0.95 in late season in Bangladesh [47] for 140 days growing period(Allen *et al.*, 1998a). In this study evaluate the local climate influence and seasonal variation of Kc value and found 1.05, 1.22 and 0.96 for initial, midseason, and late season respectively, for boro rice growing season. In rainy season aus rice growing season the Kc estimated Kc value in initial stage is 1.05, mid-season stage 1.18 and late season stage 0.98. In case of amon season paddy rice the Kc value are 1.05, 1.10 and 0.96 for the similar growth stage. The AWD irrigation management changed the Kc value in midseason stage of rice growth. The AWD adjusted Kc value in midseason for boro, aus amon rice are 0.80, 0.94 and 0.87, respectively. In **figure 4.2** shows the FO guided, climate adjusted and AWD applied Kc vale for seasonal rice growth stages.

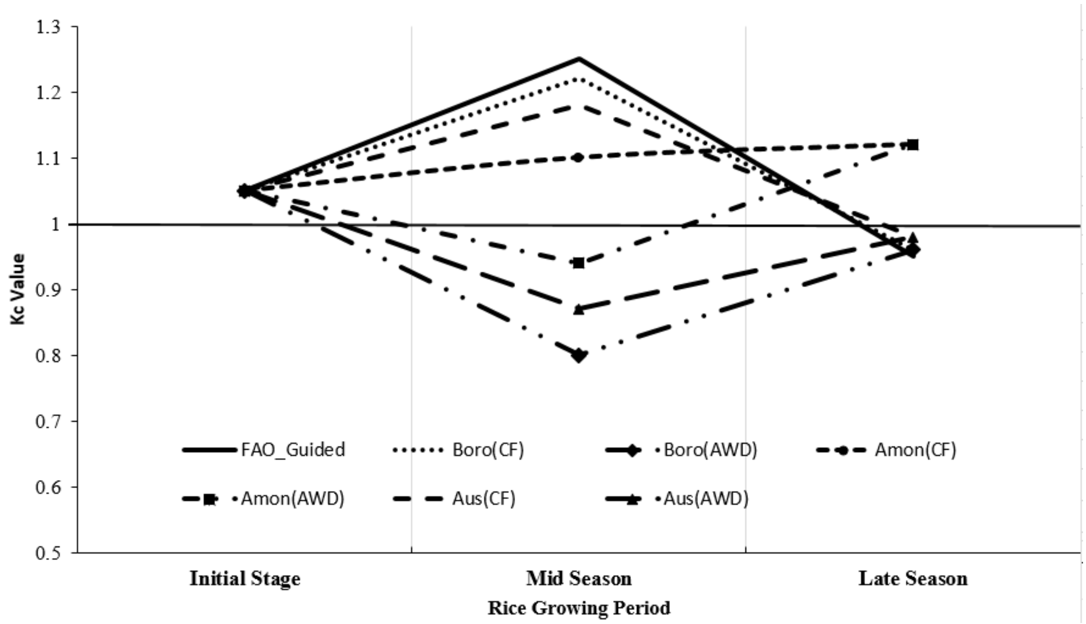


Figure 4.2 The FAO guided crop coefficient (kc) value, climate adjusted estimated Kc value, AWD irrigated rice Kc value for boro, aus and amon rice.

4.4.1.2 Effective precipitation estimation result

The effective precipitation estimation depends on crop types, rainfall intensity and magnitude, physiographic condition, and soil types. The effective precipitation has been calculated with USDA S.C, FAO AGLW and fixed ratio Indian-1 method (Pruitt, 1984). The different Ep calculation method's result have been compared; the results are showed in **figure 4.3**. Due to the precipitation pattern, intensity, physiographic similarities, the Indian-1 fixed ration methods show the best fitted curve in the study area. Based on the literature review, physical condition and rainfall pattern, the Indian-1 method select for the effective precipitation calculation.

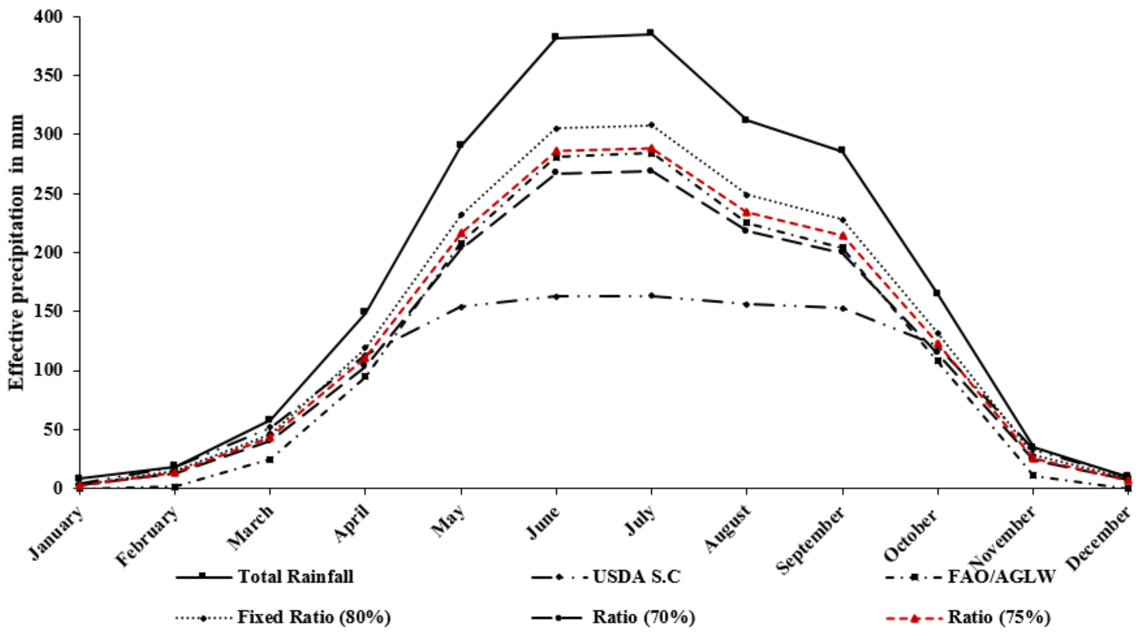


Figure 4.3 The monthly total rainfall and estimated effective precipitation result with FAO/AGLU, USDA and Indin-1 methods (0.70, 0.75, and 0.80 fixed ratio) in the study area.

The Indian-1 fixed ratio with three different value used and calculate the sensitivity on irrigated rice area estimation result. Three different set of value considered for the sensitiveness analysis on the estimated irrigation area. In **table 4.1** shows the different set range value for this study. The fixed ratio 0.75 showed the best result from the sensitivity analysis and it used for the effective precipitation estimation for rice paddy irrigation assessment in this study.

Table 4.1 Three set of range values for irrigated, supplementary irrigated and rainfed rice area determination and sensitivity analysis for asses the seasonal variation of the irrigated area over Bangladesh.

(Ep-CWR) set	A	B	C
Irrigated	< -300	< -200	< -100
Supplementary Irrigated	-300 – 0	-200 – 0	-100 - 0
Rainfed	> 0	> 0	> 0

4.4.1.3 *Seasonal CWR for AWD and CF irrigated rice*

The methodology used for this study to estimate the irrigated, supplementary irrigated and rainfed rice area estimation has great influence of precipitation and evapotranspiration. The CWR result for three different rice growing season also observed variation. In the boro rice growing season the CWR for CF irrigated rice speckled from 350 mm to 950 mm and for AWD irrigation case 300 mm to 830 mm over the study area. The AWD irrigation estimated CWR is 5 to 14 % less than the CF irrigated rice. In the CWR distribution for boro rice area, the north-western and central-norther part of the country required more CWR and southern and eastern part of the country shows less CWR comparatively. In aus rice growing season the CWR for CF irrigation varied from 430 mm to 1020 mm and AWD irrigation application 430 to 930 mm over the country. As the evapotranspiration rate is higher in rice growing season, the estimate CWR also slightly higher than the boro rice season. The amon rice paddy CWR for CF irrigation also varied from 350 to 1100 mm over the region. Like the aus rice growing season the early growth stage of amon rice paddy experienced higher ET rate. The central and southern part of the country required higher CWR for CF irrigation. In **figure 4.4** showed the AWD and CF CWR for boro, aus and amon rice season of a selected year, the details seasonal CWR added in appendix.

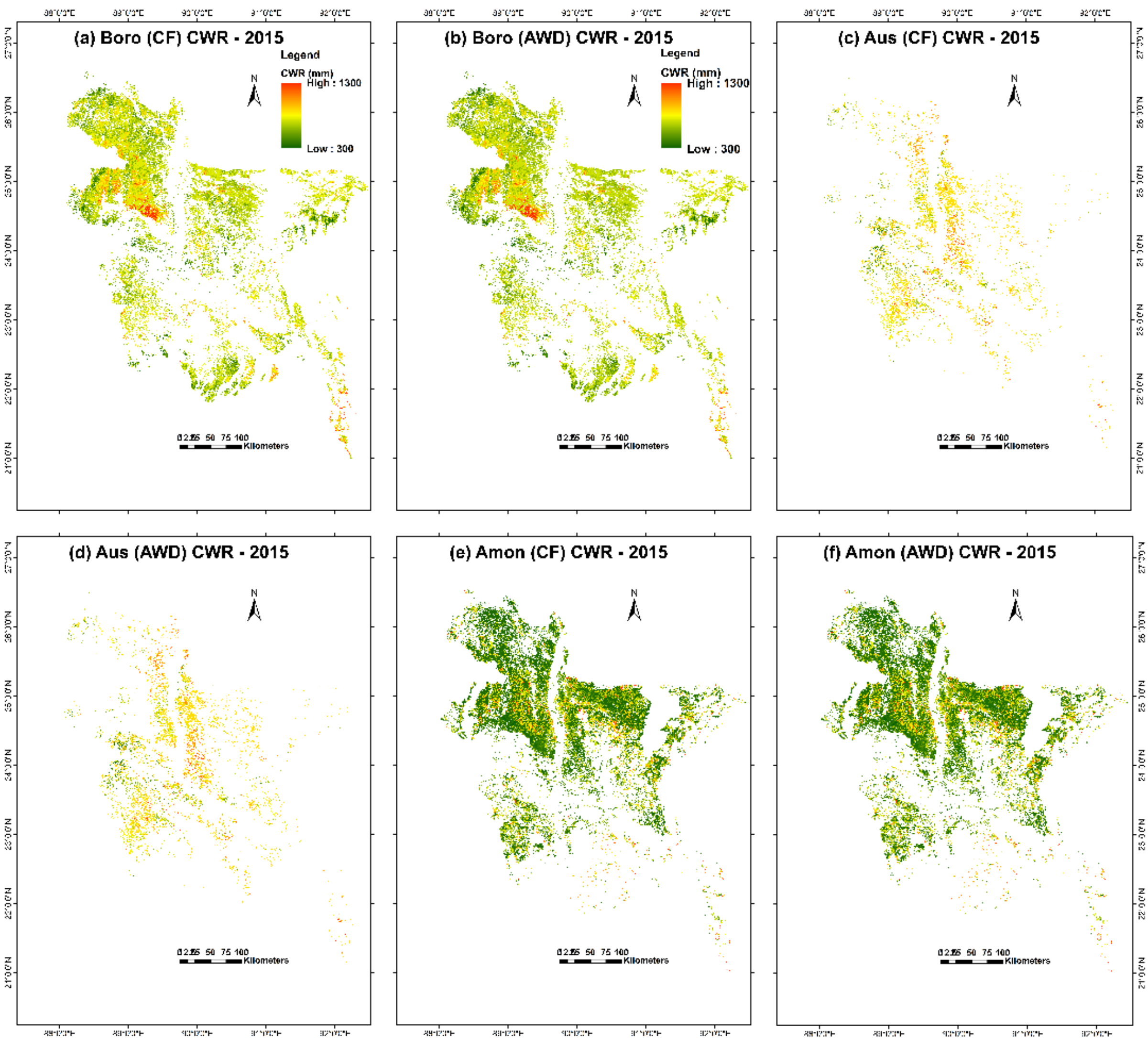


Figure 4.4 Seasonal CWR for boro, aus and amon rice growing season with CF irrigation and AWD irrigation techniques in 2015.

4.4.1.4 Annual CWR for AWD and CF irrigated rice

The annual CWR for continuous flooded (CF) rice was 52.55 km^3 in 2001 and 49.45 km^3 in 2018. In case of AWD irrigation the CWR was 49.45 km^3 in 2001 and 49.61 km^3 in 2018. The CWR increased over the time as the rice cultivated area also increased. The CF CWR values varied over the time and 2013 and 2015 was the maximum CWR for the study area. Similarly, the AWD CWR also fluctuated with the CF CWR changed. The annual CWR depends on climatic factors, crops type, crop growth stage, and cropping intensity. The CWR for rice paddy in the study area also varied with the rice cropping pattern changed. Rice is cultivated as single, double, and triple cropping pattern in the study area. The north-western and central northern part of the country, whereas the dominant cropping pattern is boro-amon as double rice are higher water consumed region. The western and southern part of the country showed comparatively lower CWR region as the single rice cropping pattern is dominant cropping pattern. Especially, the southern part of the country is coastal area and due to the salinity and seasonally tidal waterlogged are inducing the region single rice pattern. The distribution of CWR for AWD and CF irrigated rice area shows in **figure 4.5** and **4.6**.

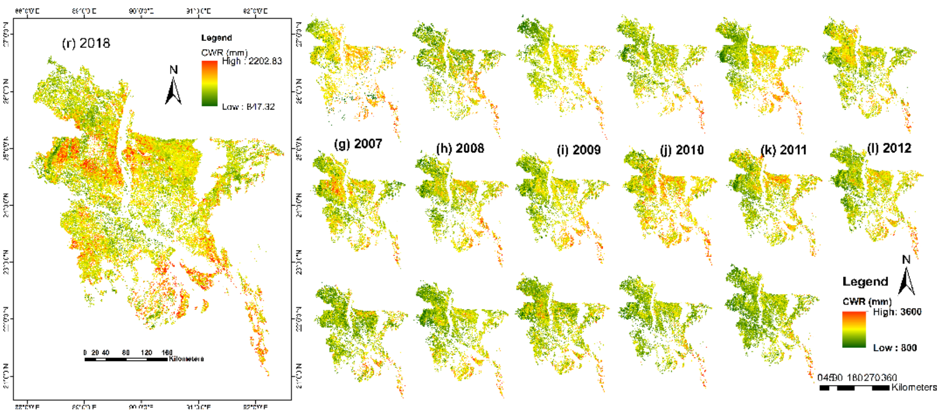


Figure 4.5 Estimated annual CWR for CF irrigated rice over the study area; (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, (j) 2010, (k) 2011, (l) 2012, (m) 2013, (n) 2014, (o) 2015, (p) 2016, (q) 2017 and (r) 2018.

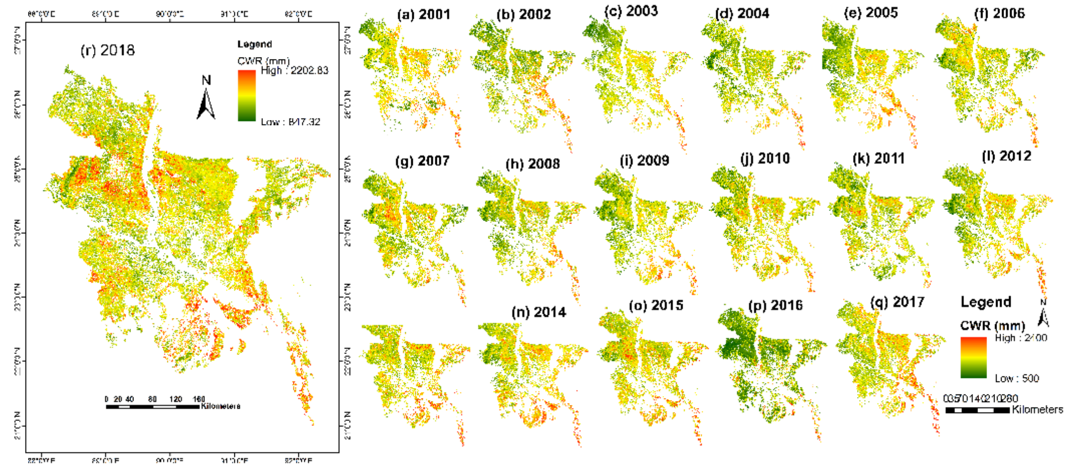


Figure 4.6 Estimated annual CWR for AWD irrigated rice over the study area; (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, (j) 2010, (k) 2011, (l) 2012, (m) 2013, (n) 2014, (o) 2015, (p) 2016, (q) 2017 and (r) 2018.

4.4.1.5 CWR saving from AWD irrigation

The CWR changes due to AWD irrigation application. The several studies showed CWR reduced up to 30% water compared with CF irrigated rice. But the CWR is different from the irrigation water use. The amount of water applies to fulfill the crop water demand is irrigation and crop only absorb the amount need s to fulfill the CWR. As a result, the CWR save by AWD irrigation in this study save up to 15.50% compared with CF irrigation. Bangladesh is one of the lowest irrigation efficiency country and it is only 30% of total irrigation (Alam, 2011). In rice paddy irrigation case it expose up to 45% efficiency and in that case 15.50 CWR saving refers as 35% irrigation water saved. The maximum water saved result observed in 2012 and lowest in 2002. The CWR saved from AWD irrigation depends on the region, soil texture, drainage, irrigation efficiency and the management practice. In this study, we evaluate the climatic parameters induced Kc value as a fixed measurement and the practice management also considered at a fixed rate. Moreover, the different scenario based on the AWD irrigation application rate save CWR indifferent level. In **figure 4.7** demonstrated the detail CWR for CF and AWD irrigation system. Moreover, based on the AWD suitability in Bangladesh (Chapter 3), we proposed three different scenario on CWR saved; (i) CWR save by total rice growing (Physically suitable area, 98%) under AWD irrigation, (ii) CWR save by 48% (Physio-climatically suitable) of total area under AWD irrigation, (iii) CWR save by 58% (Socio-economically suitable) of total area under AWD irrigation of for total rice area under AWD irrigation. Bangladesh could save up to 8.32 km^3 annual CWR through total area considered as AWD irrigation and 4.32 km^3 through physio-climatically suitable, and 5.12 km^3 through socio-economically suitable area under AWD irrigation application.

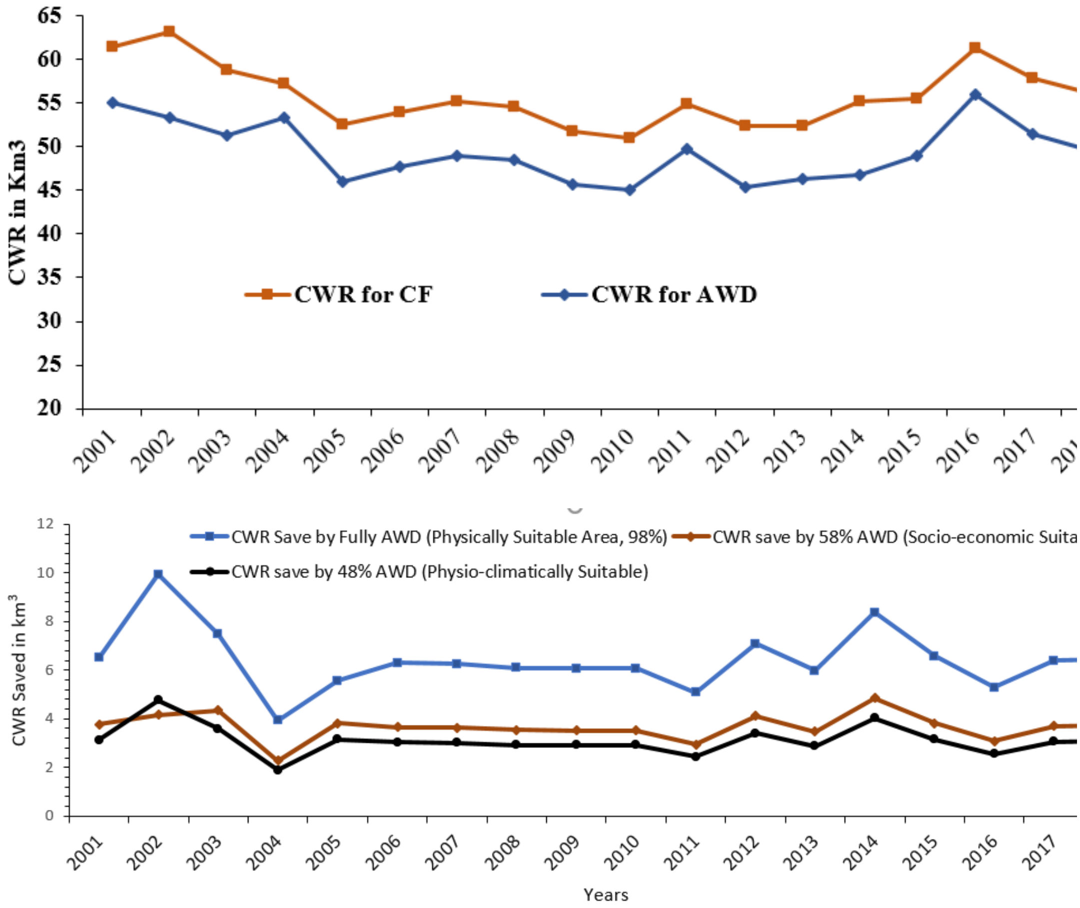
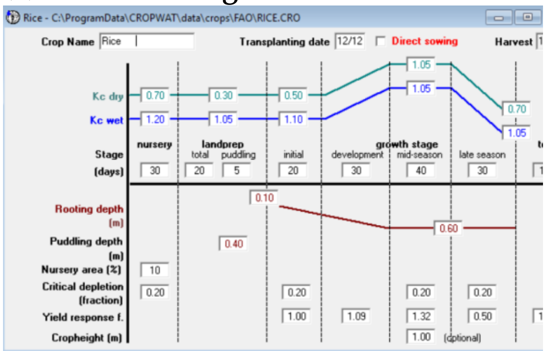


Figure 4.7 The estimated annual CWR for CF irrigated rice, AWD irrigated rice and CWR saving from the AWD irrigation over the study area from 2001 to 2018.

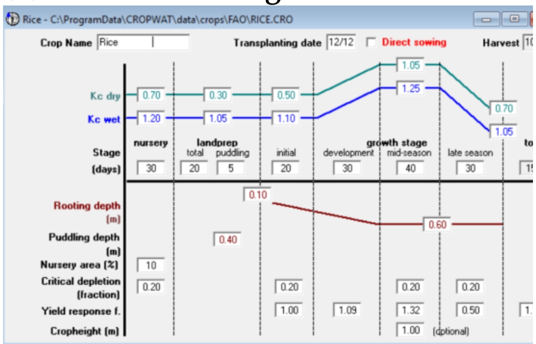
4.4.1.6 CWR result validation with CROPWAT model

The local climate adjusted estimated CWR for seasonal rice paddy is compared with the FAO-CROPWAT result. The model used for this study to estimate CWR with the MODIS data derived ET and local climatic parameter adjusted monthly Kc value. We also evaluate the AWD irrigation water saving at a fixed ratio for the study area. The CROPWAT model used CLIMWAT dataset, soil parameters, transplanting date, growing period, and irrigation schedule management. In this study the CROPWAT and CLIMWAT model used with the changing value of irrigation scheduling and Kc value. In **figure 4.8** showed the screenshot of CROPWAT model used Kc value and crop water requirement in Bogura station.

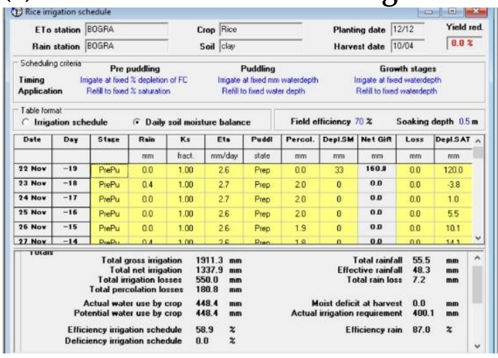
(a) Kc for CF irrigated rice



(b) Kc for AWD irrigated rice



(c) CWR and IWR for CF irrigation



(d) CWR and IWR for AWD irrigation

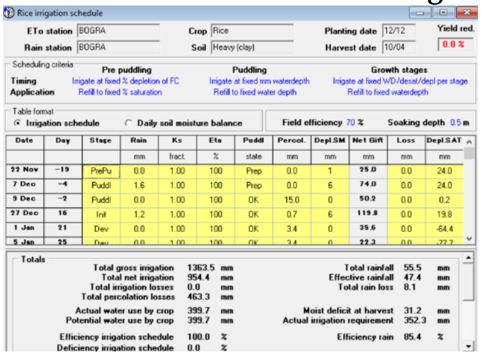


Figure 4.8 The estimated Kc value with CROPWAT model and CLIMWAT data; (a) Kc value for CF irrigated rice, (b) Kc value for AWD irrigated rice; The estimated IWR and CWR with CROPWAT model; (c) CWR for CF irrigated rice, (d) CWR for AWD irrigated rice in Bogura station.

The result from the climate adjusted model and CROPWAT model compared in different weather station in the study area. The climate adjusted CWR model showed little bit overestimated compared with the CROPWAT model. The climate adjusted model estimated CWR for CF irrigated rice in Bogura, Mymensignh and Khulna station are 581-635 mm, 595-778 mm, and 612-743 mm, respectively for boro rice season. Whereas the CROPWAT model estimated CWR are 488, 512 and 514 mm, respective station. The estimated CWR for AWD irrigation with climate adjusted model are 441-635 mm, 516-678 mm, and 567-682 mm at Bogura, Mymensingh and khulna station, respectively. In similar station, CROPWAT estimate CWR for AWD irrigation are 399 mm, 386 mm, and 492 mm, respectively. The estimated CWR for boro, aus and amon rice also varied over the time. In **table 4.2** shows the comparative result from climate adjusted model estimation and CROPWAT estimated CWR for AWD and CF irrigated rice.

Table 4.2 Comparision of estimated CWR for seasonal rice with this study used climate adjusted model and CROPWAT model in sellected station.

		Climate adjusted Model Estimation		CROPWAT model Estimation	
Location	Rice Season	CF-CWR (mm)	AWD-CWR (mm)	CF-CWR (mm)	AWD-CWR (mm)
Bogura	Boro Rice	581-756	441-635	488	399
	Aus Rice	680- 742	512-765	520	470
	Amon Rice	636-720	542-783	514	487
Mymensingh	Boro Rice	595-788	516-678	453	386
	Aus Rice	645-812	599-732	512	477
	Amon Rice	630-786	588-654	554	492
Khulna	Boro Rice	612-743	567-682	514	492
	Aus Rice	643-734	587-695	535	512
	Amon Rice	634-712	465-653	497	442

4.4.2 Irrigated rice area mapping result

4.4.2.1 Irrigated boro rice area result

The boro rice season is the maximum rice producing season by total rice production and second one by area. The highest per unit yield and favourable climatic condition with irrigation facilities development are inducing the boro rice season as popular among the farmer. The boro rice season is the mostly irrigated with very few areas supplementary irrigated. There is no rainfed boro rice paddy in the study area and almost negligible rice area is supplementary irrigated. The estimated irrigated boro rice was 3.19 M ha in 2001 and becomes 4.57 M ha in 2018. The irrigated boro rice area demonstrated drastic increases over the time. This change happened due to the boro rice area expansion not due to the supplementary or rainfed rice area increased. The supplementary irrigated area shows comparatively higher in 2015. **Figure 4.9** shows the irrigated and supplementary irrigated boro rice area in Bangladesh.

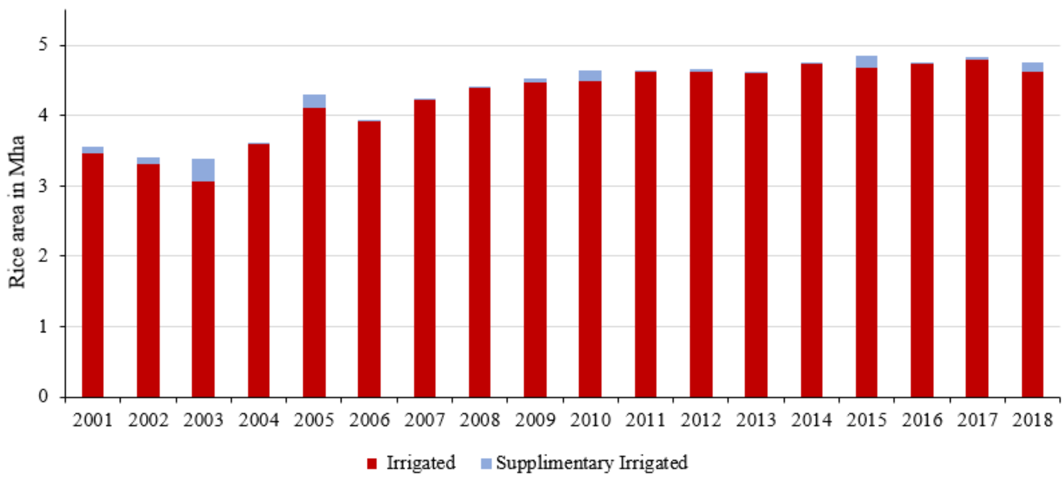


Figure 4.9 Estimated irrigated, supplementary irrigated and rainfed boro rice area in study area from 2001 to 2018.

The estimated irrigated boro rice area showed the similar distribution pattern as boro rice distribution pattern (chapter 2). The central-northern and the north-western region of the country's irrigated boro rice area. The north-western part of the country is the drought prone area and the region faces severe water scarcity during summer season. The government subsidise deep irrigation water pump installed to ensure the irrigation facilities. The eastern part of the country boro rice is mainly seasonal wet land and it's the most rainfall pattern experienced. As a result, the supplementary irrigated are mainly in this area. **Figure 4.10** shows the irrigated and supplementary irrigated area distribution over the study area from 2001 to 2018. The details maps added at appendix C.

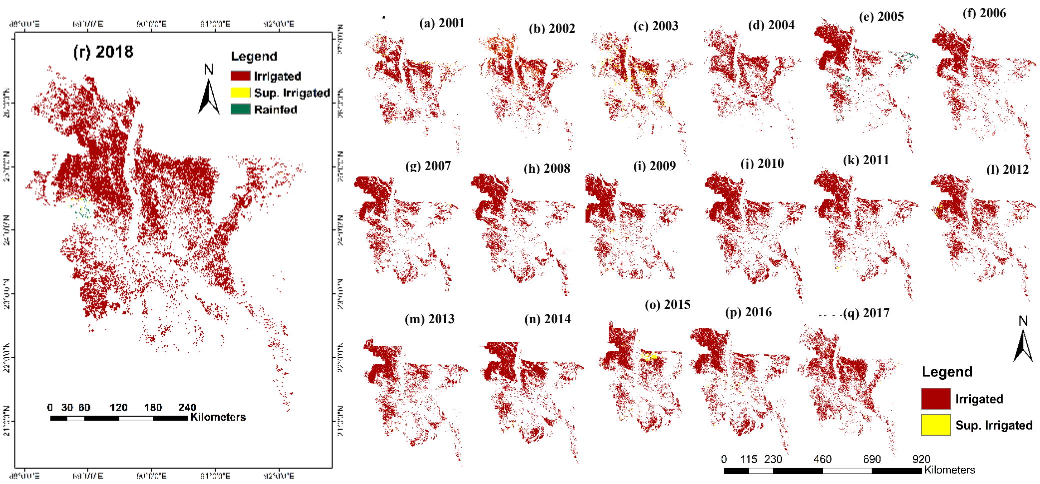


Figure 4.10 Distribution of estimated irrigated, supplementary irrigated and rainfed boro rice area in study; (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, (j) 2010, (k) 2011, (l) 2012, (m) 2013, (n) 2014, (o) 2015, (p) 2016, (q) 2017 and (r) 2018.

4.4.2.2 Irrigated aus rice area result

The rainy season aus cultivating season is dominated by supplementary and rainfed rice area. The country experienced huge amount of precipitation especially during to the harvested season. Due to the excess rainfall the season frequently face severe flood and production loss. The season is lest rice cultivated season in the country. The irrigated aus rice area was 436 thousand ha in 2001 and becomes 649 thousand ha in 2018. The irrigated, supplementary and rainfed area fluctuated with the rainfall pattern change. **Figure 4.11** shows the supplementary and rainfed aus rice area in the country.

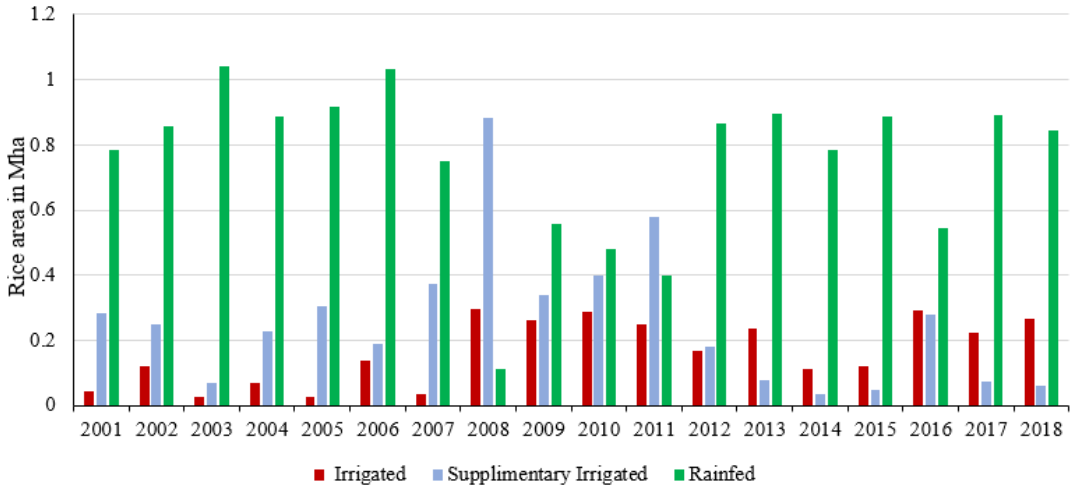


Figure 4.11 Estimated irrigated, supplementary irrigated and rainfed aus rice area in study area from 2001 to 2018

The estimated irrigated aus rice area demonstrated that the north western part of the country is the mainly irrigated aus rice area. Along with, the north-western part of the country also the major aus rice cultivated area. The region is the less rainfall region in the country and face water scarcity during the summer season. Moreover, the region is comparatively high elevation and less flood risk zone. The southern part and the north-western part of the country's aus rice area are fully rainfed. The supplementary irrigated area is the dominant most of the year as the early planted aus require irrigation due to the monsoon season start from June. **Figure 4.12** shows the irrigated, supplementary and rainfed aus rice area distribution map.

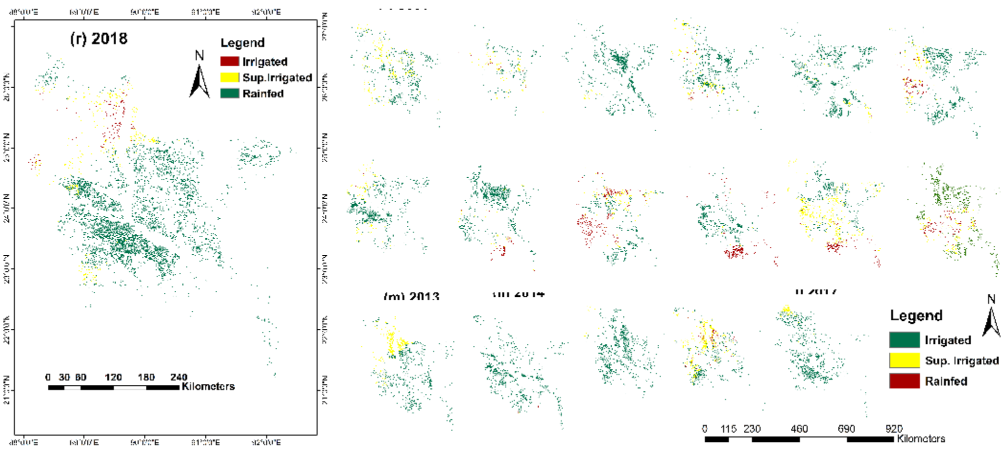


Figure 4.12 Distribution of estimated irrigated, supplementary irrigated and rainfed aus rice area in study; (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, (j) 2010, (k) 2011, (l) 2012, (m) 2013, (n) 2014, (o) 2015, (p) 2016, (q) 2017 and (r) 2018.

4.4.2.3 Irrigated amon rice area result

The amon rice growing period is started from the monsoon season and end at the late monsoon season. It is the largest rice growing season in the country by area. Although the season is considered as rainfed rice season but mostly in late season need irrigation. The estimated irrigated amon rice area was 2.2 M ha and becomes 1.7 Mha in 2018. The estimated irrigated amon rice area shown decline trend as the amon rice area also declined over the time. The irrigated, supplementary irrigated and rainfed rice area fluctuated among the years over the country. The common trends are with decreased the irrigated area means increases the supplementary irrigated and rainfed rice area or vis versa. The irrigated area estimation model used in this study mainly depends on the climatic parameters, especially the rainfall. With the variation of precipitation pattern and magnitude the irrigated, supplementary irrigated and rainfed rice area also changed. **Figure 4.13** shows the estimated irrigated, supplementary irrigated and rainfed rice in the study are from 2001 to 2018.

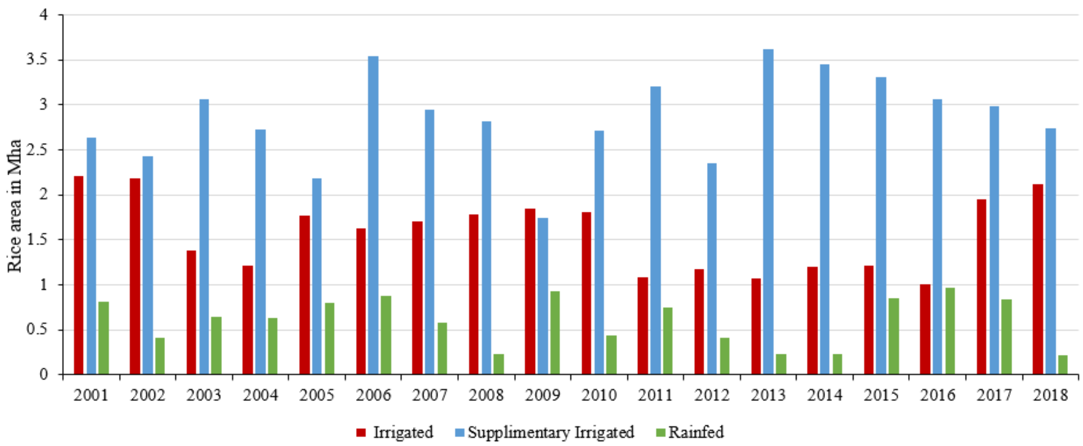


Figure 4.13 Estimated irrigated, supplementary irrigated and rainfed amon rice area in study area from 2001 to 2018

The irrigated, supplementary irrigated and rainfed amon rice distribution followed the amon rice distribution pattern. The central-western and central-southern part of the country are dominant irrigated amon rice area. The region is less rainfall and higher temperature observed area. The central-northern part of the country's amon rice area demonstrated as supplementary irrigated area. The north-eastern and south-eastern part of the country is rainfed amon area. The **figure 4.14** shows the irrigated, supplementary irrigated and rainfed amon rice area distribution.

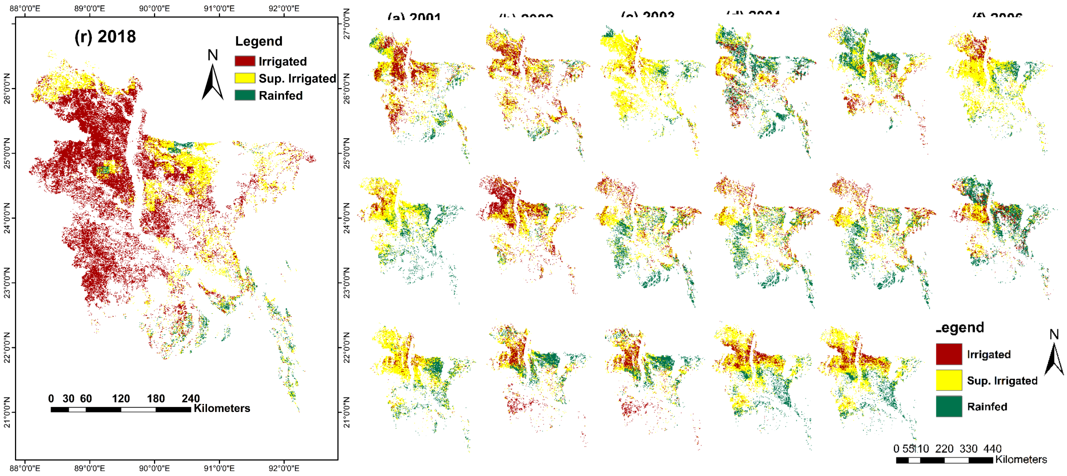


Figure 4.14 Distribution of estimated irrigated, supplementary irrigated and rainfed amon rice area in study; (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, (j) 2010, (k) 2011, (l) 2012, (m) 2013, (n) 2014, (o) 2015, (p) 2016, (q) 2017 and (r) 2018.

4.4.2.4 Irrigated rice area validation with Governmental statistical data

The irrigated rice area of Bangladesh has been calculated using the climatic parameter; evapotranspiration (MOD_ET) and effective precipitation (GSMaP). The estimated data compared with the national statistical data. The boro rice area has a very good relationship with the statistical data. Due to the very high difference between the effective precipitation and crop water requirement, the irrigated Boro rice area calculation has a very good agreement. The calculated irrigated Boro rice area little bit overestimated compared to the statistical data. The linear scatter plot of the estimated and reported irrigated boro rice area showed very good agreement, where the R^2 value is 0.087. The aus season is considered as rainfed and there is no available statistics of irrigated aus rice area. The irrigated Amon rice area shows a fluctuation trend with the national statistical data. In 2015 and 2016 the comparison curve for irrigated amon rice area showed almost similar value. Due to the climate change impacts the precipitation pattern changing and the rainy season shrinking with higher magnitude in the country (Kirby *et al.*, 2014). The overall correlation of estimated irrigated and reported irrigated amon rice area show poor agreement with R^2 value 0.55. The probable causes of overestimation of irrigated Amon area are; i) due to the climate change, ii) farmers lately planted for save the Amon rice from damaged to flood and growing period extended to the dryer months, iii) the variation of irrigated area definition and calculation between the remote sensing-based our methodology and national statistical methods. The calculated rice area fluctuated with the weather condition of the year. Although, there are not available data on supplementary irrigated area but several studies also found the supplementary irrigated area is increasing in the country (Kirby *et al.*, 2014; Rashid, 2014; Sen *et al.*, 2017). The comparison of calculated irrigated rice area and statistical data shows in **figure 4.15**.

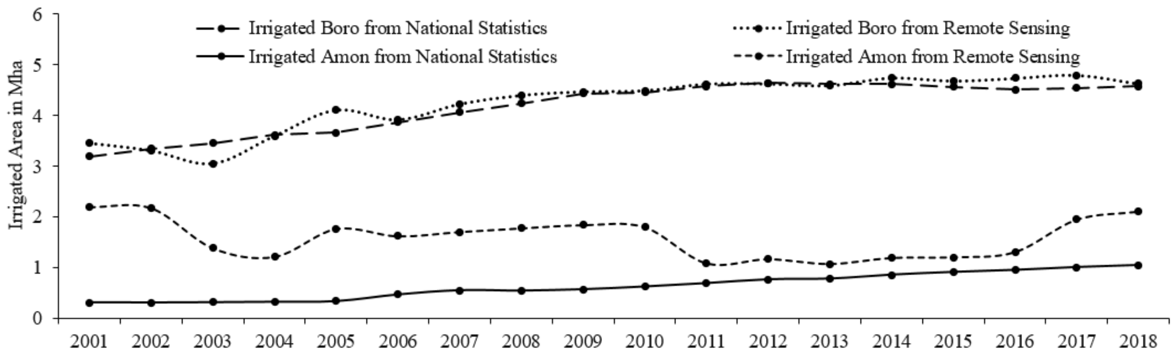


Figure 4.15 Estimated irrigated boro and amon rice area comparison with the government reported national statistical data.

4.5 DISCUSSION

4.5.1 CWR result comparison with relevant studies

The CWR for AWD and CF have been calculated with remote sensing and model-based data. The CWR is different from the irrigation water requirement (IWR) as a result, the water-saving through AWD application in this study is only CWR saving. The CWR saving from this study showed up to 13.50%. The total irrigation water save from the AWD irrigation reported several studies as 15 to 30% (Carrijo, Lundy, *et al.*, 2018), up to 23.5% (Tabbal *et al.*, 2002), maximum 38% (Carrijo, Lundy, *et al.*, 2018). The irrigation water saves field data from RDA supervised AWD irrigation site also reported water save with AWD irrigation varied site to site from 3% to 29.51% in the study area. The estimated climate adjusted Kc value for CF irrigated and AWD irrigated rice result showed the similar value by other study reported for rice(M. Hossain *et al.*, 2017; Sakti and Takeuchi, 2018; Sciences, 2019). The effective precipitation estimation results from this study and the reported from relevant study almost similar pattern.

4.5.2 Irrigated rice area comparison with relevant studies

The estimated irrigated area compared with the national irrigation survey data from Bangladesh Agriculture Research Council (BADC, 2018). The irrigated area is mainly defined in the country as the form of groundwater use irrigation by different types of irrigation pump and the surface water irrigation as cannel, dam, and others. The 80% of total irrigated area is used groundwater irrigation. As a result, the number of irrigation pump is an important indicator of irrigated area. The higher number of irrigation pump refers the higher percentage of area under irrigation. We compare our result with the number of irrigation pump over the country. In **figure 4.16** shows the different types of operating irrigation pump in Bangladesh. As the deep tube well (DTW) irrigation pump lifted water from deep aquifer and the irrigation coverage area also larger. The installation cost of the DTW is very high and generally government organization installed the pump among the farmer co-operative level. The shallow tube well (STW) is comparatively less irrigated coverage area and installed under the farmer ownership and the most convenient irrigation system in the country. The low lifted pump (LLP) is the very small irrigation coverage irrigated area and low-cost operation. As the DTW number is almost fixed after 2011 but the STW irrigated pump increased drastically up to 2014 and decreased from 2015. The result from this study also show similar statistics in term of irrigated, supplementary irrigated and rainfed rice area.

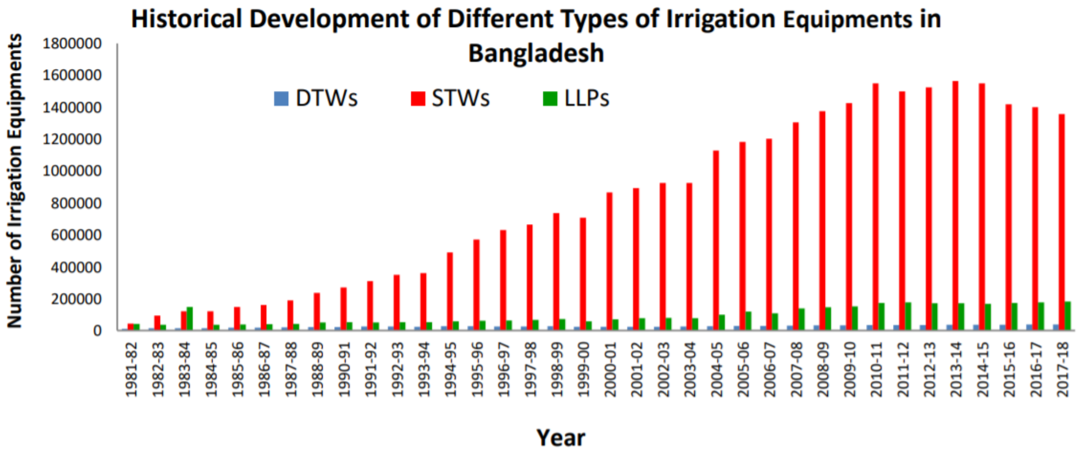


Figure 4.16 The number of operating irrigation pump over the country as deep tube well (DTW) pump, Shallow tube well (STW) pump and low lifted pump (LLP).

Moreover, the sub national level irrigated area without different irrigation pump compared with the result of this study. The number of DTW and STW irrigated pump are comparatively high number and the irrigated area also larger in Rangpur and Rajshahi division. Whereas the Sylhet and Barishal division are the comparatively less irrigated area coverage with a smaller number of irrigation pump. The irrigated area from our study also showed higher estimated in central-north (Rangpur, Mymensingh division) and central western part (Rajshahi division). On the other hand, the Sylhet, Khulna and Barishal division are less irrigated area in both estimated and reported irrigated area (**figure 4.17**).

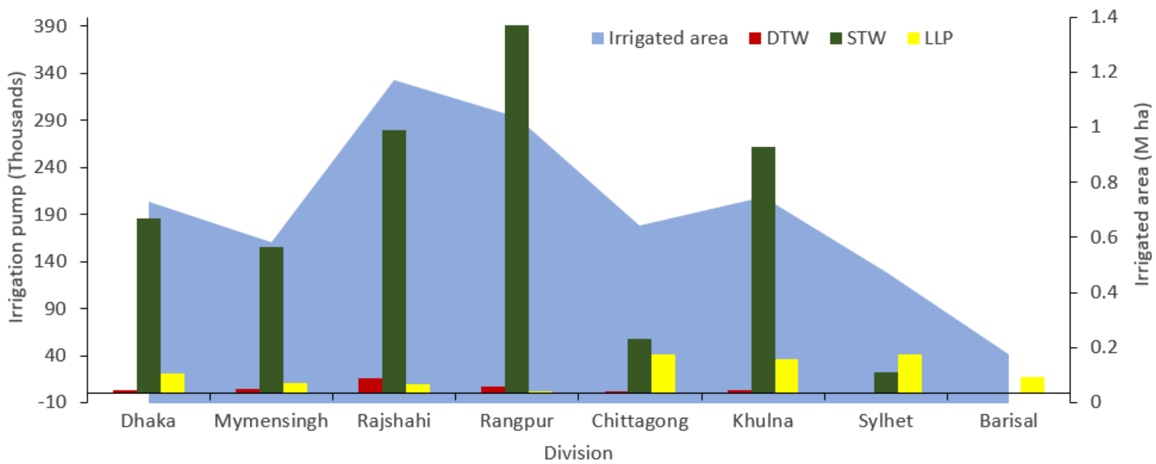


Figure 4.17 Irrigated area and the numbers of irrigation pump installed in the country under major administrative boundary (Division) level.

The area equipped for irrigation (AEI) statistics from Global irrigated Area Map (GIAM) also compared with the result from this study. Although the area equipped for irrigation does not refers as irrigated rice area but it's another indicator for irrigated rice area map. Moreover, the irrigated agriculture area and irrigated rice area also different term. The FAOSTAT reported AEI area and the estimated rice area from this study shows also good agreement. The reported irrigated area shows increasing trend over the time and the estimated rice area in boro season also showed increasing trends. The irrigated aus and amon rice comparison is very difficult due to the unavailable seasonal irrigated area statistics. But the monthly precipitation and evapotranspiration data in the country also a potential tool for seasonal irrigated rice area validation. The monthly ET and precipitation difference in the aus and amon season fluctuated through the season and the irrigated area also fluctuated. In **figure 4.18** shows the comparison result of this study estimated irrigated rice area and FAOSTAT reported AEI in Bangladesh from 2001-2018.

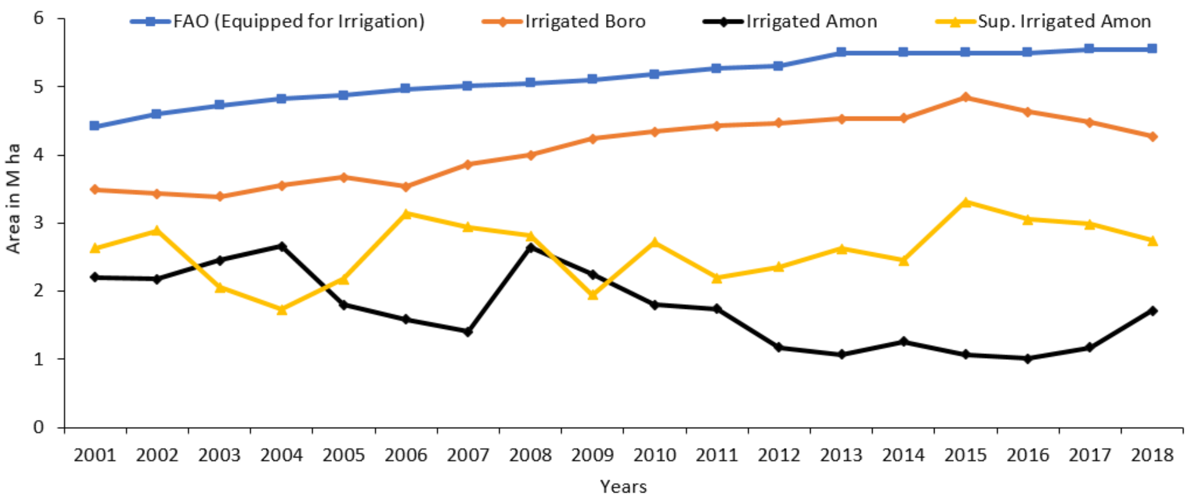


Figure 4.18 Irrigated area comparison with FAOSATA area equipped for irrigation area in Bangladesh from 2001 to 2018.

4.5.3 Uncertainties

The CWR and irrigated area mapping with remote sensing is challenging and there are several uncertainties of estimation. The CWR depends on ET and Kc value for rice. In this study used MOD16A2 dataset which greatly influenced by cloud contamination especially during rainy season. The Kc value used in this study is dimensionless monthly value, but the Kc value change every day with the crop growth. So, this is the limitation of this study and probable causes of discrepancy. The irrigated area estimated with the climatic parameter effective precipitation and CWR for entire growing period. There is difference between monthly irrigated area and seasonal irrigated area. Like in case of amon irrigated area estimation, the amon rice planted in July/August is rainy season and there is almost every day precipitation occurred. So, in July/August the amon rice area is rainfed. Similarly, September also rainfed but from October to November the rainfall pattern decreased, and it's need supplementary water and becomes irrigated. But for entire growing period the amon rice area become irrigated. The estimated irrigated area compared with national statistics reported irrigated area. The national statistics data collection based on field visit, expert opinion and previous years' experience. The statistical data also have some biasness which is another source of uncertainties.

4.6 CONCLUSION

This chapter had four objectives of estimating the CWR for AWD and CF irrigated rice, evaluate the water saving from AWD irrigated rice, the irrigated rice area mapping and the last one was validation and comparison of the result. Basically, first three objectives are based on our study and we conclude as follow.

As for the first objective, we estimated the CWR for AWD and CF irrigated seasonal rice with MOD16A2 ET and climate adjusted kc value. The CWR for AWD and CF result shows the seasonal CWR for CF irrigated boro, aus and amon rice are varied from 350 to 1020 mm and the CWR from CROPWAT model shows almost similar estimation in site specific. The annual CWR for CF and AWD irrigated rice was 55.55 km^3 and 49.45 km^3 in 2001; and 56.07 km^3 and 49.61 km^3 in 2018, respectively.

As for the second objective, the CWR save from AWD irrigation with the previous section result. The estimated CWR for CF and AWD irrigated rice used for the water saving estimation from AWD irrigation application. The result shows the CWR save from 3 to 13.49 % compared with CF irrigated CWR.

As for the third objective, we estimated irrigated, supplementary irrigated and rainfed rice for boro, aus and amon season. The rice area map from the chapter 2 used as the input for this part. The result shows that the boro rice area is almost fully irrigated and very good agreement (R^2 value 0.87) with national statistics reported data. The estimated irrigated amon rice area showed fluctuation over the time and illustrated poor agreement (R^2 value 0.55) with the reported irrigated rice area. The aus rice area shows almost rainfed and supplementary irrigated.

The outcome from this chapter will be used as input dataset for chapter 3 and 5. The irrigated, supplementary irrigated and rainfed rice area map will be used for methane emission estimation from rice paddy (Chapter 5).

Chapter 5: Methane emission estimation from rice paddy

5.1 OVERVIEW OF CHAPTER

In this chapter we first briefly discuss the background of the study and review deferent approaches in methane emission assessment from rice paddy field in section 5.2. Then we describe the adopted methodology in detailed section 5.3. In section 5.4 results, 5.5 for discussion followed by conclusion in section 5.6.

5.2 INTRODUCTION

5.2.1 Background

Agriculture is estimated to be one of the largest sources of GHG emissions in Bangladesh, estimated at 78 Tera-gram (Tg) carbon di-oxide (CO2)-eq. in 2016, to which rice cultivation contributes approximately 30% of total GHG (CO2-eq.) emitted from agriculture (‘FAOSTAT, 2019, Metane Emission from Paddy Rice in Bangladesh 2001-2018, data_7-17-2019). Rice paddy is a well-known source of methane emission, which accelerated the climate change impacts. Bangladesh is the 4th largest rice producing country in the world and greenhouse gas emission from rice paddy is a severe challenge for the country. Among the greenhouse gas from agriculture, methane is the most emitted gas. Although Methane is a short living greenhouse gas in atmosphere but it has 28-36 times global warming potential (GWP) than CO2 within the 100 years lifetime.(US EPA, 2018). Along with the methane nitrous oxide (N2O) also emitted from rice paddy field which has 265-298 times GWP than CO2 within 100 years lifetime. Annually methane emission from rice paddy field increased from 1037 Gg in 1990 to 1138 Gg in 2017 (FAOSTAT, 2017). The country total methane emission was 57.2 MtCO2e in 2018, whereas the emission from agriculture and rice paddy was 33.5 MtCO2E and 23.53 MtCO2e, respectively. Bangladesh as a climate vulnerable country, and methane emission from rice paddy accelerating the climate change impacts.

As a signatory country of Paris Agreement, the country committed to reduce the emission. Bangladesh Climate change Strategic Action Plan (BCCSAP) is developed to mitigate and resilience towards the climate change. In section 5 of this action plan, the country proposes low carbon emission strategy from agriculture with rising irrigation and water use efficiency through improved agronomic practices (MoEF, 2008). Recently the country achieved the first step status towards the developing country and committed to adopt strategy to climate change adaptation besides mitigation. The country submit 1st Intended Nationally Determination Contributions (INDC) report to United Nation Framework Convention on Climate Change (UNFCCC) and committed to reduce emission from energy, transportation, and industrial sectors conditionally 15% and unconditionally 5% by 2030 (Government of Bangladesh, 2015). The plan mentioned If the world fails to take ambitious action, the costs to Bangladesh of climate change could amount to an annual loss of 2% of GDP by 2050 and 9.4% of GDP by 2100. Bangladesh therefore wants to play its part in the global collective action to reduce future emissions as part of a robust and ambitious international agreement. Agriculture is one of the leading emissions sectors, but it does not pay much attention in the action plan. Although, there is huge potential to reduce GHG emissions from agriculture. To adopt the greenhouse gas emission reduction from agriculture, the proper information on emission is very important. There is no national emission inventory dataset for emission estimation. This study is attempts to estimated greenhouse gas (Methane) emission estimation from cultivated rice paddy in Bangladesh.

5.2.2 Objectives

Therefore, the objectives of this chapter are:

1- To estimate methane emission from CF irrigated rice paddy field with remotely sensed data and IPCC model.

2- To measure methane emission from AWD irrigated rice paddy field

3- To evaluate the methane emission reduction with AWD irrigation implementation, and

4- To evaluate the AWD irrigation status, constraints, and potential solutions in Bangladesh.

5.2.3 Literature review

So far there are a huge number of studies conducted on methane emission estimation from various sources as well as from rice paddy field in regional and global scale. The methane emission estimation studies are generally based on; (i) Site specific field experiment and simulation (ii) processed based modelling and simulation, and (iii) remote sensing-based methane emission concentration estimation.

Intergovernmental panel on climate change (IPCC) guideline for GHG’s emission from agriculture is the most widely used methane emission estimation methods in the research arena. The model accounted the rice paddy field information and developed default value for methane emission factor over globe. The revised version of the guideline also evaluates the site-specific emission factor methane emission estimation. The default values for methane emission factors are validated with various national inventory data sources and relevant research work(Guidelines, Greenhouse and Inventories, 2006).

Ito et al., (2019) estimated the methane emission from various anthropogenic sources in East Asia from 199o to 2015 with Emission Database for Global Atmospheric Research version 4.3.2 (EDGAR) and Vegetation Integrative Simulator for Trace gases (VISIT) model. The result compared with other inventories and found very good agreement. The study found that the 88% of total methane emission in Eat Asia from anthropogenic sources and the urban, agricultural land and wetland as the hotspot of methane emission.

Khan *et al.*, (2015) estimated the methane emission from dry season irrigated rice paddy field in Bangladesh. The study conducted intensive field experiment in 6 different rice paddy field and collected the methane emission data with close chamber method. The continuous flooded irrigation and alternate wetting and drying irrigation techniques with various water regime and interval period were tasted. The result found that the methane emission from AWD irrigated rice were 13.349 $g/CH_4/m^2$/season, which 28.08% lower than the CF irrigation emission. The study also compares the yield, quality of gain and production cost for AWD and CF irrigated rice.

Another study based on field experiment data by Ali, Hoque and Kim, (2013) discuss the CH4 and N2O emission in Bangladesh under CF and AWD irrigated condition and organic parameters amendment rice paddy field to evaluate the CH4 emission reduction from AWD irrigation. The study also used the close chamber for methane and nitrous oxide measurement. The finding from their study mentioned that Biochar and calcium carbide amendments, acting as nitrification inhibitors, decreased N2O emissions by 36–40 % and 26–30 % under continuous and intermittent irrigations, respectively.

The model based methane estimation study by Khan and Saleh, (2015) estimated methane emission for dry and wet season rice paddy field with CH4MOD2.5 model, IPCC model and field data in Bangladesh. The study use IPCC guided adjusted value from field study and run the model for seasonal methane emission and compared with the IPCC model-based estimation result. The result shows that the estimated methane emission from IPCC model was 1071 Gg/yr^{-1} whereas the CH4MOD2.5 estimated methane emission rate was 464 Gg/yr^{-1}. The study used the statistical data on rice cultivated area in Bangladesh.

Begum *et al.*, (2019) evaluate the methane emission from rice paddy field DayCent rice version model and field data in Bangladesh. The study evaluates the organic amendment, different water regime (AWD and CF), and yield for methane and nitrous oxide emission estimation from rice paddy field. The result found that integrated management is a promising option for farmers and policy makers interested in either yield increase, GHG mitigation or both. Yield scaled emissions intensity under AWD was found to be about 24% lower than carbon sequestration, GHG emission and yield under water, residue, organic fertilizer, and manure management.

Remote sensing based methane emission estimation study by Hayashida *et al.*, (2013) studied methane emission over the monsoon Asia with scanning imaging absorption spectrometer atmospheric chartography (SCIAMACHY) column averaged methane concentration data, satellite data derived indices as land-surface water coverage (LSWC) and the normalized difference vegetation index (NDVI) and compares with bottom up inventory dataset. The study found very good correlation of estimated methane concentration with NDVI and LSWI indices (0.6). The CH4 concentration value is high in the region where rice cultivated and demonstrated strong r value over the region. The satellite observation and remote sensing data derived various indices could be a very useful too estimated the methane emission from rice paddy field.

Arai et al., (2018) studied methane emission estimation with dynamic land surface character with remotely sensed data and ground flux data in Mekong delta Vietnam. The study used (Phased Array type L-band Synthetic Aperture RADAR) PALSAR-2 dataset for rice paddy field inundation condition detection and the inundated/non-inundated condition dataset with flux data reproducible model to estimated methane emission. The PALSAR-2 surface inundated condition result compared with AMSR-2 LSWC and MODIS LSWI indices and found PALSAR-2 dataset is highly potential to estimate the soil inundation condition and could be an important tool to estimated methane emission from rice paddy field.

Peters, Bennartz and Hornberger, (2017) estimated methane emission from inundated land in Bangladesh with remote sensing dataset. The study used methane column mixing ratio from Atmospheric Infrared Sounder (AIRS), Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), and Greenhouse Gases Observing Satellite (GOSAT) to estimate the contribution of Bangladesh emissions to atmospheric CH4 concentrations. The RS based inundation area used as proxy data and apply an inverse advection model to evaluate the emission and estimate the average annual CH4 surface fluxes to be 4, 9, and 19 mg CH4 m^{-2} h^{-1} in AIRS, SCIAMACHY, and GOSAT, respectively. The result from the study compared with field observation data which ranged between 0 and 260 mg CH4 m^{-2} h^{-1}.

It is h challenging to estimated methane emission from rice paddy field. Both the model and satellite-based estimation shows uncertainties. The previous studies are used different techniques to estimated methane with flux data, model based and satellite-based data. In this study, we use satellite data derived rice area (chapter 2), irrigated rice area map (chapter 3) for water management, local rice paddy management practices adjusted parameter with IPCC model to estimate methane emission from rice paddy field.

5.3 METHODOLOGY

The methodology adopted for this chapter mainly composed of (i) seasonal rice area map, 2001-2018, (ii) Irrigated, supplementary irrigated and rainfed rice area map from 2001 to 2018, (iii) local climate and practice management accounted parameters and (iv) IPCC model to estimate the methane emission from rice paddy field. The flowchart of this chapter shows in **figure 5.1**.

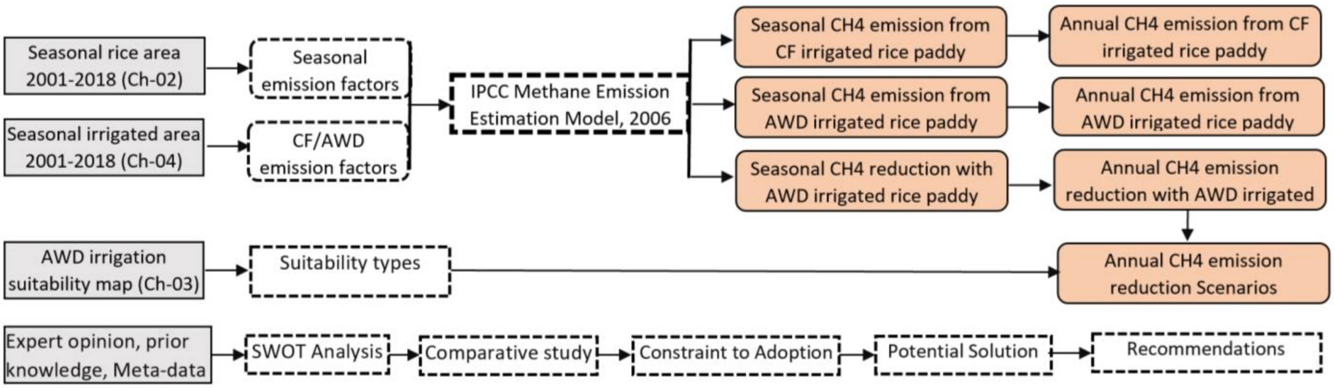


Figure 5.1 Flowchart of the research methodology.

5.3.1 Dataset used

Several datasets used for this chapter. The rice area extend dataset for chapter, the irrigated, supplementary irrigated and rainfed rice area dataset from chapter 2, methane emission estimation parameters from literature survey, expert opinion and others relevant sources used in this study. The IPCC model and default value for some parameter used from the IPCC guideline. The model result compared with inventory data and relevant studies.

5.3.2 Methane emission estimation

The IPCC revised guideline 2006 used for the methane emission estimation. In the model, the emission factor and scaling factors for various amendment adjusted for the country specific emission factor. The daily emission factor estimated by the IPCC guideline and local condition adjusted value, the cultivated period for the seasonal rice considered 120days per season. The remote sensing derived rice area from the chapter 2 used as the model parameter. The water regime case, we used the RS based irrigated, supplementary irrigated and rainfed rice area data from chapter 3. The organic amendment case, we consider the straw incorporated farm manure in this study. The ecosystem amendment and soil data are not considered for this study. The basic equation for methane emission estimation from rice paddy field is as follow equation 5.1.

$$CH_{4\,\text{Rice}} = \sum i,j,k(EFi,j,k \times ti,j,k \times Ei,j,k \times 10^6) \qquad 5.1$$

Where
CH4 Rice = Annual Methane emission from rice paddy field, Gg CH4 yr-1
EFi,j,k = Daily Emission factors under i,j,k conditions, kg CH4 ha-1yr-1
ti,j,k = Cultivation period for i, j, and k conditions, days
A i,j,k = Annual Rice cultivated area under i, j and k conditions, yr
i,j and k= Represent different ecosystems, water regimes, type and amount of organic amendments, and other condition under which CH4 emissions from rice may vary.

5.3.2.1 Emission factor estimation

The emission factor is very important part for the methane emission estimation. In this part we used several adjusted scaling factors for daily emission factor estimation. The daily baseline emission factor for rice paddy methane is used IPCC default value 1.30 kgCH4h-1d-1. The scaling factor for different water regime, we used 1 for irrigated rice area case, 0.70 for supplementary irrigated case and 0.28 for rainfed rice area case(Guidelines, Greenhouse and Inventories, 2006). The scaling factor for preseason water regime case, as the crop intensity is very high and except few lowland rice area most of the rice paddy field experienced double or triple rice cropping pattern or rice and others crop double and triple crop in the country and we didn't considered it and used the default value 1. In organic amendment case. This study considered straw incorporated amendment and the soil, ecological and practice management did not consider for this study. Finally, the daily emission factor estimated with equation 5.2.

$$EF_{\text{i}} = (EFc \times SFw \times SPp \times SFo \times SFs,r) \qquad 5.2$$

$\boldsymbol{EFi}$ = Adjusted daily emission factor for cultivated rice area
$\boldsymbol{EFc}$ = Baseline emission factor without organic amendment
$\boldsymbol{SFw}$ = Scaling factor for different water regime
$\boldsymbol{SFp}$= Scaling factor for preseason water regime before cultivation period
$\boldsymbol{SFo}$= Scaling factor for organic amendment
SF s,r= Scaling factor for Soil type, rice cultivar etc.

5.3.2.2 *Scaling factor for organic amendment estimation*

The scaling factor for organic amendment in term of straw incorporation considered in this study. The rice harvesting system of the country mostly manually harvested the rice paddy. Due to the huge demand of rice straw as cattle food, the farmer cut the rice with very short portion left in the field. Even the farmer harvested the rice straw left higher portion the other people collect it for cattle food and fuel for cooking. As a result, amount of straw left in the field, the farmer does not burn it. Prior to the transplanting date, the farmer ploughed the land with the straw and used as organic matter. In this study, we considered this amendment and the straw incorporated value are used from expert opinion, prior knowledge and literature survey(Khan and Saleh, 2015). The straw incorporated manure value varied from season to season and rice types, but we adopted the seasonal value. The IPCC guided equation 5.3 used for this study.

$$SF_o = [1 + \{(ROAi\ RS \times CFOAi\ RS) + (ROAi\ FM \times CFOAi\ FM)\}]^{0.59} \qquad 5.3$$

$ROA_{i\ RS}$ = Application rate of rice straw (Boro = **0.70**, Aus/Amon = **0.40)**
$ROA_{i\ FM}$ = Application rate of Farm manure (**0.60**)
$CFOAi_{RS}$ = Conversion factor for organic amendment (Rice Straw) =**1**
CFOAi FM = Conversion factor for incorporated shortly before cultivation = **0.14**

5.3.2.3 *Seasonal methane emission estimation*

The daily emission factors and the scaling factors used for the daily adjusted methane emission rate estimation. The daily emission rate use for the seasonal emission estimation. Daily emission factors multiply with the length of growing period for seasonal emission rate calculation. The three different rice growing season, boro, aus and amon rice growing season considered to estimated seasonal methane emission. The seasonal rice area map from the previous chapter used for the seasonal emission estimation and representation. Finally, the methane emission from boro, aus and amon rice paddy from 2001 to 2018 estimated.

5.3.2.4 *Annual methane emission estimation from CF irrigated rice paddy fields*

The estimated seasonal methane emission rate and amount used for the annual methane emission estimation. The methane emission from there different rice season composed as an annual emission. The annual rice growing map from the chapter 2 used for the annual methane emission representation. The annual methane emission from 2001 to 2018 estimated and the result compared with the inventory and relevant dataset.

5.3.2.5 *Annual methane emission estimation from AWD irrigated rice paddy fields*

Based on the IPCC guideline, the rainfed rice paddy emission factors considered as AWD irrigation emission factors. In case of rainfed rice cultivation, paddy field water regime depends on the rainfall and naturally the paddy field suffers for continuous flooded condition. In AWD irrigation system, farmers manually control the water regime and interrupt the flooded condition. In this study, we used IPCC default value for AWD irrigated rice paddy emission factors. But the dataset used from chapter-2 and chapter 4, along with special concern on irrigated, supplementary irrigated and rainfed rice paddy data.

5.3.2.6 *Annual methane emission reduction with AWD irrigated rice paddy fields*

Methane emission from CF irrigated and AWD irrigated rice paddy field estimated with RS_IPCC based model. The irrigation water regime considers for AWD irrigated rice paddy emission scaling factor determination. With the AWD irrigated rice emission factor, seasonal AWD irrigated rice paddy emission has been estimated. Finally, the annual methane emission reduction from AWD irrigated rice paddy field estimated. Moreover, the methane emission reduction scenarios have been proposed based on the AWD irrigation suitability data and three different scenarios; (i) methane emission save with physically AWD irrigated suitable rice area, (ii) methane emission save with physio-climatically AWD irrigated suitable rice area, and (iii) methane emission save with Socio-economically AWD irrigated suitable rice area.

5.4 RESULTS

5.4.1 Emission factor result

The daily emission factor results with considering the baseline emission factor, manure amendment, and different water regime in term of irrigated, supplementary irrigated and rainfed condition shows seasonal variation. The daily emission factor for boro rice is estimated highest among the season and is 1.822 kg/ha^{-1}/d^{-1}). The boro season is considered fully irrigated and the scaling factor was constant, whereas the amon season is considered irrigated, supplementary irrigated and rainfed value are 1.63, 1.14 and 0.45 kg/ha^{-1}/d^{-1}), respectively. The aus season also exposed similar trend as amon rice (**table 5.1**). Considering the different water regime, the daily emission factor changed over the season. rainfed and scaling factors are different, Moreover, the organic amendment scaling factor also different for the boro, aus and amon season.

Table 5.1 The daily emission factor for boro, aus and amon rice paddy

	Daily emission factor ($kgha^{-1}d^{-1}$)		
Rice season	Irrigated	Supplementary irrigated	Rainfed
Boro rice	1.822	1.27	0.61
Amon rice	1.63	1.14	0.45
Aus rice	1.19	1.19	0.47

5.4.2 Scaling factor of organic amendment result

The straw incorporated organic amendment scaling factor for boro rice 1.40 whereas the amon and aus rice season are 1.31 and 1.26. The plant height varied from season to season and the harvesting period weather condition influenced the filed incorporated organic amendment variation (**figure 5.2**). The

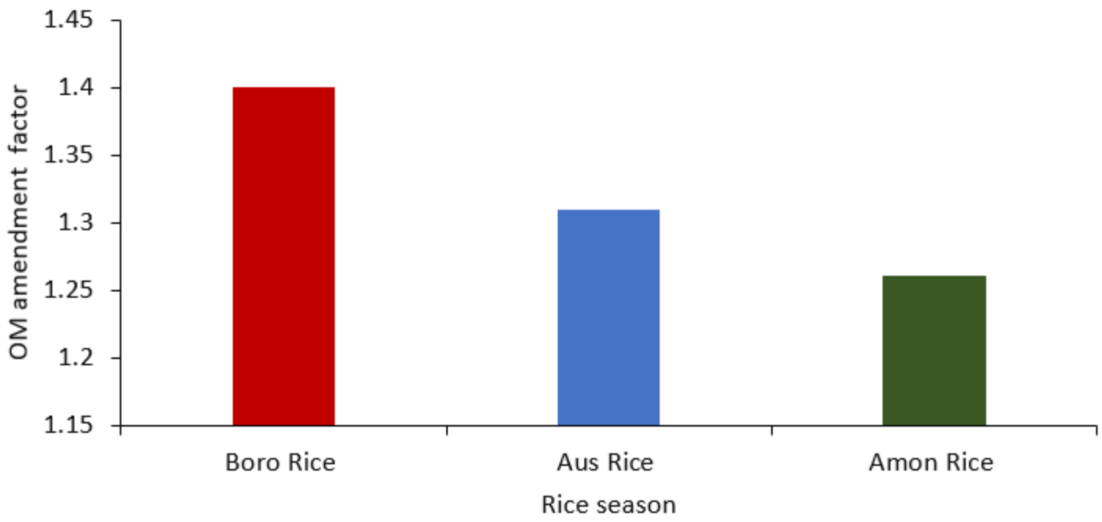


Figure 5.2 Rice straw incorporated organic amendment factor for seasonal rice.

5.4.3 Seasonal methane emission result

The adjusted daily emission factor used seasonal emission factors also observed variation among the seasons. The seasonal emission factors are varied, firstly based on the rice growing season and secondly based on the irrigation practices. The seasonal emission factor for irrigated boro, aus and amon season rice area 218 kg/CH4/ha^{-1}, supplementary irrigated and rainfed case are 195.6 kg/CH4/ha^{-1} and 204.3 kg/CH4/ha^{-1}, respectively. Similarly, the seasonal emission rate for supplementary irrigated boro, aus and amon rice growing season are 152.0 kg/CH4/ha^{-1}, 136.25 kg/CH4/ha^{-1} and 143.01 kg/CH4/ha^{-1}, respectively. In case of rainfed irrigation system the similar values are 61.05 kg/CH4/ha^{-1}, 57.50 kg/CH4/ha^{-1} and 54.76 kg/CH4/ha^{-1}, respectively. The rainfed irrigation system depends precipitation and in IPCC guideline case, it's considered as AWD irrigation system and scaling factor fixed as 0.28. The details seasonal emission factors for irrigated, rainfed and supplementary irrigated case is shown in **figure 5.3**.

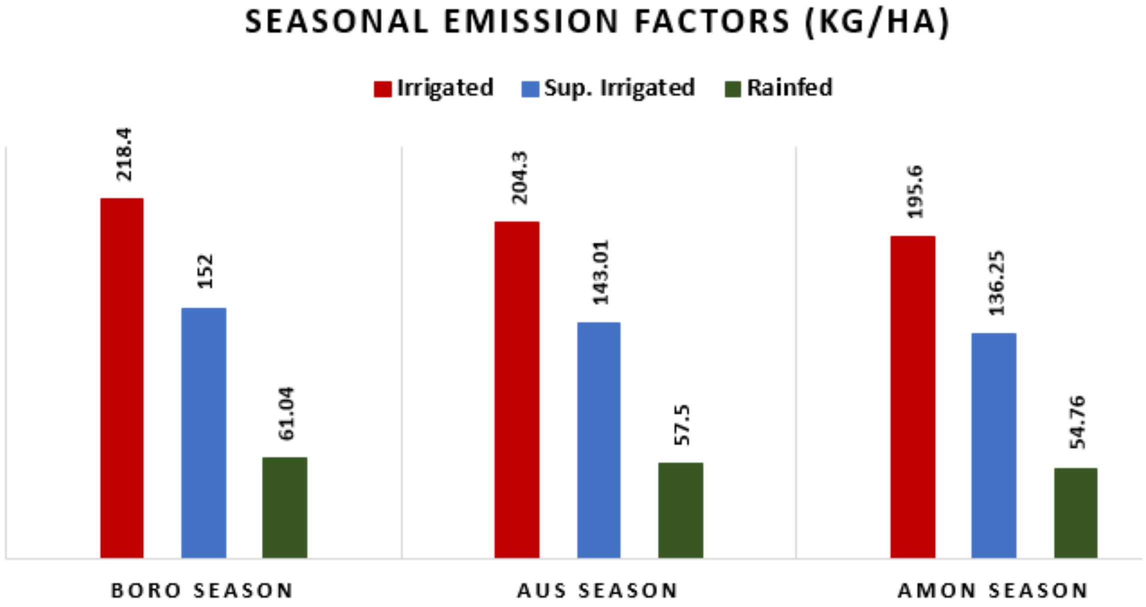


Figure 5.3 Seasonal methane emission rate from irrigated, supplementary irrigated and rainfed rice paddy field (in kgCH4 ha^{-1})

The seasonal methane emission from boro, aus and amon rice are also showed the seasonal difference. The boro season estimated methane emission increased 797.49 GgCH4 to 1029.44 Gg CH4 from 2001 to 2018 and followed by Amon (481.21 to781.91 Gg CH4) and Aus season (106.26 to 111.05 Gg CH4). There are three causes of the methane emission variation among the season, (i) the different daily emission rate, (ii) the seasonal rice cultivated area fluctuation and (iii) different irrigation practice dominant as boro is dominant irrigated, aus rainfed and amon rice season is dominant by irrigated and supplementary irrigated. **Figure 5.4** shows the seasonal methane emission from rice paddy field over the study area.

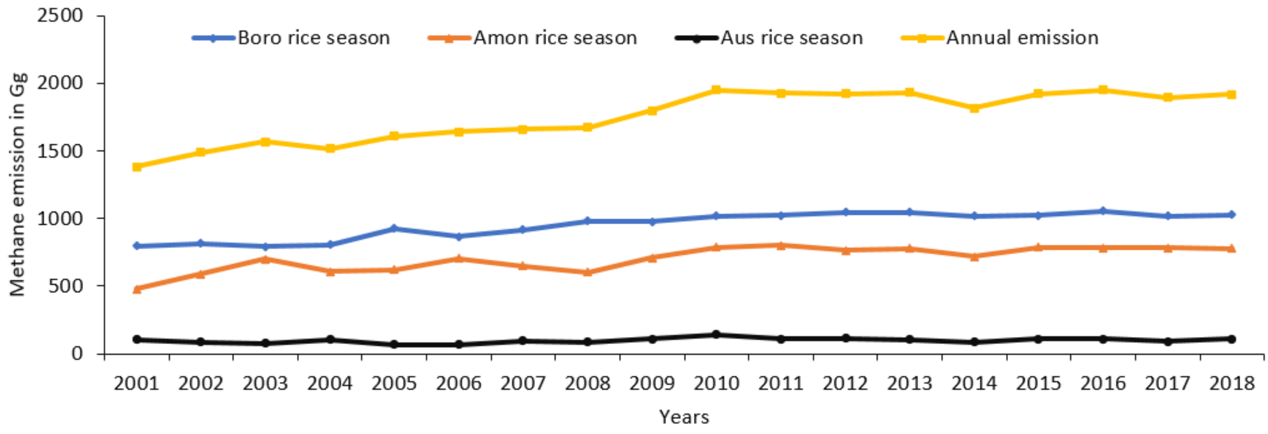


Figure 5.4 Methane emission from seasonal and annual total rice paddy field of Bangladesh from 2001 to 2018

5.4.4 Annual methane emission from CF irrigated rice paddy field

The Annual methane emission was 1384.97 Gg CH4 in 2001 and 1941.21 Gg CH4 in 2018. The methane emission from rice paddy field in Bangladesh gradually increasing over the time. The annual methane emission increased from 1384.97 Gg CH4 in 2001 to 1921.46 Gg CH4 in 2018. The rice growing season specific emission factor associated with the different irrigation application used methane emission estimation could be a more reliable tools for emission estimation. The Methane emission distribution showed that the central north part of the country is highest emission region and the central-southern part of the country is the lowest emitted region due to the rice cropping patten change single to double and triple rice and irrigation mode. In **figure 5.5** shows the annual methane emission distribution map from 2001 to 2018.

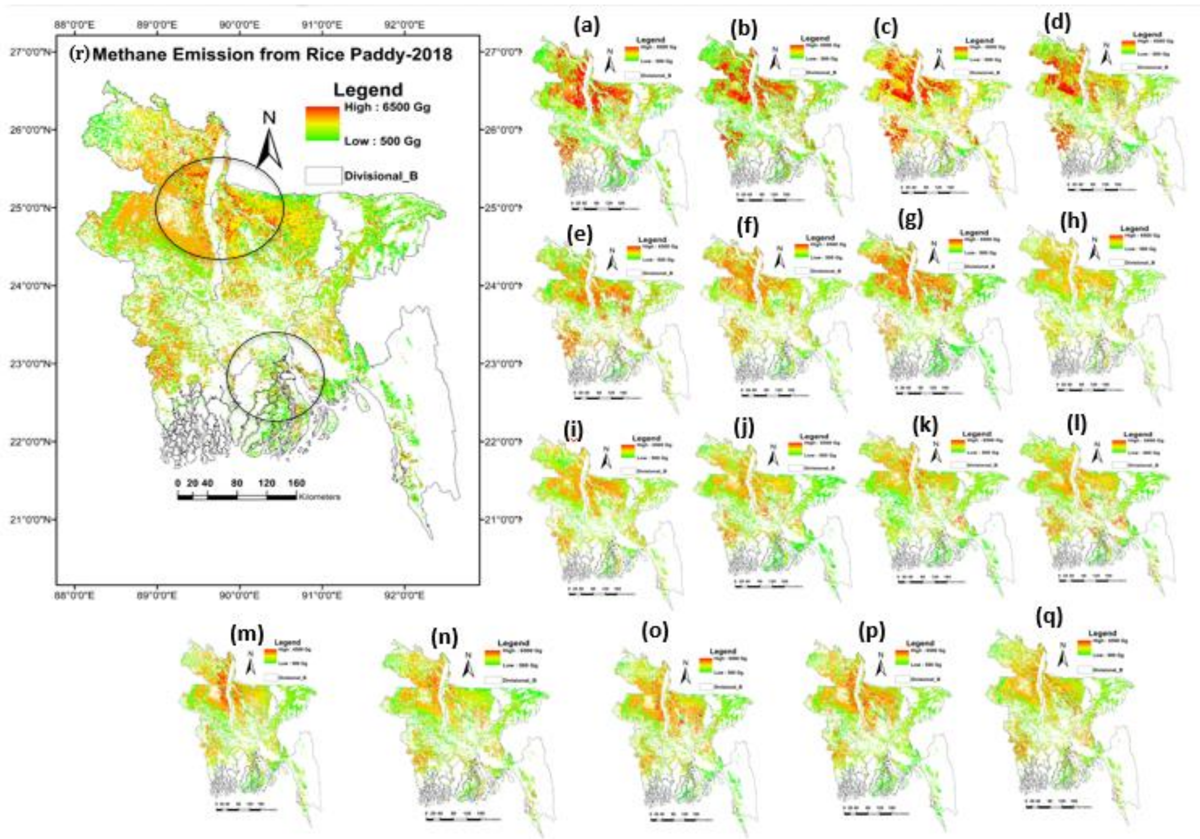


Figure 5.5 Annual methane emission distribution from rice paddy field of Bangladesh; (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, (j) 2010, (k) 2011, (l) 2012, (m) 2013, (n) 2014, (o) 2015, (p) 2016, (q) 2017 and (r) 2018.

5.4.5 Methane emission from AWD irrigated rice paddy field

AWD application reduced methane emission from rice paddy field. The IPCC default emission scaling factor 0.28 for AWD irrigated rice paddy have been used for this study. With the AWD irrigation emission factor and organic amendment scaling factor apply for season specific emission estimation. The AWD irrigated boro rice season emission rate 61.4 kgCH4 and CF irrigated case 218.4 kgCH4. Similarly, CF irrigated seasonal emission rate for aus and amon rice are 204.3 kgCH4 and 195.6 kg CH4 whereas the AWD irrigated emission rate is 57.5 and 54.76 kgCH4, respectively (**figure 5.6**).

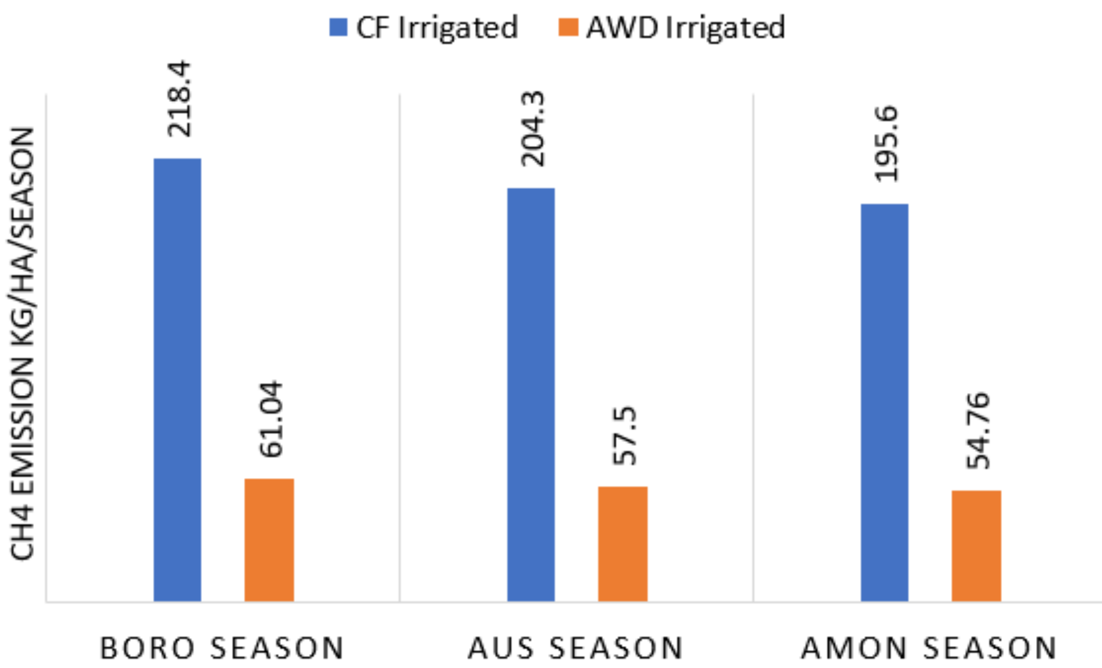


Figure 5.6 Seasonal emission factor for AWD irrigated rice paddy field and CF irrigated rice paddy field in Bangladesh.

Considering the seasonal emission factor for AWD irrigated rice case and the seasonal irrigated, supplementary irrigated and rainfed rice area data (Chapter 4), the seasonal methane emission with AWD irrigated rice paddy field have been calculated. Although amon season is the lowest seasonal methane emission rate but due in term of seasonal emission expose the highest seasonal emission. The emission varied from minimum in 2005 was 437.59 Gg**CH4** and maximum in 2006 was 619.14 Gg**CH4**. The probable causes of higher emission are; (i) Only irrigated area are consider as AWD irrigated rice area and amon season has comparatively fewer irrigated area, (ii) the higher supplementary irrigated area, and (iii) the total seasonal cultivated rice area is the largest in the study area. The boro season is the second largest seasonal methane emission with AWD irrigated rice paddy field. The seasonal total emission is varied from 215.13 Gg**CH4** in 2002 to maximum in 2015 was 310.60

Gg**CH4**. The boro season is almost fully irrigated and the AWD irrigated drastically reduced the emission rate. The aus season is the lowest seasonal total emission due to the fewer cultivated and rainfed dominant season. In **figure 5.7** shows the detailed seasonal emission total with AWD irrigated rice paddy field.

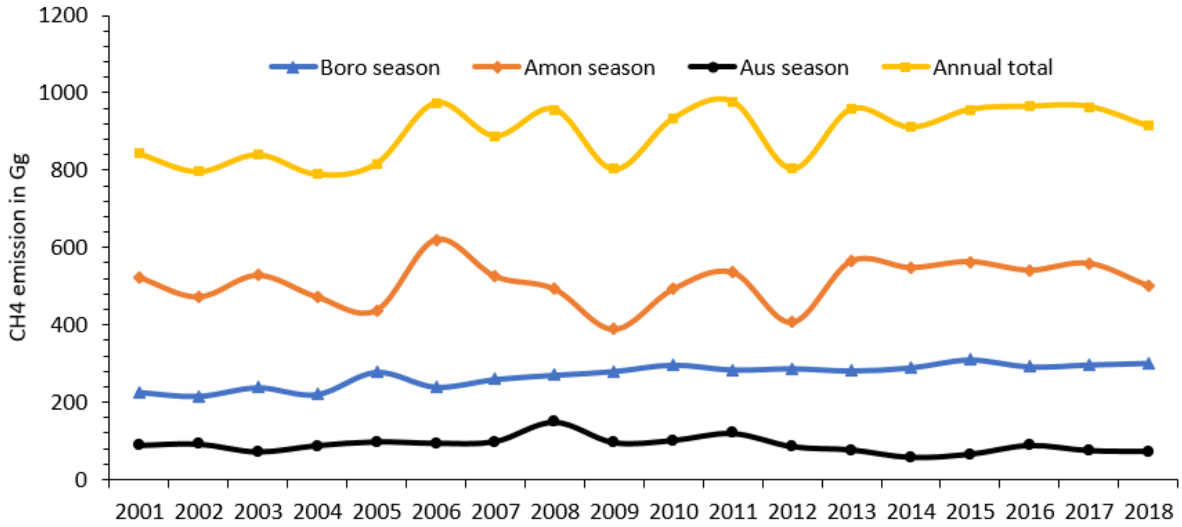


Figure 5.7 Estimated methane emission from AWD irrigated boro, aus and amon season rice paddy field including annual total methane emission from 2001 to 2018.

5.4.6 Methane emission reduction with AWD irrigated rice paddy field

AWD and CF irrigated seasonal emission rate and the irrigation water regime considered annual methane emission estimated with RS_IPCC model. The CF irrigated rice paddy based annual estimated methane emission was 1698.17 Gg in 2001 and becomes 19.39.76 GgCH4 in 2018. At the same time, the AWD irrigated rice paddy based estimated methane emission was 837.10 GgCH4 and 875.17 GgCH4, respectively. In this study, we considered only the irrigated area for AWD irrigated methane emission estimation case. The AWD irrigation application could reduce annually 44% to 54% methane emission in Bangladesh. The highest reduction rate was 54.52% in 2009 and the lowest was in 2003. The reduction rate fluctuated among the year due to the irrigated rice area fluctuation. In **figure 5.8** shows the methane emission from CF and AWD irrigated rice paddy and emission reduction with AWD irrigation in Bangladesh from 2001 to 2018.

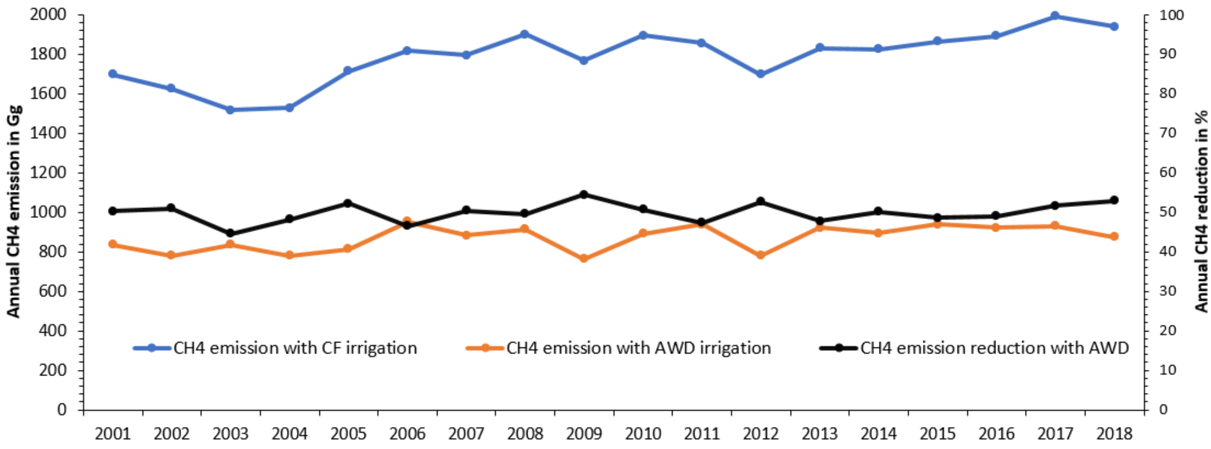


Figure 5.8 Estimated annual methane emission with CF irrigated rice paddy field, AWD irrigated rice paddy field and annual methane emission reduction rate with AWD irrigation in Bangladesh from 2001 to 2018.

Moreover, the scenario-based methane emission estimated considering the AWD irrigation suitability ration from chapter 3. We proposed the basic scenarios of methane emission save with emphasis on; (i) Physically suitable AWD irrigated area (98%) consider under AWD irrigation implementation, (ii) Physio-climatically suitable AWD irrigated area (48%) consider under AWD irrigation implementation, and (iii) Socio-economically suitable AWD irrigated area (58%) consider under AWD irrigation implementation (**figure 5.9**). With physically suitable AWD irrigated area under AWD irrigation, the annual methane emission saving amount is 669.23 Gg CH4 to 1045.66 Gg CH4. With physio-climatically suitable area considered under AWD irrigation, the methane emission saved from 348.61 Gg CH4to 543.62 Gg CH4. Similarly, with socio-economically suitable area saved from 397.27 Gg CH4 to 619.82 Gg CH4 methane in the study area.

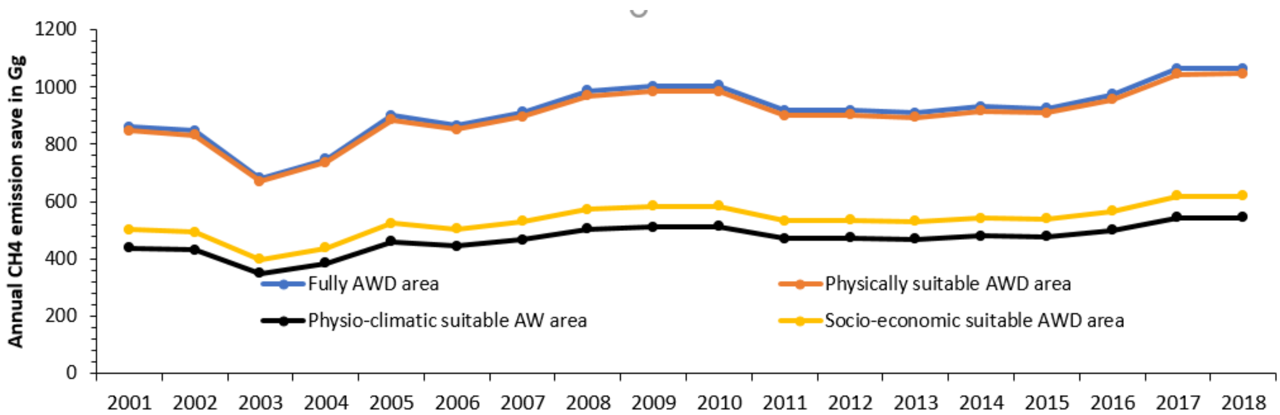


Figure 5.9 Estimated methane emission scenario's with total rice area under AWD irrigation, physically suitable area under AWD irrigation, physio-climatically suitable

area under AWD irrigation and socio-economically suitable area under AWD irrigation in Bangladesh.

5.5 DISCUSSION

5.5.1 Emission and scaling factor comparison

The methane emission factors from this RS-IPCC model based compared with relevant studies. The result compared with CH4MOD2.5 (Khan and Saleh, 2015), DayCent model (Begum *et al.*, 2019) and methane flux field data based estimation(Ali, Hoque and Kim, 2013). Although, the studies data input and methodology are different, but our result shows logically comparable with those studies result. Especially, the remote sensing data based seasonal rice area and irrigated regime accounted. The season specific and different water regime makes the difference in seasonal emission factors from the relevant studies. Moreover, in our study the irrigation practice and season specific emission factors accounted. **Table 5.2** shows the details comparison result.

Table 5.2 Comparison our RS-IPCC based seasonal emission rate with CH4MOD2.5, DayCent, and field level CH4 flux data.

	Annual emission rate (KgCH4/ha/yr)		
Estimation Methods	Boro	Aus	Amon
CH4MOD2.5(Khan and Saleh, 2015)	99.6 – 116.4		24.48
DayCent (CF)	150-251		
DayCent (AWD)	150		
CH4 Flux (CF)	106-129		
CH4 Flux (AWD)	90		
RS_IPCC	69.76 to 218.4	57.-204.3	55.00- 195.6

5.5.2 Methane emission result comparison with inventories data

The annual methane emission result from this study compared with the inventory dataset. The result slightly under-estimated from EDGAR3.2 emission inventory and PIK estimation; and over-estimated from FAOSTAT and CIAT inventory estimation. But the trend of methane emission estimation is almost similar. The inventory emission estimation methodologies are different from our study and the input dataset also varied from each other are the probable causes of this discrepancy. We compared the result with US EPA dataset and found good agreement. The similar study with statistical data used estimation result shows similar trend as this study. The methane estimated with RS_IPCC model, we used seasonal rice area and seasonal irrigated, supplementary irrigated and rainfed rice area data. Moreover, the organic amendment and different water regime evaluated in this study. As a result, the estimated result demonstrated such discrepancy with inventory estimation. **Figure 5.10** shows the comparison details.

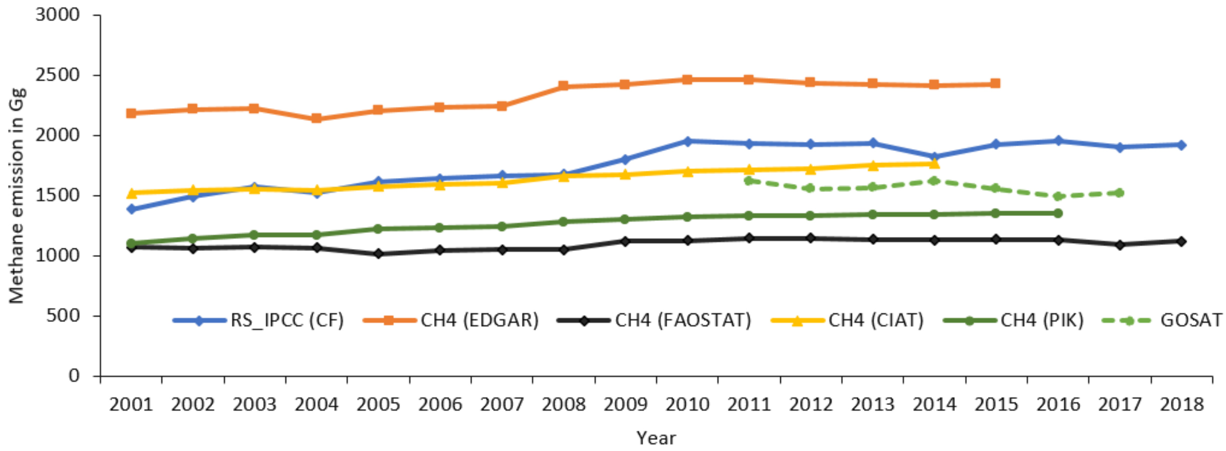


Figure 5.10 Comparison of our RS-IPCC based annual methane emission from rice in paddy field Bangladesh with FAOSTAT, EDGAR3.2, CIAT and PIK inventory estimation.

5.5.3 Methane emission result comparison with Remote sensing data

Methane emission estimation result have been compared with (i) Methane emission estimation with Atmospheric Infrared Sounder (AIRS) data, Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) and Greenhouse Gases Observing Satellite (GOSAT) sensor from inundation Bangladesh (Peters, Bennartz and Hornberger, 2017) and (ii) country scale methane emission estimation with GOSAT and surface observation based result (Janardanan *et al.*, 2020). The WebPlotDigitizer have been used for the estimated methane emission data extraction from the following studies (Rohatgi, 2015).

Peters, Bennartz and Hornberger (2017) estimated atmospheric methane concentration in Bangladesh with AIRS, SCIAMACHY and GOSAT column mixing ratio data. The study used satellite derived inundated area as sources of emission and inverse advection model to estimated annual average methane surface flux. Although, the methane emission concentration from inundation area and methane emission from rice paddy are slightly different process. But rice paddy cultivated in inundated condition which is the major part of the inundated condition of Bangladesh. In figure 5.11 demarcated the monthly XCH4 concentration over Bangladesh from three different satellite. The general trends of the emission are (i) January to April showed a very small fold, (ii) April to July/August medium fold of emission and (iii) August to November is the pick of the XCH4 concentration. In figure 5.11 illustrated the estimated CH4 emission with RS_IPCC model from Boro, Aus and Amon rice season in Bangladesh. The boro rice season (December to March) is the maximum CH4 emission season which is less rainfall and natural inundated season. Satellite derived

CH4 emission during this season is highly contributed from rice paddy inundation. The aus season (April to July/August) is the monsoon season and the country experienced huge rainfall and natural inundation. Although there is very less CH4 emitted from rice paddy, but satellite observation showed higher CH4 concentration which contributed from natural inundation. The amon rice season (July to November) is also higher rainfall and surface inundated season and CH4 concentration observed highest pick in this time. Amon rice season is the largest rice growing season by area and second largest estimated CH4 emission (RS_IPCC) season (**figure 5.12**). As a result, the highest pick of CH4 concentration mostly comes from amon rice paddy field and natural inundation surface. The RS-IPCC based estimated CH4 emission and satellite derived CH4 concentration logically showed very good agreement.

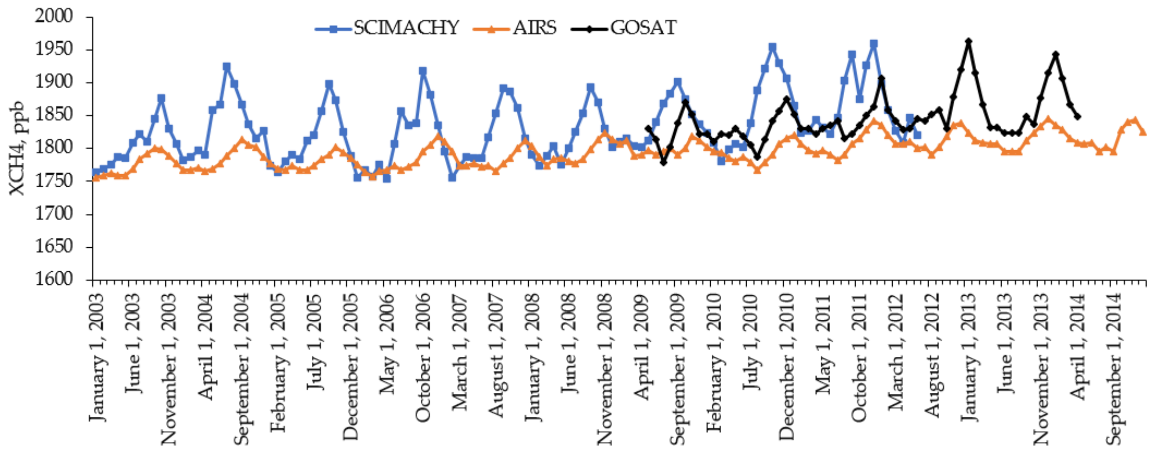


Figure 5.11 Methane emission observation from AIRS, SCIAMACHY and GOSAT satellite based estimation in Bangladesh (Peters, Bennartz and Hornberger, 2017)**.**

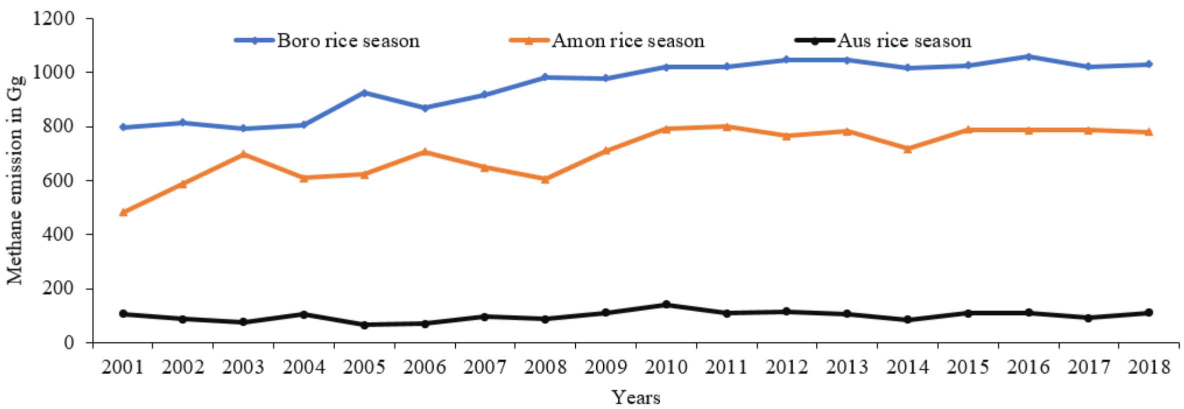


Figure 5.12 Seasonal methane emission estimation with RS based rice area and IPCC model from rice paddy in Bangladesh.

Janardanan *et al.*, (2020) estimated CH4 emission from anthropogenic and natural sources with GOSAT data, EDGAR v 4.3.2, Vegetation Integrative Simulator of Trace gases (VISIT) model, Global Fire Assimilation System (GFAS) model and transport model. The annual estimated CH4 emission from anthropogenic sources is compared with RS_IPCC model. In **figure 5.13** illustrated that the RS_IPCC model estimation is over estimated than the GOSAT prior and posterior estimation in Bangladesh. In RS_IPCC model, we considered adjusted emission factor for water regime and organic management which leads higher estimation of CH4 emission. In **figure 5.14** shows the seasonal variation of natural and anthropogenic CH4 emission. The CH4 emission from natural sources demonstrated huge seasonal variation but the anthropogenic CH4 emission trends comparatively smoothed. Among the anthropogenic CH4 emission, rice paddy cultivation is the main sources in Bangladesh. The anthropogenic CH4 emission trend shows slight pick in March/April month whereas slightly decreasing trend in June/July and again small picked in October/November. The probable cases of this variation are CH4 emission from rice paddy field.

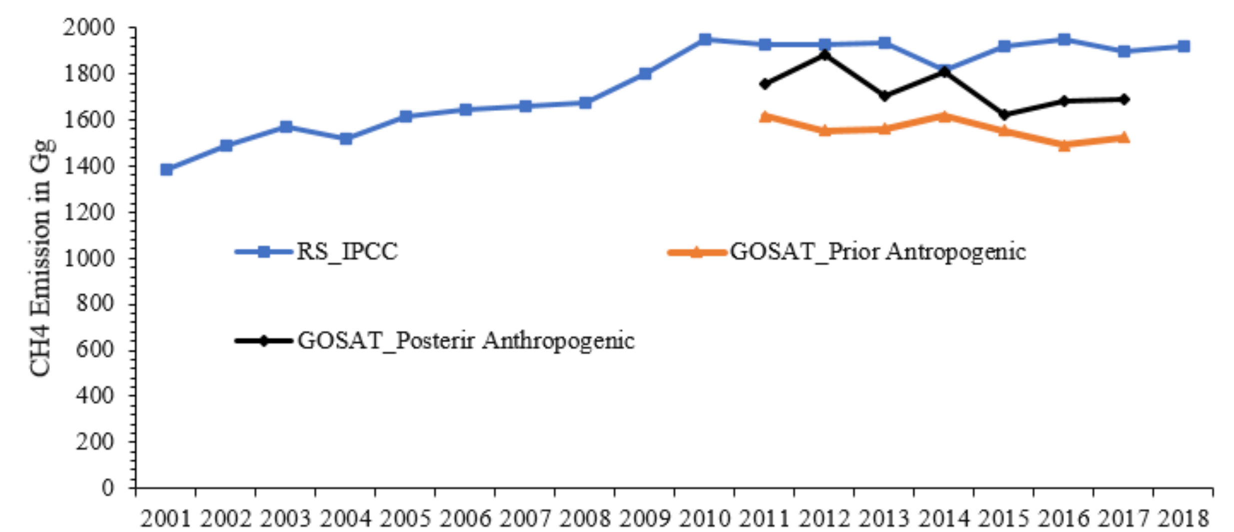


Figure 5.13 Comparison between RS-IPCC based methane emission estimation and GOSAT derived methane estimation in Bangladesh.

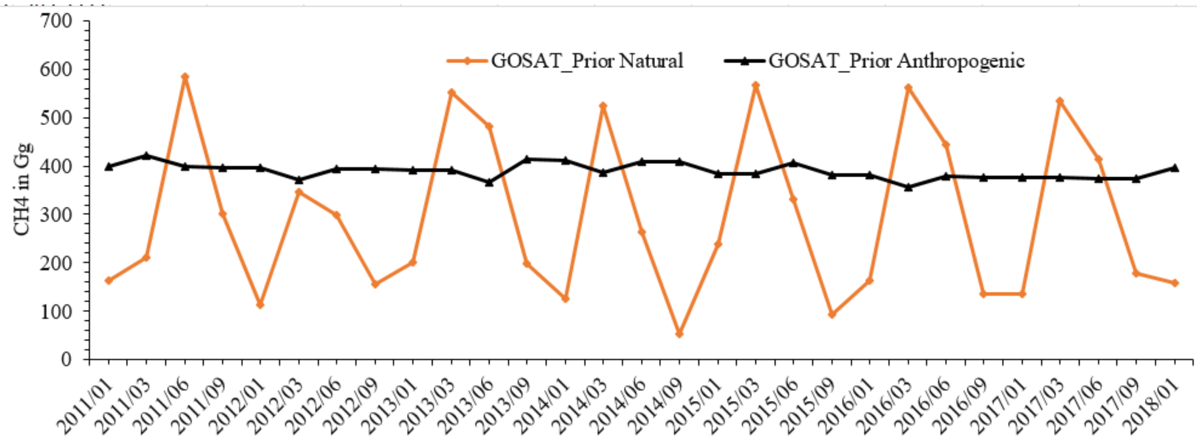


Figure 5.14 Seasonal methane emission from natural and anthropogenic sources in Bangladesh (Janardanan *et al.*, 2020)**.**

5.5.4 Methane emission result comparison with previous studies

Methane emission estimation from rice paddy field in Bangladesh with RS-IPCC model result compared with the relevant previous studies. The IPCC guideline and SPOT VGT NDVI derived rice map used methane estimation result is underestimated than RS_IPCC model estimation(Manjunath et al., 2014). The region specific emission factors, organic and water regime amendment scaling factors associated with statistical data of rice area used methane emission result shows good agreement with RS_IPCC model (Yan, Ohara and Akimoto, 2003). The IPCC guideline and region-specific emission factors evaluate methane emission estimation result showed slightly overestimated than RS_IPCC model (Sass, 2003). The field data used and model simulation methane emission estimation in Bangladesh result demonstrated great disagreement with the RS-IPCC model. The IPCC tiyer-1 methodology and country specific statistical data on rice area used methane emission estimation from rice paddy result showed very good agreement with our model estimated result (Yan et al., 2009). The United States of Environmental Protection Agency (USEPA) and national Institute for Environmental Studies, Tsukuba, Japan reported methane emission data and RS_IPCC model estimation methane emission result showed higher discrepancy (Rose and Lee, 2009). The CH4MOD2.5 estimated methane emission estimation from rice paddy in Bangladesh result showed almost half than RS_IPCC model estimation (Khan and Saleh, 2015). The emission inventory data from carbon tracker methane (Carbon Traker, 2016), the country specific methane emission (World Data Bank, 2016), and anthropogenic sources emission methane emission from rice paddy (EDGAR3.2, 2016) data also demonstrated both over and underestimation than the RS_IPCC model estimation. Although the different data used and methodological difference the relevant studies reported methane emission showed a logical trend with the RS_IPCC estimation the result. **Figure 5.15** showed the detail comparison with this study used RS_IPCC methane estimation from rice paddy.

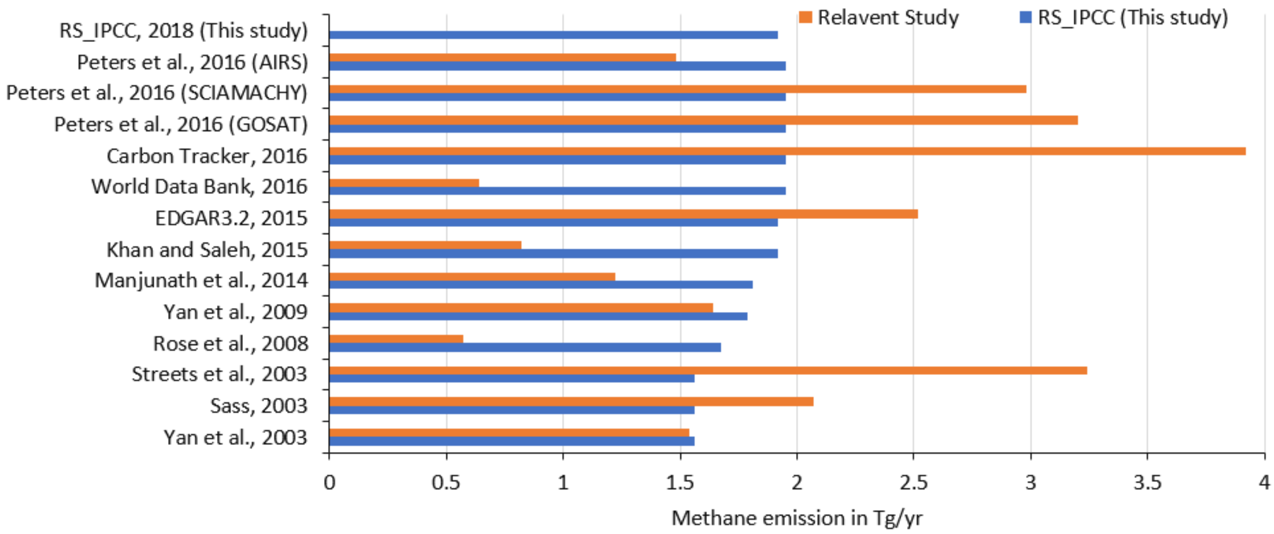


Figure 5.15 Annual methane emission estimation result from relevant studies comparison with the result of this studies in Bangladesh.

5.5.5 Performance analysis of AWD irrigation in Bangladesh

Strengths, Weakness, Opportunities and Threats (SWOT) is a proven tool for strategic and planning performance analysis. Although SWOT analysis originated from business management discipline but now widely uses for others discipline (Yuan, 2013). We conducted SWOT analysis for find out the answer to the question, "Why farmer should adopt AWD irrigation techniques?". The strengths of AWD irrigation are low cost technology, reduced methane emission, water use (Chapter 4 and 5), fuel, arsenic contamination, transmitted diseases, and production cost; increase yield, income, and nutrient contains. The major weakness of AWD irrigation are intensive observation, increases weeds, applicable only for control irrigation system, and well drainage system required. AWD irrigation system offers opportunities such as climate change mitigation, groundwater saving, the suitable condition (Chapter 3), and sustainable rice production. There are a very few threats of AWD irrigation implementation such as production reduction in case of inappropriate application and N2O emissions. Among the threats, N2O emission reduction is comparatively low in terms of GWP of methane emission reduction and yield reduction happened only in case of inappropriate application otherwise increased. The detailed result of SWOT analysis shows in **figure 5.16.**

STRENGTHS	WEAKNESSES
• Very low installation and maintenance cost • Reduced methane emission • Reduce water use • Reduce production cost • Increase farmer income • Increase yield • Reduce energy use and emission • Prevent from transmission and fungal diseases • Reduce cadmium accumulation • Reduce arsenic concentration	• Need intensive field observation • Increased weeds • Inapplicable in rainy season • Need trained/experienced farmer • Well irrigation and drainage facility required • Influence availability and uptake of phosphorus
OPPORTUNITIES	**THREATS**
• Global warming mitigation • Groundwater conservation • Sustainable rice production • Physically suitable condition to adopt • Easy to apply • Large scale implementation • Volumetric water pricing could make it more popular	• Extreme AWD decreased yield • Increased nitrous oxide emission

Figure 5.16 SWOT analysis result of AWD irrigation techniques in Bangladesh.

5.5.6 Comparison of AWD adoption rate among major rice growing countries

China is the most populated country in the world. Rice is the staple food and the country is the top rice producing and 3rd largest importing country in the world (IRRI, 2018). Rice cultivation facing challenges of scarcity of irrigation water and the country reforms institutional reforms, policies and goals to water saving rice production. China introduce water saving irrigation (WSI) system in early 1990's decades as almost similar forms of AWD irrigation system. The major water saving technologies are (i) engineering technologies, such as canal lining, drip irrigation, underground pipe irrigation, and intermittent irrigation which is the modified form of AWD irrigation; and agronomic practices like as water-matched production, biological water saving technologies, and soil moisture conservation (Wang, Liu and Zhang, 2002). AWD irrigation save water use up to 50%, methane emission reduction 60%, increase farmer profit and some extended yield (Li and Barker, 2004). In last decades China expanded the effective irrigation area more than 10 million hectares and increased to 68.27 million hectares in 2018. Almost half of them were based on water saving irrigation technologies. Recently, Chinese government planned 'National Agricultural Sustainable Development Plan, 2015–2030' to increase the proportion of water-saving irrigation areas to 75% of the total effective irrigated areas and the level of water use efficiency for irrigation to at least 0.6 by the end of 2030 (Du *et al.*, 2019). In the western and northern region of China 40% - 50% of total rice area under AWD irrigation and others forms of water saving system. The institutional arrangement, volumetric water pricing, governmental strong influence, and policies making successful adoption of AWD irrigation at wide scale (Yao, Zhao and Xu, 2017).

India is the 2nd largest populated country in the world. The country is also the 2nd largest rice producer (169 million tonnes) and top rice exporting country in the world (*Statista, 2019*). The rice production of the country also facing challenges of climate change impacts on agriculture especially change of precipitation pattern, temperature anomalies, global warming, and irrigation water shortages. To cope the climate change impacts the country introduce several management practices for rice cultivation such as Direct Seeds Rice (DSR), System of Rice Intensification (SRI), Alternate Wetting and Drying (AWD) Irrigation, irrigation at Minimum Depth (IMD), Drip Irrigation (DI), Supplementary Irrigation, Integrated Pest Management (IPM) etc. India is country with diverse physiography and socio-economic environment and there is huge variation of agricultural practices among the states. Among these, AWD is the proven climate smart technology which reduced water use 30%, reduce methane emission up to 60%, yield increased and reduced fuel cost in the country (Mondal, 2017). AWD adoption rate also varied among the regions such as in West Bengal 11%, Tamil Nadu 23%, Karnataka 35%, Eastern Region 6%, Northern Region 31% of total rice area (Palanisami, K. et al., 2019), and Western Region 80% farmer adopt AWD irrigation in India (Meryl Richards et al., 2014). The Central Government also trying to adopt water saving technologies as a climate change mitigation option for the country.

Vietnam is the 5th largest rice producing and 3rd topmost rice exporting country in the world. Rice is the most important agricultural crops in the country. The Red river delta and Mekong river delta is the major rice growing region in the country. The almost similar physiographic and socio-economic condition like as Bangladesh. The rice production of the country tackling challenges of climate change, drought, and water scarcity. Like the others rice growing country, the Vietnam also introduced AWD irrigation with IRRI in 2005. Its reduced 30% water use, 68% CH_4 emission reduction, farmer income increased 6 – 42 %, labour and fuel cost reduced 1 – 46 % compared to the CF irrigated rice paddy (Rejesus, R. M. et al., 2013; Richard M, 2014). The Vietnam's Ministry of Agriculture and Rural Development (MARD) highlighted AWD as one of the most promising irrigation techniques and planned to adopt 3.2 million hectares of rice area by 2020 (Richard M, 2014). The MARD launches a) AWD and b) 3G3R programme; Three Reduction (fertilizers, pesticides, and seeds), Three Grain (income, yield, and quality) for country's NDC plan in 2006. Subsequently, the country launces 1M5R; one must do (quality seeds) and five reductions (sowing seeds, N-fertilizer, pesticide, irrigation water, and post-harvested loss) as a national policy to promoted and wide scale implementation in the field level. The AWD adoption rate in the An Giang province almost 52% and at 0.68, 0.66 and 0.67 at 1 scale during winter, summer and autumn season, respectively. Similarly, 0.68. 0.68 and 0.63 in Dong Thap province and 0.73, 0.04 and 0.25 in Bac lieu province, respectively (Lovell, 2019). Eventually, some farmers applying AWD irrigation in wet season for the yield increasing purpose (Yamaguchi *et al.*, 2016). The Vietnam government takes several steps to dissemination AWD irrigation as a climate change mitigation strategy in the country. The government combinedly focus on AWD with 1M5R, 3G3R programme in the agricultural NDC execution plan; evaluate the existing irrigation network and determine AWD suitable area; and finally integrated the investment plan for AWD rice production as well as provides financial support to local farmers from national, international aids and private sector (The *et al.*, 2019)

Philippine is the 8th largest rice producing and 5th largest rice importer country in the world (IRRI, 2018). AWD irrigation have been introduced in 2001 in the country. It's reduced irrigation water use up to 30%, reduced methane emission 48% with keep N2O emission same level as CF irrigation (Arnaoudov, Sibayan and Caguioa, 2015). Moreover, AWD irrigation save fuel cost, upper and lower stream irrigation conflicts, increases farmers income and no production los. The AWD irrigation was introduced in 2001 but the adoption rate is very slow and only 8% of total rice area under AWD irrigation adoption (Siopongco, Wassmann and Sander, 2013). But the government planned to adopt AWD irrigation up to 50% of total irrigated rice area within 2020 and reduced methane emission approximately 12,151 ktCO2e/yr of emission reductions within the time. IRRI and Lampayan *et al.*, (2015) reported that although AWD irrigation grows positive perception to adopt but some farmers give up AWD irrigation after the project finished and revert to the CF irrigation. Although, the country has abundant water resources but in future decades it will face water challenges and government seeking to adopt more rice area under AWD irrigation.

Japan is the 9th top ranked rice producing and 10th rice importing country in the world (IRRI, 2018). Among the developed countries, Japan is the only country where rice agriculture competing with the others industrial and service sector. The country is a Paris Agreement Signatory and committed to reduce GHG's. As a developed country, the rice cultivation practices, and management also developed and well managed. The country's rice irrigation and drainage infrastructure are highly advanced and fully controlled. It is found from "Seiryoki" published in 17th century that the country practicing midseason drainage as almost similar management of AWD irrigation. Although there is no water shortage problem in the country but the midseason drainage and AWD has been widely adopted as GHG's reducing techniques and reported 39% of CH4 emission in Japan (Kajiura et al., 2018). The midseason drainage adoption rate in Japan is very high and overall adoption rate 87% of total rice area. The adoption rate in norther region is comparatively low (25% at Hokkaido) and high at southern region (92%) (Minamikawa, 2019). The government policies such as economic incentives for "Direct payment for environmentally friendly agriculture," programme which the prolonging of midseason drainage is a regionally approved alternative in several prefectures helps to disseminate the water saving irrigation system in the country.

In Thailand, 40% of total agriculture land under rice cultivation. The country is in the top three ranked country for rice exporting and the 4th largest GHG emitter related to rice, especially methane. Moreover, some province facing challenges to produce rice due to the water scarcity. The country adopting AWD irrigation system as GHG's mitigation option. Chidthaisong et al., (2018) reported that the AWD irrigation reduce irrigation water by 42% compared to CF irrigation and reduce methane emission 49% than CF irrigation without yield loss and maintaining the level of N2O emission. The Thailand Ministry of Agriculture and cooperatives and Ministry of Natural Resources and Environment along with the international agencies working to promote AWD adoption in farmer level at wide scale. The National Appropriate Mitigation Action (NAMA) introduce Sustainable Rice Programme (SRP)/ Good Agricultural Practices (GAP) plan to disseminate AWD irrigation amon 100,000 farmers with in 2021. The country switch to low emission practices from conventional method and plan to avoiding emissions of 1.664 Mt CO2e cumulative over the 5-year lifespan of the NSP with increasing annual mitigation potential, reducing baseline emissions from irrigated rice by more than 26 per cent (Thailand – Thai Rice NAMA, 2017).

In Bangladesh, AWD irrigation introduced in 2008 as pilot project and in farmer level adoption started on 2012. Several governmental organization, NGO's and international organization and donor agencies are working to disseminated AWD irrigation in Bangladesh. Several studies reported the advantages of AWD irrigation implementation. It's reduced water use up to 30%, reduced methane emission maximum 70%, increases N2O emission, increased yield up to 15%, increases farmer income 15-30% and as well as reduced fuel consumption compare to CF irrigated rice (Karim et al., 2014; Basak, 2016; Carrijo, Lundy and Linquist, 2017; Rahman and Sander, 2017; Oo et al., 2018b; Begum et al., 2019; Alam et al., 2010). But the AWD adoption rate is very low in farmer level. IRRI, BRRI, BARC and several government institutions, and NGS's working for AWD dissemination in Bangladesh. Despites of environmental and economic benefits of AWD irrigation system adoption, the farmers are reverting to the CF irrigation system just immediately the AWD irrigation uptake project end. Moreover, some farmers apply AWD irrigation partially like only in the early stages of rice growth (Carrijo, Lundy, et al., 2018). Due to some socio-economical structural complexity, irrigation water rental system and lack of awareness are the probable causes. Although the AWD irrigation system is proven as water saving and production increased irrigation method, but the adoption rate is less than 10% of total irrigated rice area. But the government committed to bring 20% of total rice growing area under AWD irrigation by 2030 according to the UNFCC national determined contributions (P. Joven Bernadette, 2018).

AWD adoption rate among the major rice growing countries varied. The socio-economic and environmental condition also differ among the countries. The AWD adoption rate in Japan, China, India, and Vietnam is very high, whereas the adoption rate in Thailand, Indonesia and Bangladesh is very low. The irrigation water availability in Indonesia and Thailand comparatively higher than Bangladesh. In Bangladesh perspectives; (i) the physio-climatic condition is highly suitable for AWD irrigation, AWD irrigation, (ii) the country experienced severe irrigation water scarcity, (iii) highly vulnerable to climate change impacts, (iv) AWD irrigation demonstrated good environmental and economic advantages. As a result, wide scale adoption of AWD irrigation could be highly potential technology to cope the rice production challenges for the country. The detailed AWD adoption rate among the major rice growing countries shows in **figure 5.17**.

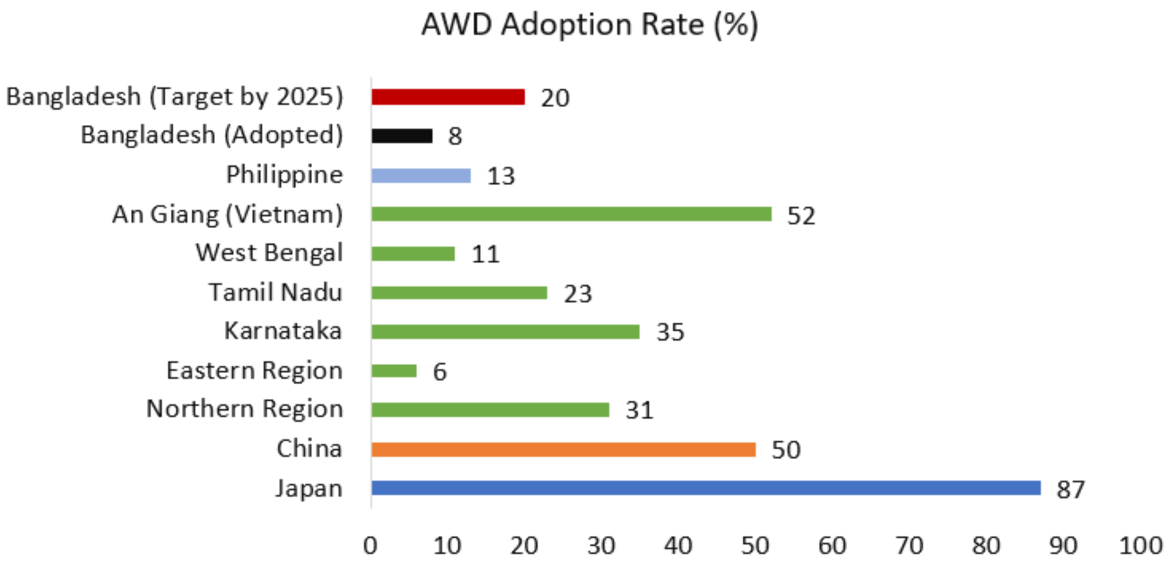


Figure 5.17 AWD adoption rate in major rice growing countries in the world.

5.5.7 Barriers and potential solution for AWD uptakes in Bangladesh

There are numerous advantages and opportunities of AWD irrigation implementation in Bangladesh. Although the AWD irrigation technique is advantageous but the implementation rate in farmer level is very slow. We conducted a meta-synthesis analysis to find out the reason behind it and found some barrier to adopt it as follow-

- **Fixed rate irrigation water pricing**: Generally, the rice irrigation system in Bangladesh depends on pump ownership. Most of the case the landowner and pump owner are different personnel except some STW's irrigation scheme. Only 2% farmers have their own irrigation map and used as services to the others farmers (Mottaleb, Krupnik and Erenstein, 2016). The rice and wealthier farmers are belonging to DTW with huge irrigation command area and the middle income and poor farmers used irrigation water by paying money or the portion of produced rice (Chakravorty, Dar and Emerick, 2017; Pandey *et al.*, 2020;Chakravorty, Dar and Emerick, 2017; (Basak, 2016b). The pricing system is fixed by season and not fluctuated on "How much water used?". In AWD irrigation case, farmers need less water than the CF irrigation rice paddy, but the payment amount is fixed, and AWD irrigation farmer did not get any direct feedback. As a result, the irrigation water rented farmers are not interested to adopt AWD irrigation practices.

-Land ownership and farm size: Bangladesh is a small country with huge population and per capita land is only 0.04915 ha (FAO, 2017). Moreover, only 37% farmers have their own land, 34% are poor tenants and 29% cultivated their own land plus tenant lands (Pearson *et al.*, 2018). Moreover, the average rice paddy field size is very small and farmers land are not located in same place or irrigation scheme. Besides the land holding sizes, the plantation date, rice varieties, land location from pump such types of heterogeneity in an irrigation pump command area makes difficulties to apply AWD irrigation. The average irrigation command area under STW's varies from 3-4 ha and 26 ha for DTW's (BADC, 2018). In case of landless poor farmer who rent land from the landowner and have not the rights for long time. These lands less farmer could not establish irrigation facilities for rice cultivation and fully depends on rental irrigation water. Moreover, it's very difficult to control irrigation water in a small spices of rice paddy within a large irrigation scheme. As a result, farmer could not apply AWD irrigation even though have wiliness.

-Incentive: The primary interest of farmer to adopt AWD irrigation for saving water cost as well as production cost. But, due to the rental irrigation water system, the farmer did not get any benefit of water saving even saved huge amount of irrigation water (Basak, 2016b; Carrijo, Lundy, *et al.*, 2018; Pandey *et al.*, 2020). Moreover, the Ministry of agriculture gives direct subsidies on irrigation fuel (electricity and diesel) and the pump own got this benefit and the tenants farmer deprived from it (Babu, De Pinto and Paul, 2019). Although the government subside 602.68 billion BDT in fertilizer, irrigation fuel, rehabilitation, and agricultural mechanization sector in last 9 years but there are no additional incentives for former to adopting AWD irrigation (The Financial Express, 2018). In **figure 5.18** shows the government subsides in different agriculture sector from 2009-2017. As a result, the farmers are not interested to adopt AWD irrigation willingly.

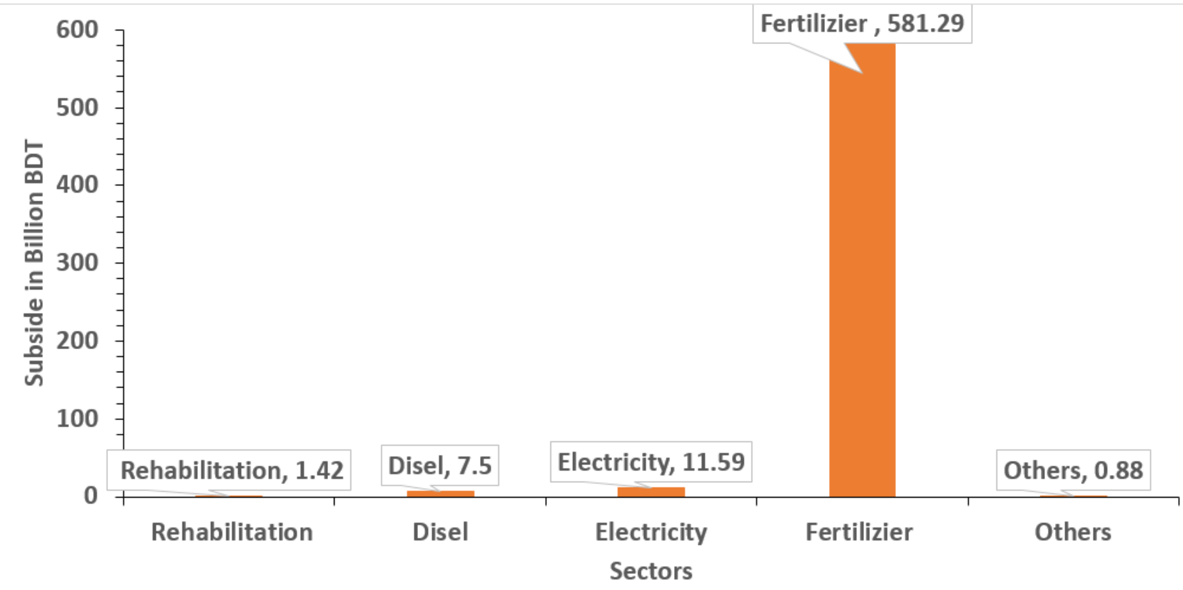


Figure 5.18 Bangladesh government subsidies in agriculture sector from 2009 to 2017.

-Awareness: AWD irrigation is a knowledge-based water management system and need to use properly for maximum benefits. Traditionally illiterate, or comparatively less educated people are engaged in agricultural activities in Bangladesh. Most of them are not so much concern about environmental impacts. The farmers perceptions on AWD irrigation is only economic benefits like- water saving, production cost decreased and yield increased. The others direct and indirect benefits of AWD adoption as like methane emission reduction, arsenic contamination reduction, precious groundwater saving is not pay attention to the farmers. Although, some government institution and NGO's are working to disseminate AWD irrigation in farmers level but it's not up to the mark. Moreover, in some case the farmers whose are adopt AWD irrigation during pilot study or project and after end of the project tenure again swap in to the CF irrigation (Rejesus, R. M., Martin A. M., Gypmantasiri, 2013). As a result, lack of farmers awareness is another major limiting factor to adopt AWD irrigation.

Weed increase and Yield decrease concepts: Due to the lack of proper knowledge about AWD irrigation application especially when to start AWD and stop AWD impacts on production. Sometimes it is decreased rice production per unit yield (Rejesus, R. M., Martin A. M., Gypmantasiri, 2013; Mottaleb, Krupnik and Erenstein, 2016; Carrijo, Lundy, *et al.*, 2018). Moreover, due to the dry up cycle in AWD irrigation, the paddy field weed increased and need more labour cost for rice production. Although, proper AWD application increased yield and weed management with herbicide in not a major problem. But, such concept in farmers mind makes them not interested to adopt AWD irrigation.

-Government policy:

The national agriculture policy of the country mainly production oriented. The major agricultural plan also emphasis on the rice production increase and become self-sufficient in food production. The latest fifth year planning ‘Seventh Five Year Plan (7FYP 2016-2020)’ which approved in 2015, mainly focused on food security, nutrition security, sustainable intensification and diversification of climate resilience agriculture production, crop sub-sector development for raise rural people income and employment opportunities (FAO, 2016). Along with 7th fifth year plan, Government also introduce ‘National Agriculture Policy (NAP 2013)’ aims to improve food and nutrition security to improve quality of life through increased production and agriculture diversification. The Government of Bangladesh also drafted the ‘National Agricultural Extension Policy (NAEP, 2015) for providing integrated agricultural extension service of Department of Agriculture Extension, Department of Fisheries, Department of Livestock and Department of Forestry under one umbrella through “National Agriculture Extension System (NAES)”. Besides that, the digitized (e-agriculture) extension service promotes to assist farmers provisioning valuable information, integrated pest management (FAO, 2016). All the national agricultural plan adopted to emphasis on increase food production, crop diversification and nutrition security and not concerned about the climate change mitigation.

Bangladesh is a signatory country of “Paris Agreement “and committed to reduce greenhouse gases. Recently the country listed into developing country from least developed country and need to reduce GHG’s. The country submitted “Intended Nationally Determined Contribution’s (INDC)” to United Nations Framework Convention on climate change (UNFCC) and proposed two-fold strategy (Conditional and Unconditional) (MoEF, 2012). The plan emphasis on GHG’s emission reduction from Power, Industry and Transportation sector and did not considered agriculture sector. The country has also introduces ten years plan of “Bangladesh Climate Change Strategy and Action Plan (BCCSAP) as climate change mitigation action plan (Government of Bangladesh, 2015). Although the food security and low carbon mitigation considered among six targets but there is also no guideline to reduce emission from agriculture. Most of the policies focused on production increased and adoption strategies. Agriculture is the second largest GHG’s emission sector and rice paddy cultivation is the major emission sector and there is huge potential to reduce emission. So, the Government should include agriculture sector to the national mitigation plan and focused on AWD implantation as mitigation tools.

5.5.8 Proposed potential solutions

The problems associate with AWD adoption in Bangladesh have been discussed at above sections should be sought for dissemination it. We proposed some solutions within the existing structure, modifying the policy and very few additional investments for adoption. In figure 5.19 shows the barriers and proposed solutions for AWD adoption in Bangladesh.

-Volumetric water pricing: The main barrier to adoption is fixed rate water pricing for AWD and CF irrigated rice paddy. We proposed volumetric water pricing means the farmer will pay for only the amount of water used rather a fixed amount. In this case, the AWD practicing farmer need to pay up to 35% less water and money for irrigation inputs which will add benefits of AWD adoption. In China already adopted volumetric water pricing and some part of Vietnam also adopting it (Du *et al.*, 2019; Lovell, 2019). In Bangladesh case, already introduced Pre-Paid Credit (PPC) for irrigation water use in Brrind regions (Pandey *et al.*, 2020). Moreover, the country already converting the surface irrigation open drain into underground pipe drain which is very efficient for water flow gauge installation. Volumetric water pricing system will give direct financial benefit to the AWD practices farmer and helps to adopt it.

Land ownership and farm size: Due the small size of land and heterogenic plantation date and AWD irrigation cycle for individual farmer is another constraint for AWD adoption. Now AWD irrigation adopted by individual farmer level and we proposed to adopt AWD irrigation at community level. Moreover, in some case the landowner and the farmer are different person and incentives goes to the landowner. So, the incentives should give to the farmers not to the landowner. Like, under an irrigation pump command area 10 to 100 farmers cultivated rice paddy and all the farmers should practice AWD irrigation. So, in planning and policy phases should focused on irrigation scheme based AWD adoption rather individual farmer level.

Financial and technical support: Incentive is the key factor for adopting new technology. In Bangladesh, every year government subsidies huge amount of money in fertilizer, irrigation, seeds, machineries, fuels, tax exceptions and technical training for the farmers. Generally, all farmers directly and indirectly get the government incentives. Government already introduce "Smartcard" for the farmer to gives the incentives. Within the existing incentives system, government should give priorities to the AWD adopted farmer. Moreover, the Government directly bought rice paddy from farmers and in this case the AWD farmer should be priorities. Such types of economic incentive system could encourage farmer to adopt AWD irrigation technique.

Proper training and guidelines: The weeds increase due to the AWD application but in early stages of AWD implantation period. The weed can easily remove by applying herbicide with low cost. In yield decrease case, AWD practices yield decreases only in case of severe or improper AWD application. Due to the lack of proper knowledge about AWD application, farmer could not apply it properly and decreases yield. But proper AWD application increased per unit yield up to 15% compare to CF irrigation in Bangladesh (Barmon and Tarafder, 2017; Chakravorty, Dar and Emerick, 2017; Pandey *et al.*, 2020). In some region of Rajshahi division more than 50% farmer applied AWD irrigation without proper training(Pandey *et al.*, 2020). Proper and number of trained farmers could help to solve the yield decreased problem. Moreover, complete guideline for region and rice varieties specific guideline could be helpful for the farmers.

Awareness: The benefit of AWD irrigation is not only the financial but also has a long- term environmental impacts especially mitigated climate change. The farmers are the most sufferer for the climate change impacts and they could contribute to mitigate it. Such types of motivation could be helpful to encourage farmer for AWD adoption. The Government along with the donor agencies and NGO's could launched and increased campaign on benefits of AWD adoption. In Vietnam, MARD introduces "1M5R" campaign with print and electric media (The *et al.*, 2019) , such types of awareness campaign could be helpful to motivate the farmers.

Government Policy: The government should include agriculture sector in GHG's emission reduction strategies and AWD as a potential tool of mitigation. Although, the government aims to increased AWD irrigation implementation but there is no proper plan. Within the existing administrative structure and incentive scheme, just changing some policies could be very efficient to AWD dissemination. Like, in "Smartcard" AWD farmers information could added and introduce "Carbon Credit Certificate (CCC)" in similar way of Japan and USA. The farmer with CCC will priorities for financial incentives, tax exemption and bank loan similar to the Japan and USA(Yamaguchi *et al.*, 2016; Carrijo, Lundy, *et al.*, 2018). The graphical framework of the barriers to adoption and proposed solutions shown in **figure 5.19**.

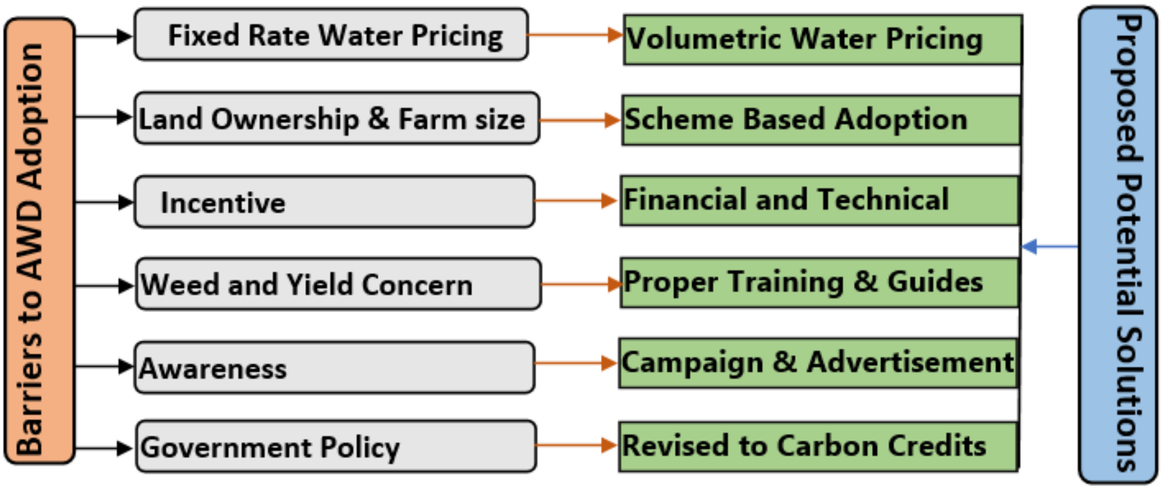


Figure 5.19 Constraints to adopt AWD irrigation and proposed potential solution to overcome the problems in Bangladesh.

5.5.9 Recommended strategies for AWD adoption

AWD irrigation dissemination is very important for Bangladesh to reduce methane emission, water use as a climate mitigation tool. To implementation of a technology is always difficult as the recipient always in doubt about its impacts. In the country, several project and initiative already running to adopt AWD irrigation by national and international agencies. But an integrated and long-term strategy is very important to sustain it. There are already some farmers who already adopt AWD irrigation under a project and swap to no AWD irrigation after completion of the project tenure. As a result, we proposed a sustainable strategy within the existing infrastructure to adopt AWD irrigation in wide scale as follow figure 5.16.

Stage-1: Suitable area and seasons selection: Department of Agriculture Extension (DAE) under Ministry of Agriculture is the largest agricultural institution in Bangladesh. Along with DAE, some other autonomous, commercial, government and non-government institutions like BARC, BRRI, RDA, BARC, RDRS, SYNGENTA, BARD etc are working in agriculture sector especially in rice paddy sub-sector. All the institution should bring under an umbrella and centrally operating the implementation strategy. Initially, should select the suitable area and time for AWD irrigation implementation (Chapter-3). Expert body could be formed by the researcher from different institutions to makes a concrete plan. Based on suitability, set out the target to adoption rate and priorities for next 5 to 10 years. Like,

(1) Physio-climatically suitable (48%) rice area could be target -1,

(2) Physio-climatically high suitable boro season could be target-2,

(3) Physio-climatically high suitable amon season could be target-3,

(4) Socio-economical suitable area (58%) under AWD irrigation could be target-4,

Stage-2: Training and awareness program: Centrally, should launched awareness program like farmers field school, skill enhanced training, creating master trainer from farmers, trained the pump owner farmers etc. Besides, the advertisement and awareness program through print and electronic media, hand leaflet, small drama could be helpful. DAE and other institutions training wing could play vital role for this stage.

Stage-3: Irrigation scheme-based adoption: Based on the suitable area selection (stage-1), trained the pump owners and farmers (stage-2) to adopt AWD irrigation. Emphasis should give to implement based on irrigation pump command area rather the individual farmers level. Block supervisor and field supervisor from different institution could be responsible person for community level.

Stage-4: Monitoring-Verifying and Reporting (MVR): MVR is an important tool for climate changes mitigation action for enhancing transparency, tracking of climate finance and mitigation action (Wartmann *et al.*, 2013). In this case MRV will considered as monitoring tool for AWD adoption in farmer level. The block/field supervisor associated with the community leader will monitoring, verifying, and reporting to the central authority about the farmer information and AWD practices result. The central ICT division will include in Smartcard as "CCC" and this information will be used to gives incentive.

Stage-5: Financial and technical support: Although proper AWD irrigation application is itself offer benefits to the cultivar. But the financial and technical support will be encouraged farmer to adopt AWD. In farmers smartcard, there should be added a CCC option for further incentives. Within existing financial and administrative structure, the CCC holder farmer should be priorities on case of fertilizer, irrigation, seeds, machineries, and fuels subsides, tax exceptions and technical training. Moreover, the farmers should get priorities to get interest free bank loan for production. Such types of opportunities could attract farmer to adopt AWD irrigation for rice cultivation. The conceptual framework for proposed implementation strategies show in **figure 5.20.**

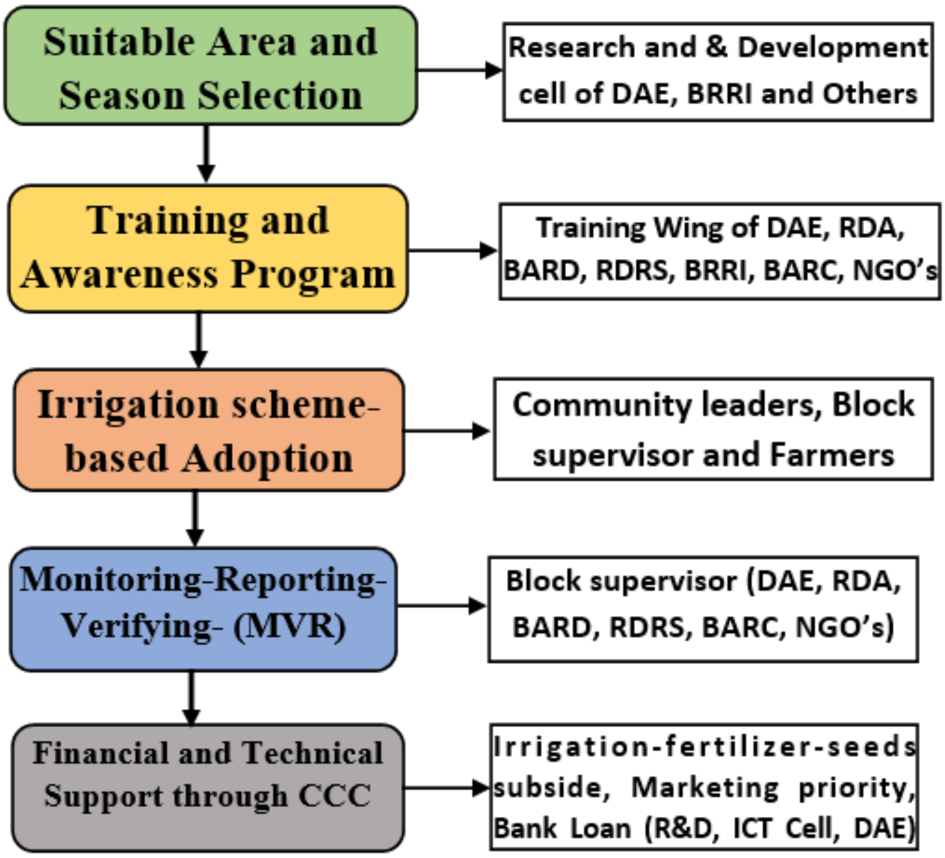


Figure 5.20 Proposed conceptual strategy for AWD irrigation dissemination in Bangladesh.

5.6 CONCLUSION

So far, the objectives of this chapter were:

5- To estimate methane emission from CF irrigated rice paddy field with remotely sensed data and IPCC model.

6- To measure methane emission from AWD irrigated rice paddy field

7- To evaluate the methane emission reduction with AWD irrigation implementation, and

8- To evaluate the AWD irrigation status, constraints, and potential solutions in Bangladesh.

To satisfy the first objective, we estimated methane emission from CF irrigated rice paddy field with IPCC model and remote sensing based seasonal rice an irrigated rice area dataset. The seasonal emission factor with accounted the organic amendment and irrigation water regime for boro, aus and amon rice season are 218.4, 195.6 and 204.3 kg/CH4/ha[1], respectively. The boro season shows the high methane emission season with 1029 Gg/yr whereas, aus and amon season emit 110.05 Gg and 780.91 Gg methane, respectively in 2018. The annual methane emission from rice paddy field increased from 1384.97 Gg in 2001 to 1921.41 Gg in 2018.

In case of second objective, the different irrigation regime considered methane emission estimation from rice paddy. Based on the IPCC default value 0.28 scaling factor for rainfed rice considered as AWD irrigated management induced methane emission scaling factor and for boro, aus and amon season AWD irrigated rice paddy field emitted methane emission seasonal factors are 61.04, 57.50 and 54.76 kg/CH4/ha^{-1}, respectively. Whereas, in CF irrigated case similar emission rate area 218.4, 195.6 and 204.3 kg/CH4/ha^{1}, respectively. Seasonal total emission case, amon season is the largest emission season flowed by boro and aus season. Annual methane emission from AWD irrigated rice paddy field was 837.10 Gg in 2001 and 875.16 Gg in 2018.

The find out from objective 3, AWD irrigation could reduce methane emission compared with CF irrigation. The seasonal emission reduction rate varied up to 62% but considering the seasonal total emission reduction rate varied from 44% to 54% over the study area from 2001 to 2018. Based on the AWD irrigated rice area suitability, the physically suitable AWD irrigated rice area could reduce maximum methane emission followed by socio-economically and physio-climatically suitable area considered under AWD irrigation implementation.

To satisfy the object 4, the SWOT analysis result shows the high strength and opportunities, low weakness, and no threats with proper AWD application. But the status of AWD adoption rate (8%) is comparatively low among the major rice growing countries. There are some major barriers to disseminated AWD irrigation in wide scale and to overcome the constraint government needs to reform policies within the existing administrative structure and financial capacity.

Chapter 6: Conclusion

6.1 GENERAL CONCLUSION

Considering the growing demand for rice consumption in the country, the county trying to increase rice production with more intensive input such as, irrigation, chemical fertilizer, pesticide, and land area. On the other hand, the country as one of the most climate change impacts vulnerable country also trying to reduce GHG emission. In the context of such dilemma, the country can take the benefit of AWD irrigation as mostly the rice growing area is moderate to high suitable for AWD irrigation implementation. This study showed that the AWD irrigation system could reduce CWR and methane emission. Along with the benefit, there is huge potential opportunity to apply AWD irrigation (**table 6.1**).

Table 6.1 Summery table of environmental benefits and opportunities of AWD irrigation in Bangladesh based on this study.

AWD Irrigation	Parameters	Quantitative assessment
Benefits	CWR Save	**5 to 15.50%** compare to CF
	CH4 Reduce	**54%** compare to CF
Opportunities	Physically Suitable	**98%** of total rice area
	Physio-climatic suitable	**48%** of total rice area
	Socio-economic suitable	**58%** of total rice area

In chapter 2 showed, the rice cultivated area of increased up to 2015 and reached almost started stage. The high yield boro rice season increased from 3.7 M ha in 2001 to 4.67 M ha in 2018 and amon rice season decreased from 5.71 M ha to 5.13 M ha within same time frame. The aus rice season is almost similar throughout the time series. Although, government trying to encourage to increased wet season amon and aus rice production but due to the high per unit yield the boro rice growing season increasing drastically. The dry season boro rice used more irrigated water and emit more methane emission and making the rice cultivation sector more vulnerable.

In chapter 3 result shows that opportunity of the country to adopt AWD irrigation. Although, the AWD irrigation system is a proven system to reduce water use and emission but the AWD implementation rate in farmer level is limited. Our study estimated physio-climatic and socio-economic suitable rice area for AWD irrigation implementation. The physically suitability analysis with the slope and soil properties data and weighted overlay model result demonstrated the highly suitable area is 39% and moderately suitable area 39% whereas only 1% of total rice area is low suitable and there is no very low suitable rice area. Physio climatically, the boro rice season is the most suitable for AWD irrigation application, where 79% of total boro area is highly suitable. The amon rice area conditionally suitable for AWD irrigation implantation as the highly suitable area is 1% but the moderately suitable area is 62% of total amon rice cultivated area. The aus rice season is low suitable for AWD irrigation application as there are no highly suitable area, only 16% area moderately suitable and dominant low suitable are 79% of total aus rice area. And, socio-economically, the 2.43% of total rice growing area is highly suitable, 55.19% moderately suitable, 28.43% low suitable and 13.95% of total rice growing area is very low suitable. Considering the AWD suitable rice are under AWD irrigation, there is huge opportunity for the country to reduce CWR and methane emission.

Even though the country is highly suitable in context of physical characteristics, but socio-economically suitable area is less than the physical suitable area. As a result, the country needs to emphasis to develop and reform socio-economic structure to implemented AWD irrigation at wide scale. Additionally, physio-climatically, the boro season is the most suitable season and the season is also the most irrigated water consumed (Chapter 4) and methane emission season (chapter 5). As a result, it also a great opportunity for the country to implement more AWD irrigation area in this season.

In chapter 4, in context of the CWR for AWD and CF irrigated rice and irrigated rice area assessment showed significant environmental benefits. The CWR for AWD and CF result shows the seasonal CWR for CF irrigated boro, aus and amon rice are varied from 350 to 1020 mm and the CWR from CROPWAT model shows almost similar estimation in site specific. The annual CWR for CF and AWD irrigated rice was 55.55 km^3 and 49.45 km^3 in 2001; and 56.07 km^3 and 49.61 km^3 in 2018, respectively. The CWR save from AWD irrigation with the previous section result. The estimated CWR for CF and AWD irrigated rice used for the water saving estimation from AWD irrigation application. The result shows the CWR save from 3 to 15.50% compared with CF irrigated CWR. In AWD suitability scenario-based reduction shows the CWR save 3 to 7 km^3 water per year.

The result of estimated irrigated, supplementary irrigated and rainfed rice for boro, aus and amon season shows that the boro rice area is almost fully irrigated and very good agreement (R^2 value 0.87) with national statistics reported data. The estimated irrigated amon rice area showed fluctuation over the time and illustrated poor agreement (R^2 value 0.55) with the reported irrigated rice area. The aus rice area shows almost rainfed and supplementary irrigated. The important outcome from this chapter is that the boro season is the mostly irrigated season and whereas the aus season is almost rainfed and amon season dominant by supplementary irrigation system. The irrigation types are responsible for water consumption as well as methane emission. The irrigated types used as regime for methane emission estimation in chapter 5.

To estimate the methane emission from rice paddy field with IPCC model and remote sensing based seasonal rice an irrigated rice area dataset used for this study. The seasonal emission factor with accounted the organic amendment and irrigation water regime for boro, aus and amon rice season are 218.4, 195.6 and 204.3 kg/CH_4/ha ^{1}, respectively. The boro season shows the high methane emission season with 1029 Gg/yr whereas aus and amon season emit 110.05 Gg and 780.91 Gg methane, respectively in 2018. The annual methane emission from rice paddy field increased from 1384.97 Gg in 2001 to 1939.41 Gg in 2018.

In case of the different irrigation regime considered methane emission estimation from rice paddy. Based on the IPCC default value 0.28 scaling factor for rainfed rice considered as AWD irrigated management induced methane emission scaling factor and for boro, aus and amon season AWD irrigated rice paddy field emitted methane emission seasonal factors are 61.04, 57.50 and 54.76 kg/CH_4/ha^{-1}, respectively. Whereas in CF irrigated case similar emission rate area 218.4, 195.6 and 204.3 kg/CH_4/ha ^{1}, respectively. Annually, 44% to 54% of total methane emission could be reduce with AWD irrigation implementation in the study area.

The AWD irrigation application could reduce annual CWR up to 15.50% and methane emission up to 54% of annual total emission. The country is highly suitable in term of physical or geographically (98%), physio-climatically (48%) and socio-economically (58%) for AWD irrigation application. Moreover, proper application of AWD irrigation has shown numerous advantages and no threats. But the AWD irrigation adoption rate is unexpectedly low compared with major rice growing countries. There are less economic incentives for the farmers, land ownership, pump ownership, lack of awareness and government policies are the major barrier to disseminate the AWD irrigation in wide scale. Although Government subsides huge amount of financial budget, but the policy reformation is very important to adopt it.

6.2 IMPLEMENTATION OF THE STUDY

The AWD irrigation system evaluation by this study are expected to immediately answer following questions:

- When? And How much area in the country used for rice cultivation?
- How much rice area is suitable for AWD irrigation?
- How much water required for CF and AWD irrigation?
- How much water saved by AWD irrigation implementation?
- How much rice area under irrigation?

- How much methane emission from cultivated rice area?
- How AWD irrigation system could reduce water use and emission?

In long term, this research is expected to have a multi-fold contribution into sustainable production of rice paddy through providing necessary information for rice cultivated season and area, AWD suitability area, water requirement and methane emission.

This study is enables to assess the dynamic rice cropping pattern and irrigated area for the policy makers to ensure the managed the rice area, irrigation facilities, and season specific strategies to improves the rice production system. The AWD suitable area information could be a very important information for policy makers, academician as well as for the farmers to evaluate which area and season area suitable to apply AWD irrigation.

6.3 LIMITATION OF THIS STUDY

In our study remotely sensed data showed great potential to model and measure CWR for AWD and CF irrigated rice, suitability analysis and methane emission estimation. However, there are some limitations which need to be addressed in our study.

1. Rice paddy distribution should be mapped accurately to estimated CWR, suitability analysis and methane emission estimation. But the fragmented field size, high cropping intensity and diversity, and the dynamic of crop rotation makes it challenging. High spatial resolution remote sensing data s very important. Although, we used 50 m grid resolution ALOS-2 ScanSAR data calibrating with MODIS 1 km resolution data but still there is option to improve the accuracy.
2. In case of CWR estimation, the Kc value is very important and it's a dynamic parameter with daily changed through the entire growing period. In this study we used seamless monthly Kc value synchronizing with the rice crop calendar.
3. The irrigated rice paddy area mapping with remote sensing data is a challenging task. In this study, the effective precipitation and evapotranspiration dataset used in monthly and seasonal composition with overall spatial resolution 1 km.
4. Remote sensing data in this study has been correlated with reported value to comparison. However, the reported data also affected by several biasness.
5. The suitability asses by using physical, climatic, and socio-economic parameters. The dataset used from different sources especially the statistical data converted

into geospatial data in smaller administrative unit upazilla level. Such conversion shows similar pixel value in a upazilla which affected the model result.

6. The methane emission estimated with IPCC model and irrigation regime and organic amendment scaling factors. In emission estimation case, different rice species types show variation in growing period and organic farm manure, but we used fixed values.

6.4 FUTURE WORK

- In future we will try to identify AWD and Non-irrigated rice paddy field with remotely sensed dataset,

-In this study used IPCC tiyer-2 model for methane emission estimation. In future tiyer-3 model will be applied associated remote sensing data for methane emission estimation in Bangladesh.

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Appendices

Appendix A

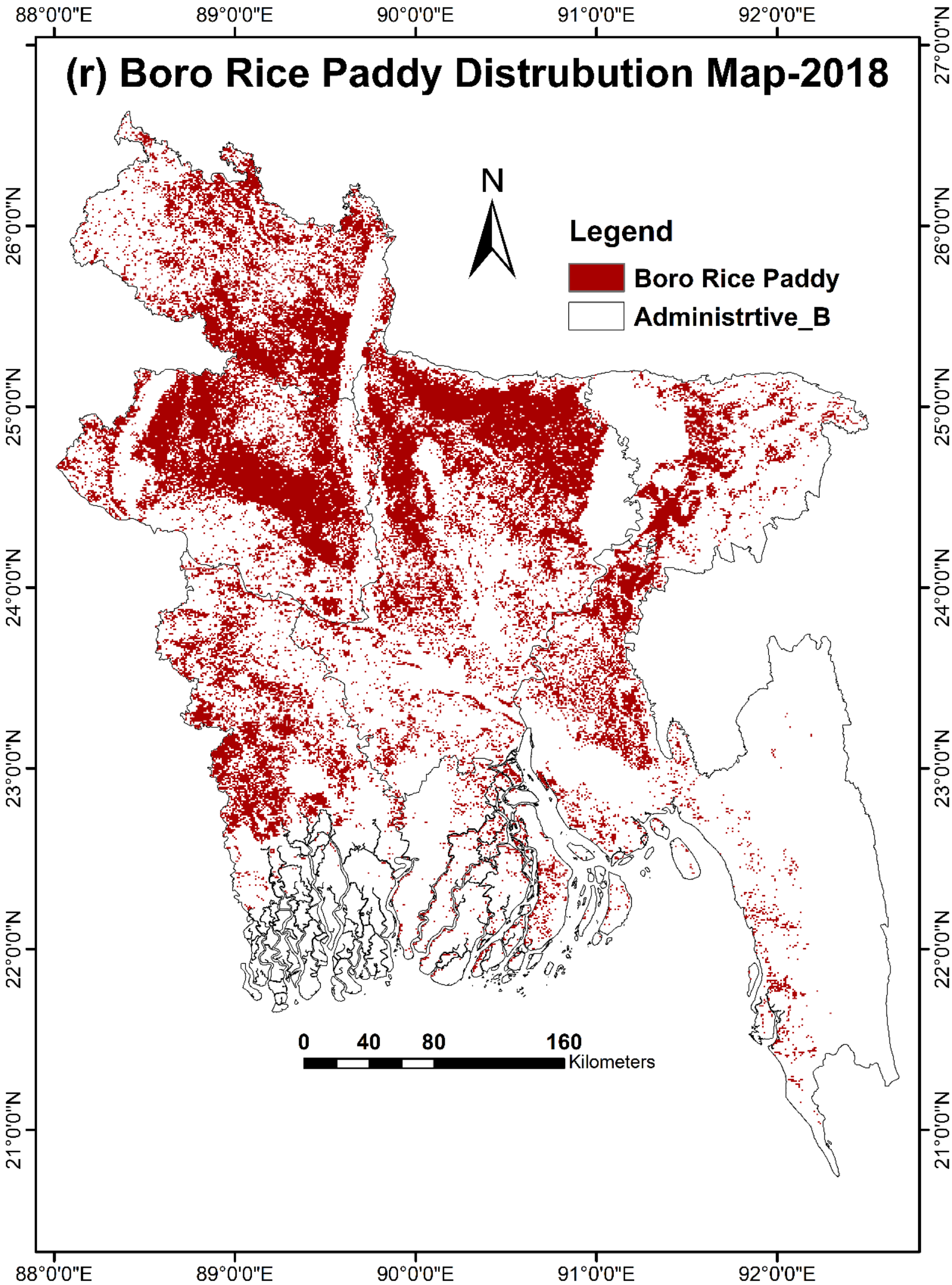
Sample data of collected GPS location and rice cropping patterns

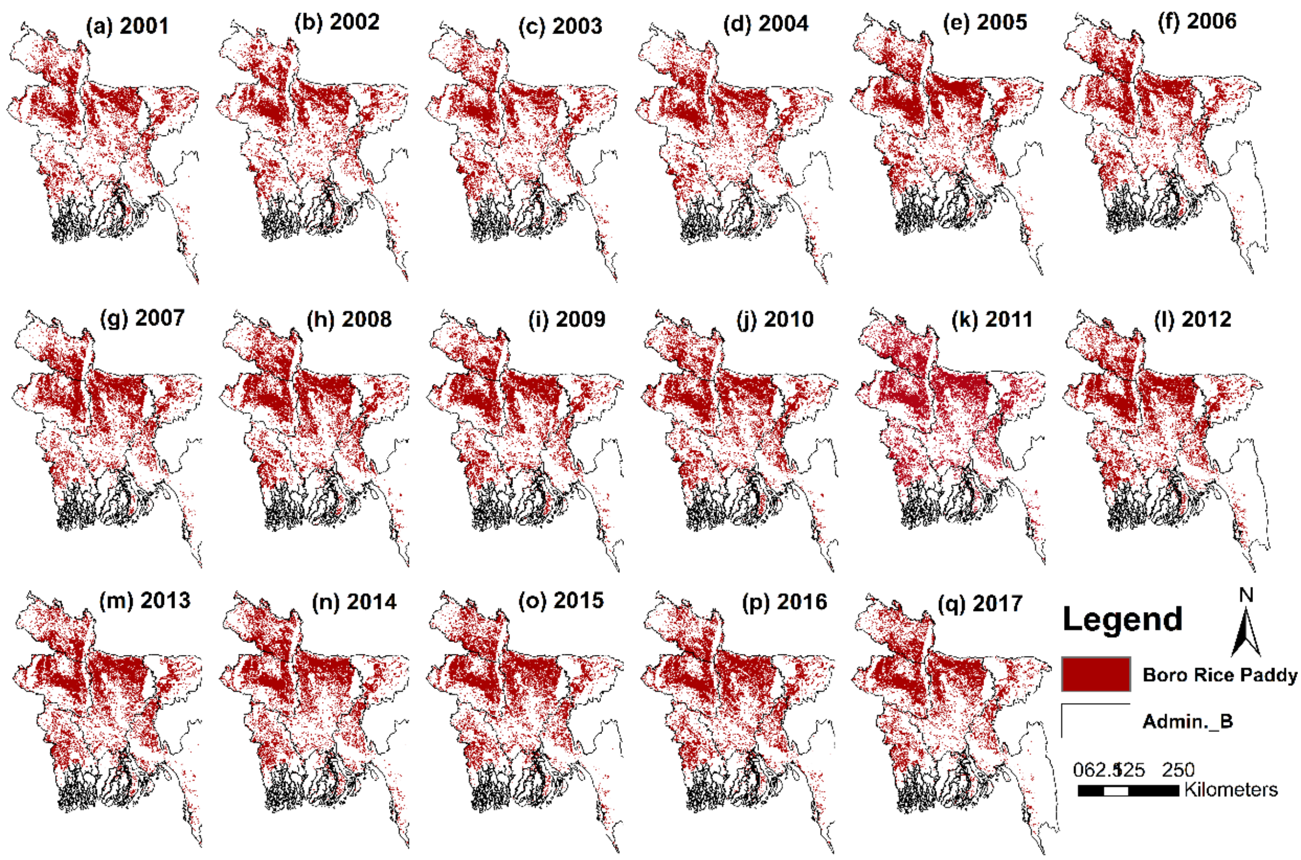
Field no	Lat	Lon	Cropping Pattern
1	89.43996	24.62143	Boro-Amon- Mustard Seed
2	89.43998	24.62152	Boro-Amon- Mustard Seed
3	89.44025	24.62208	Boro-Amon- Mustard Seed
4	89.43998	24.62152	Boro-Amon- Mustard Seed
5	89.43936	24.62176	Boro-Amon- Mustard Seed
6	89.44078	24.62192	Boro-Amon- Mustard Seed
7	89.43936	24.62176	Boro-Amon- Mustard Seed
8	89.43902	24.62122	Boro-Amon- Mustard Seed
9	89.44106	24.62196	Boro-Amon- Mustard Seed
10	89.43925	24.62063	Boro-Amon- Mustard Seed
11	89.44083	24.62191	Boro-Amon- Mustard Seed
12	89.44033	24.62166	Boro-Amon- Mustard Seed
13	89.43921	24.62062	Boro-Amon- Mustard Seed
14	89.57737	24.49744	Boro-Amon- Mustard Seed
15	89.46887	24.46044	Boro-Amon
16	89.55757	24.50861	Boro-Amon
17	89.52215	24.52499	Boro-Aus-Amon
18	89.58042	24.53542	Boro-Amon
19	89.57737	24.49744	Boro-Amon
20	91.73061	24.33165	Boro-Amon
21	91.80378	24.90687	Boro-Amon
22	89.22399	23.17408	Boro-Amon
23	89.1086	22.2373	Boro-Amon
24	89.1135	22.33931	Boro-Aus-Amon
25	89.33902	24.23426	Boro-Amon
26	89.07476	22.35554	Boro-Amon
27	89.07247	24.97266	Boro-Amon
28	89.2841	24.00626	Boro-Amon
29	89.28513	24.00741	Boro-Amon
30	88.4784	24.38183	Boro-Amon
31	88.47873	24.38216	Boro-Amon
32	88.48139	24.38394	Boro-Amon
33	88.4895	24.37421	Boro-Amon

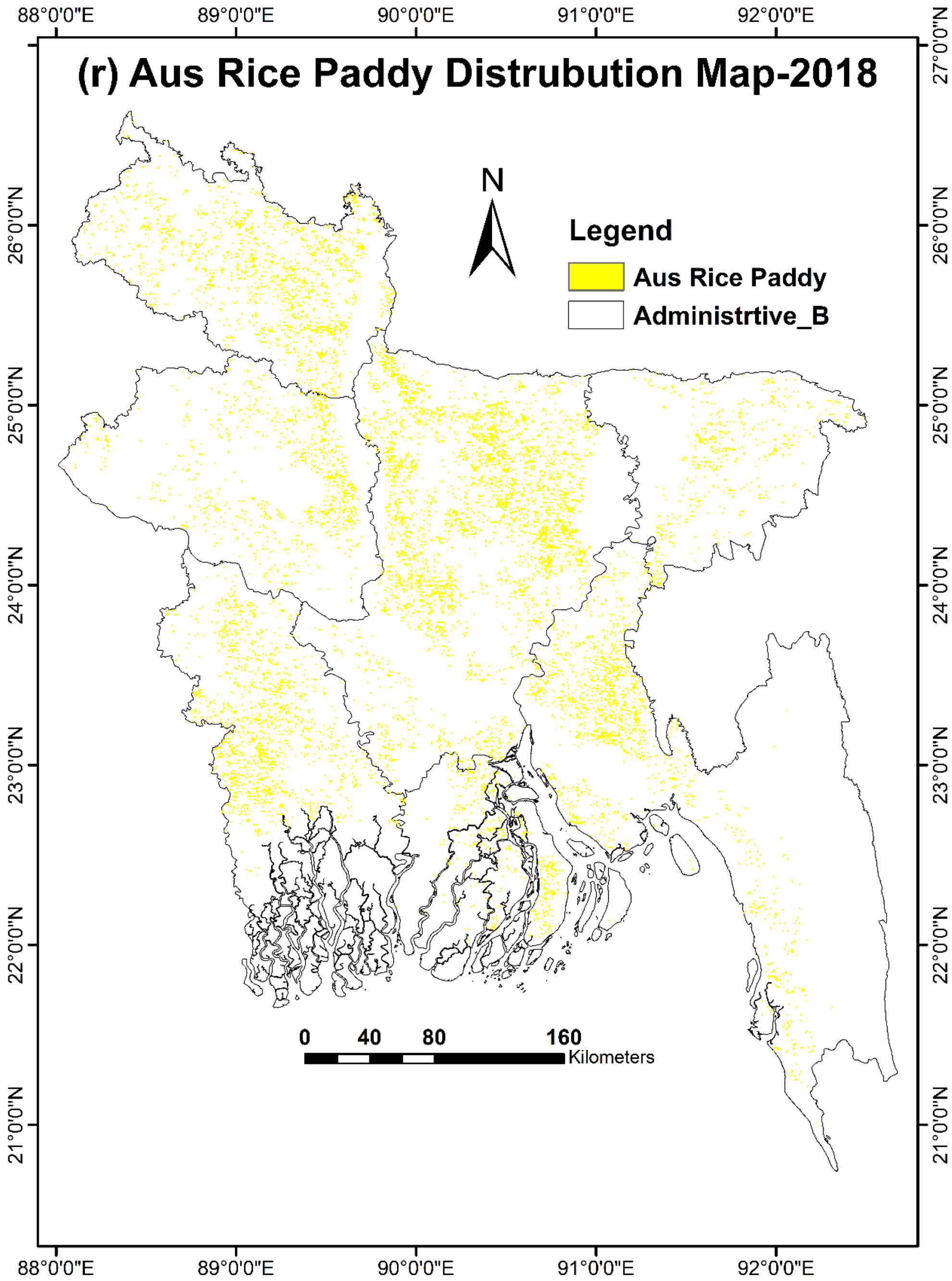
34	88.48947	24.37474	Boro-Amon
35	88.41237	24.42142	Boro-Amon
36	88.4115	24.42149	Boro-Amon
37	88.41237	24.42182	Boro-Amon
38	88.44407	24.39518	Boro-Amon
39	88.44424	24.39561	Boro-Amon
40	91.15143	23.36823	Boro-Amon
41	91.15212	23.36595	Boro-Amon
42	89.60072	25.78394	Boro-Amon
43	89.60022	25.78219	Boro-Amon
44	89.60629	25.7811	Boro-Amon
45	88.93743	25.55192	Boro-Amon
46	88.99703	23.56325	Boro-Aus-Amon
47	88.87257	25.83922	Boro-Amon
48	88.873	25.83753	Boro-Amon
49	90.31972	24.77501	Boro-Amon
50	90.31804	24.77778	Boro-Amon
51	90.32345	24.76777	Boro-Amon-Mastered seed
52	90.35222	24.78071	Boro-Amon-Mastered seed
53	90.35206	24.78031	Boro-Amon
54	89.07995	24.47715	Wheat-Crone-Amon
55	89.09793	24.44575	Wheat-Crone-Amon
56	89.35031	24.50724	Boro-Aus-Amon
57	89.36073	24.49142	Boro-Amon-Mastered seed/cucumber
58	89.38604	24.49433	Boro-Aus-Amon
59	89.4565	24.47894	Boro-Aus-Amon
60	88.95083	25.85417	Boro-Amon
61	88.95389	25.84306	Boro-Amon
62	89.23316	23.18289	Boro-Aus
63	89.2833	24.00693	Boro-Aus
64	89.28506	24.0084	Boro-Aus
65	89.62192	23.94702	Onion/mastered /Amon
66	89.62244	23.94737	Wheat/Mastered/Amon
67	89.622	23.94819	Onin-Chillie-Amon
68	89.60024	25.78176	Boro-Amon-Mastered Seeds
69	89.60024	25.7817	Boro-Amon-Mastered Seeds
70	89.6051	25.78473	Boro-Amon
71	89.6051	25.78473	Boro-Amon
72	89.60514	25.7843	Boro
73	88.06034	24.68271	Boro
74	88.17306	24.80169	Boro

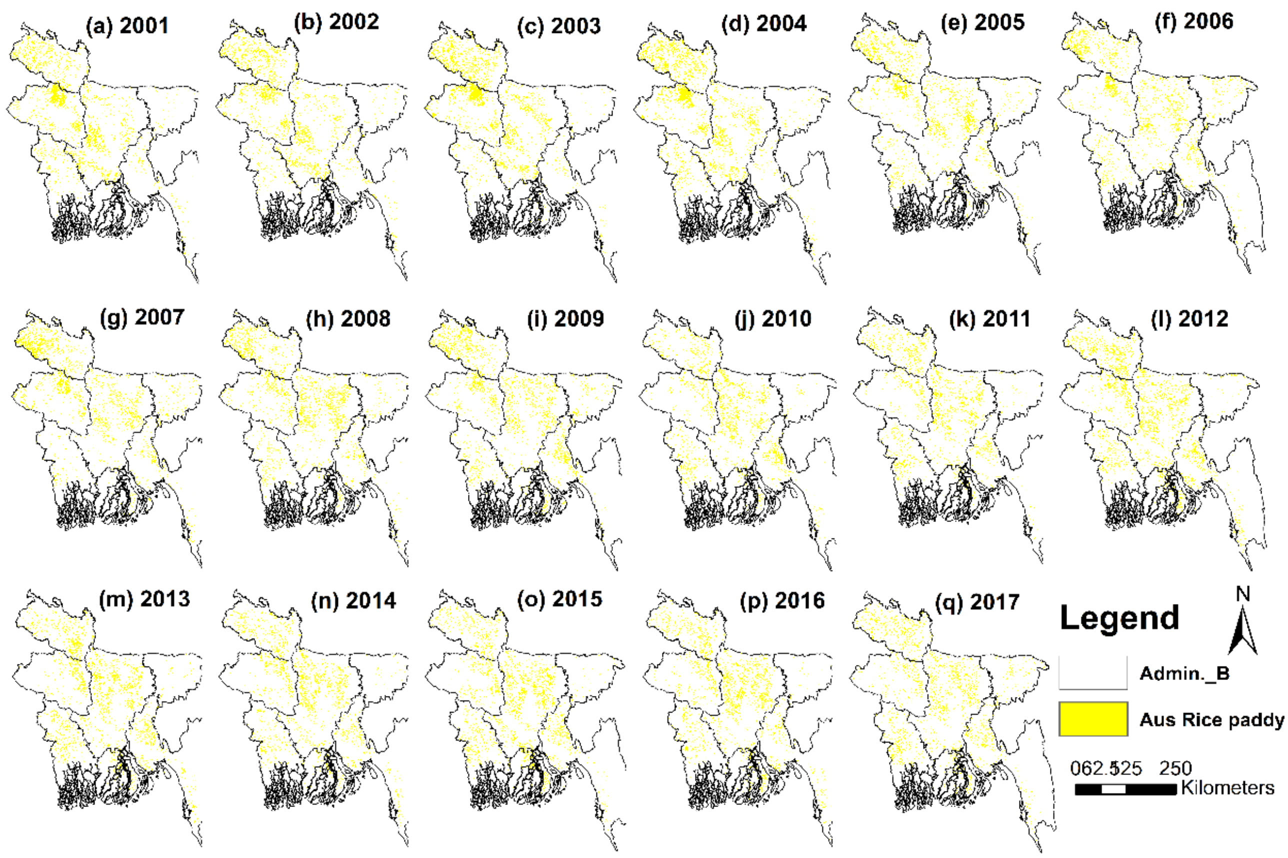
Appendix B

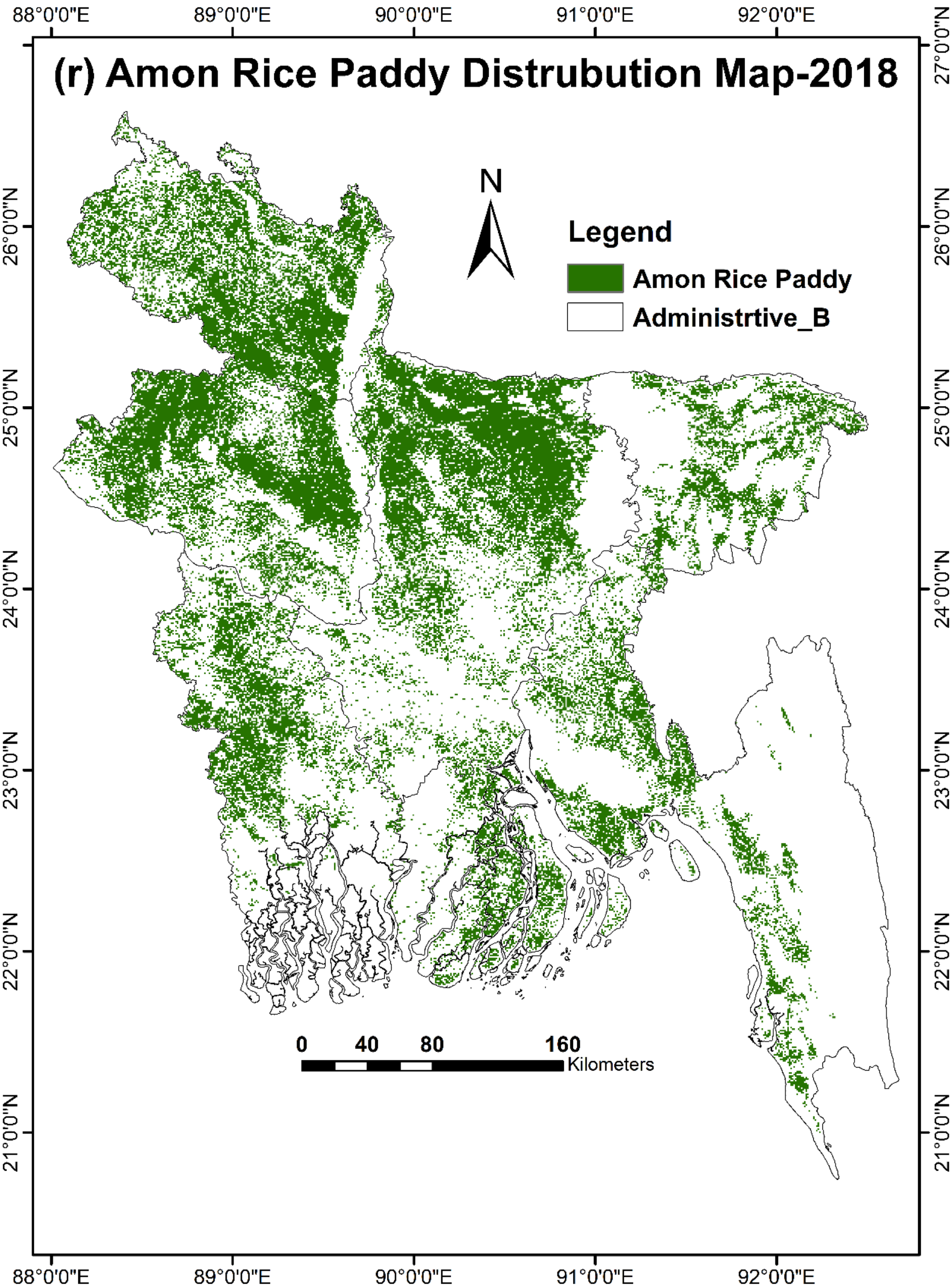
Seasonal Rice paddy distribution map from 2001 to 2018



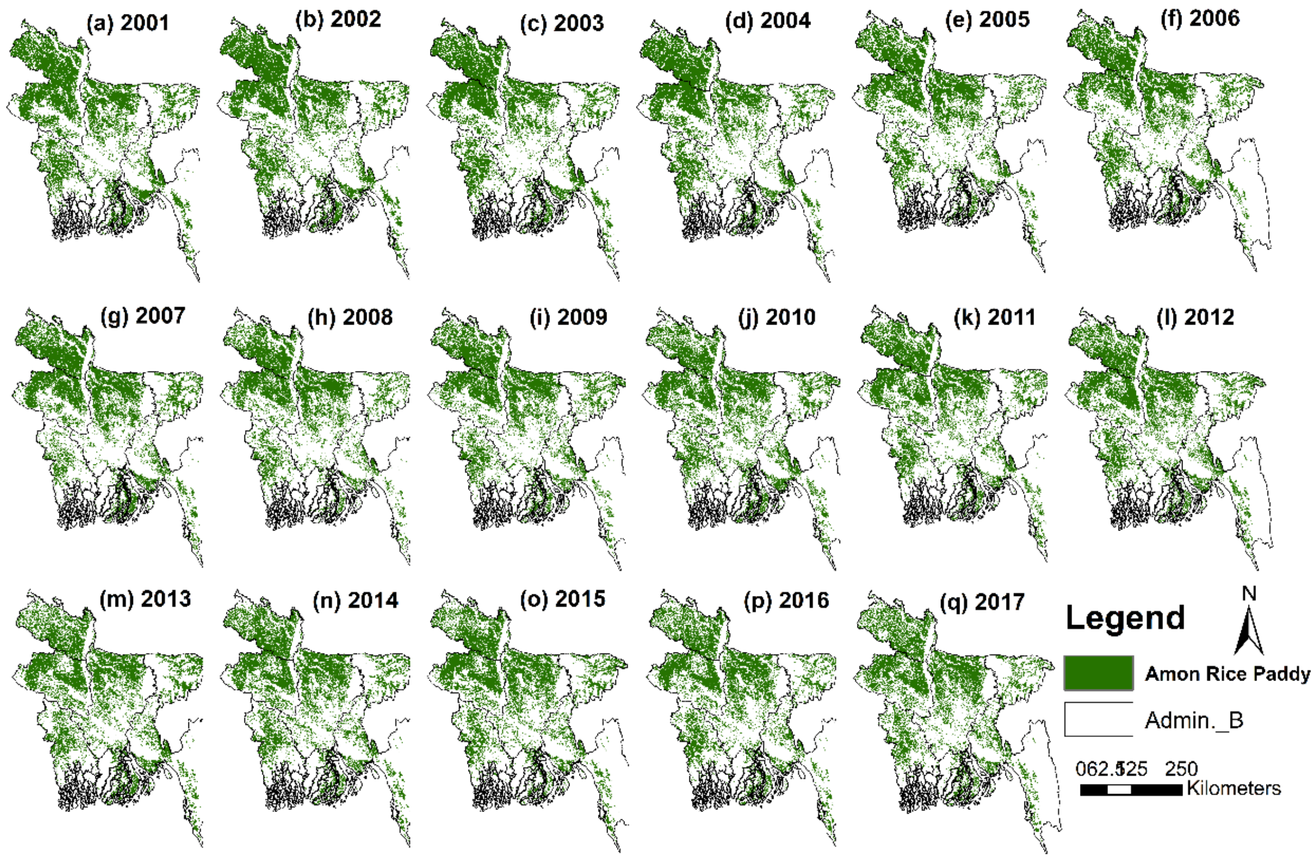

(a) 2001
(b) 2002
(c) 2003
(d) 2004
(e) 2005
(f) 2006
(g) 2007
(h) 2008
(i) 2009
(j) 2010
(k) 2011
(l) 2012
(m) 2013
(n) 2014
(o) 2015
(p) 2016
(q) 2017
Legend
N
Boro Rice Paddy
Admin._B
0 62.5 125 250
Kilometers


(r) Aus Rice Paddy Distrubution Map-2018
88°0'0"E
89°0'0"E
90°0'0"E
91°0'0"E
92°0'0"E
27°0'0"N
26°0'0"N
25°0'0"N
24°0'0"N
23°0'0"N
22°0'0"N
21°0'0"N
N
Legend
Aus Rice Paddy
Administrtive_B
0
40
80
160
Kilometers


(a) 2001
(b) 2002
(c) 2003
(d) 2004
(e) 2005
(f) 2006
(g) 2007
(h) 2008
(i) 2009
(j) 2010
(k) 2011
(l) 2012
(m) 2013
(n) 2014
(o) 2015
(p) 2016
(q) 2017
Legend
N
Admin._B
Aus Rice paddy
062.525 250
Kilometers


(r) Amon Rice Paddy Distrubution Map-2018
88°0'0"E
89°0'0"E
90°0'0"E
91°0'0"E
92°0'0"E
27°0'0"N
26°0'0"N
25°0'0"N
24°0'0"N
23°0'0"N
22°0'0"N
21°0'0"N
N
Legend
Amon Rice Paddy
Administrtive_B
0 40 80 160
Kilometers

Appendix C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(e) 2005
(f) 2006
(g) 2007
(h) 2008
(i) 2009
(j) 2010
(k) 2011
(l) 2012
(m) 2013
(n) 2014
(o) 2015
(p) 2016
(q) 2017
Legend
N
Amon Rice Paddy
Admin._B
0 62.5 125 250
Kilometers

Appendix D

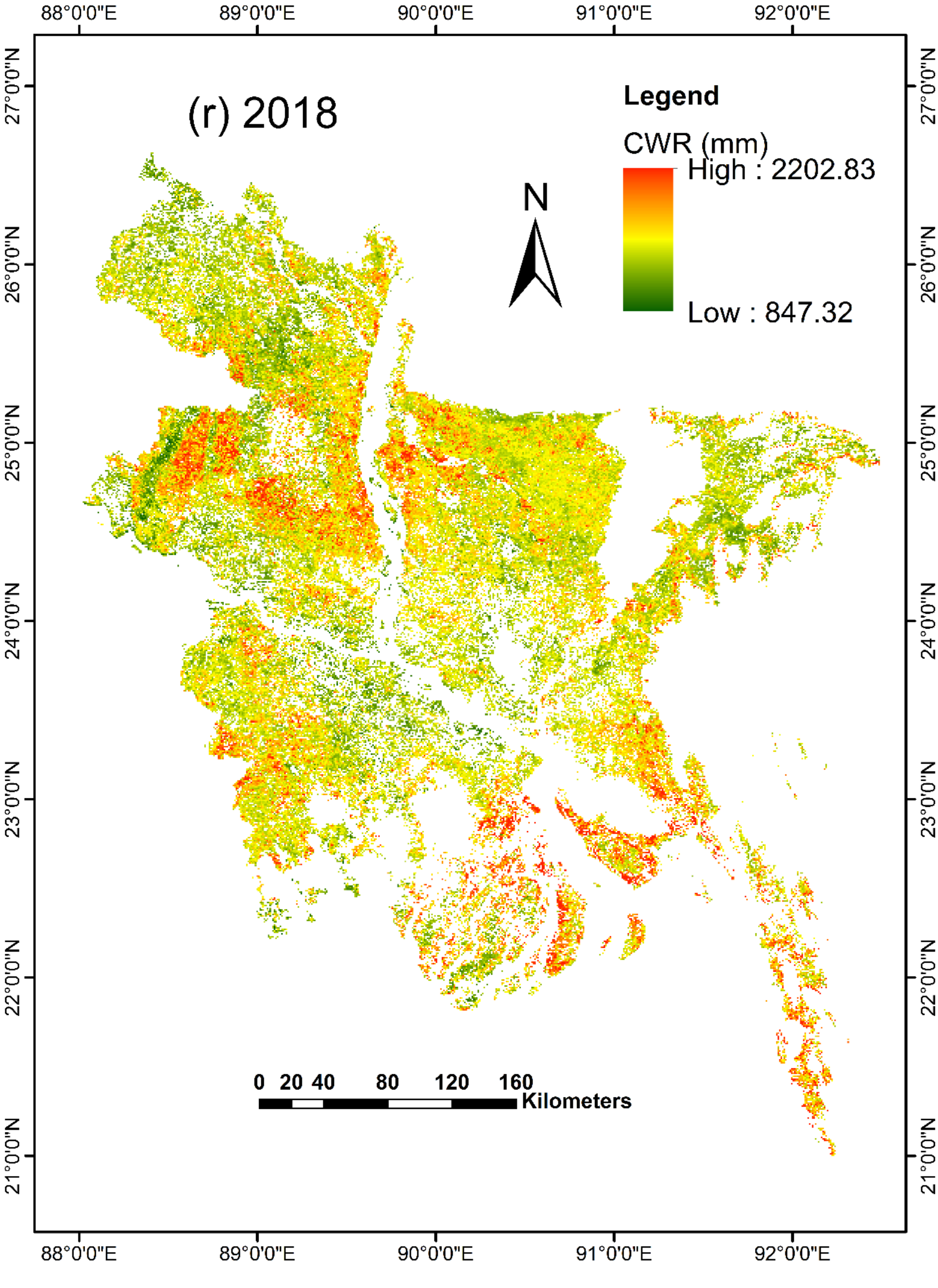
Sample data table of AWD irrigation side and water saving in the study area

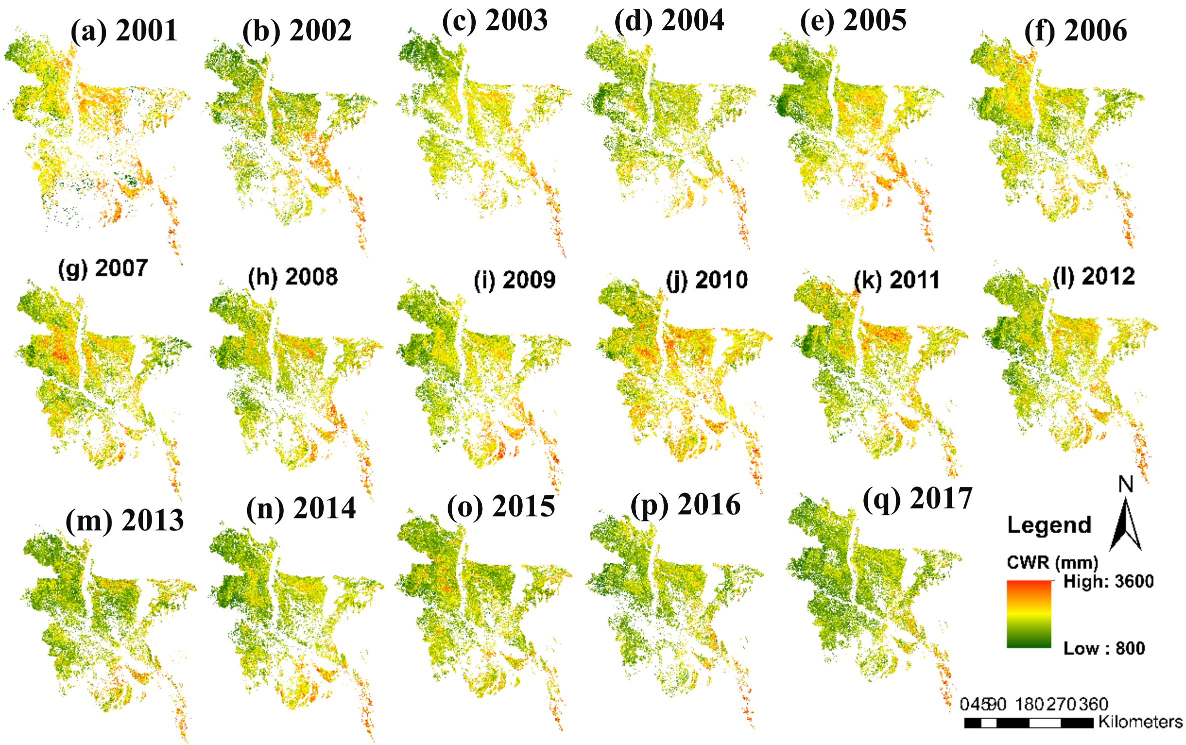
Name of Site	No. of Beneficiaries	Land Size(Dec)	Plant height(cm)		Yield/Bigha(Mns)		Quantity of Irrigated Water(liter/Bigha)		Water Saving (%)
			AWD	Traditional	AWD	Traditional	AWD	Traditional	
Chaksham	14	495	111.80	98.80	24.00	20.00	1685000	2150000	21.62791
Puranapoilo	20	495	92.70	94.30	20.50	18.00	1490000	1950000	23.58974
Majina	21	528	94.60	100.60	19.80	20.00	1565000	2020000	22.52475
Dugarpara	20	495	112.20	101.60	22.70	20.00	1865000	2310000	19.26407
Vasubihar(middle)	23	660	95.60	94.40	20.00	18.00	1790000	2250000	20.44444
Vasubihar(North)	24	495	94.50	91.60	18.80	18.00	1650000	2130000	22.53521
Majbari	33	1122	90.00	90.20	19.00	16.00	1890000	2250000	16
Birkadar	15	495	90.80	91.00	19.00	17.00	1770000	2080000	14.90385
Mirpara	15	396	90.00	90.00	18.00	16.00	1860000	2310000	19.48052
Panai	10	891	90.60	90.60	17.60	16.00	1950000	2290000	14.84716
Buroil	15	495	91.00	90.20	19.00	16.00	1890000	2150000	12.09302
Bamunia	15	297	90.00	89.80	18.00	16.00	2460000	2760000	10.86957
Katabaria	12	330	102.20	98.60	21.00	19.50	2780000	3010000	7.641196
Maria	14	495	90.20	90.40	17.00	14.00	1980000	2210000	10.40724
Choikibari	13	495	90.00	90.00	17.00	15.00	2560000	2650000	3.396226
Chakjupu	8	198	98.50	90.00	18.70	16.00	2790000	3060000	8.823529
RDA Lab Area	8	495	93.00	88.20	22.50	17.50	2860000	3240000	11.7284
RDA Farm	0	0	92.80	89.00	20.04	16.80	1760000	2340000	24.78632
Chakpahari north	20	660	100.40	99.20	23.00	21.00	1850000	2260000	18.14159
Chakpahari south	20	660	101.20	99.20	20.00	23.00	2660000	2960000	10.13514
Garidah	20	594	98.80	98.20	20.50	17.50	2680000	2860000	6.293706
Mahipur	15	495	96.80	98.40	18.90	17.00	2690000	2950000	8.813559
Dhanghara(middle)	15	495	101.80	97.20	25.00	21.00	2870000	3240000	11.41975
Natun kasba(m.t)	31	1023	99.20	98.70	21.50	17.90	2690000	3070000	12.37785
Haldibona	**21**	**693**	**98.20**	**99.30**	**22.30**	**19.80**	**2560000**	**2970000**	13.80471
Chapal	13	**495**	**94.80**	**92.80**	**20.70**	**18.50**	**2550000**	**2870000**	11.14983
Bijoynagar(East)	15	**462**	**105.30**	**102.60**	**20.30**	**18.00**	**2470000**	**2670000**	7.490637
Bijoynagar(West)	**15**	**462**	**96.50**	**95.60**	**21.00**	**19.50**	**2630000**	**2940000**	10.54422
Johirpur(East)	15	495	97.30	96.90	22.50	20.00	2850000	2890000	1.384083
Johirpur(West)	15	495	96.50	95.90	24.50	22.80	2860000	3040000	5.921053

Appendix E

Annual Crop Water Requirement (CWR) map for rice area from 2001 to 2018

CWR for CF irrigated rice paddy

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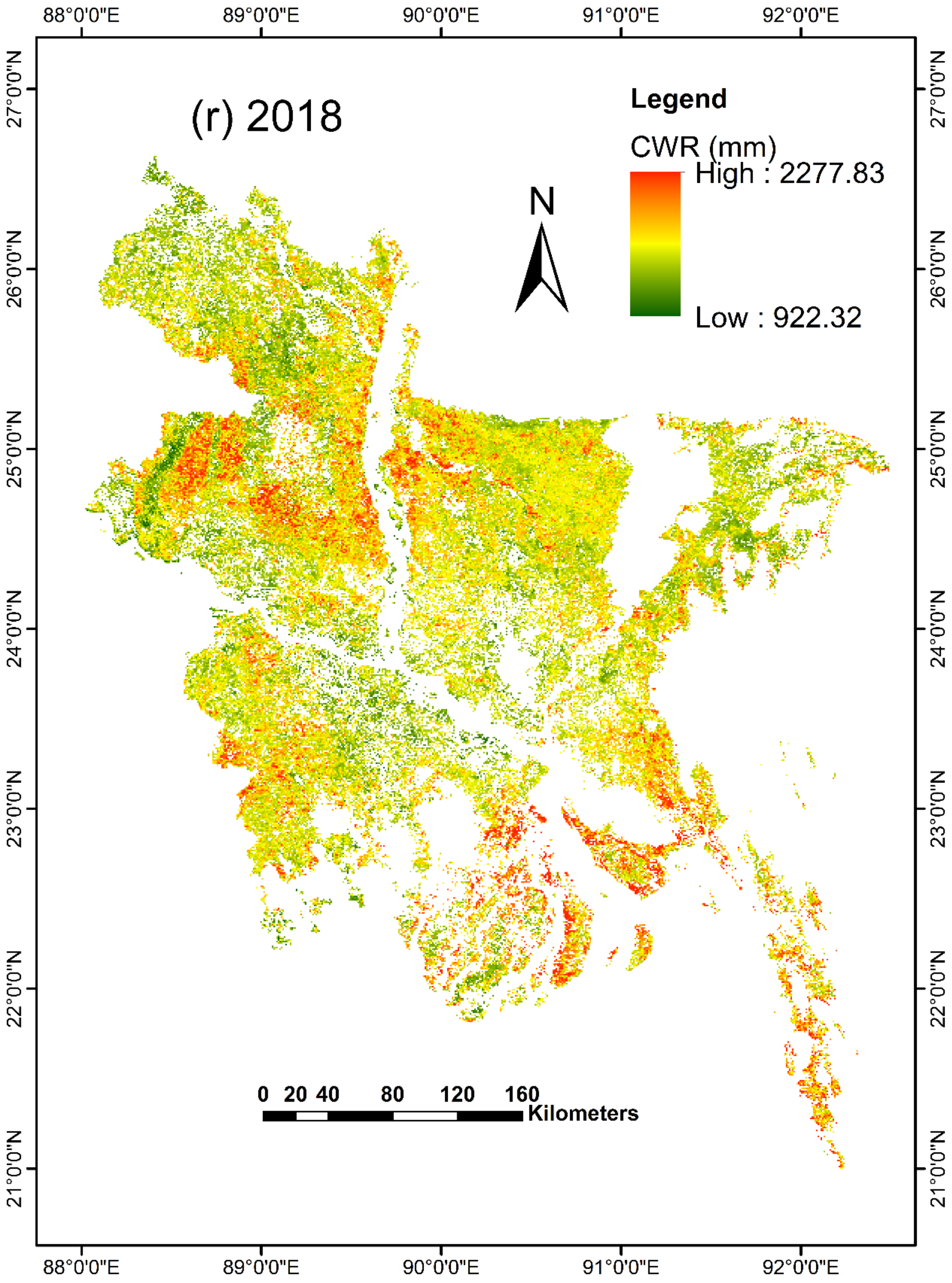
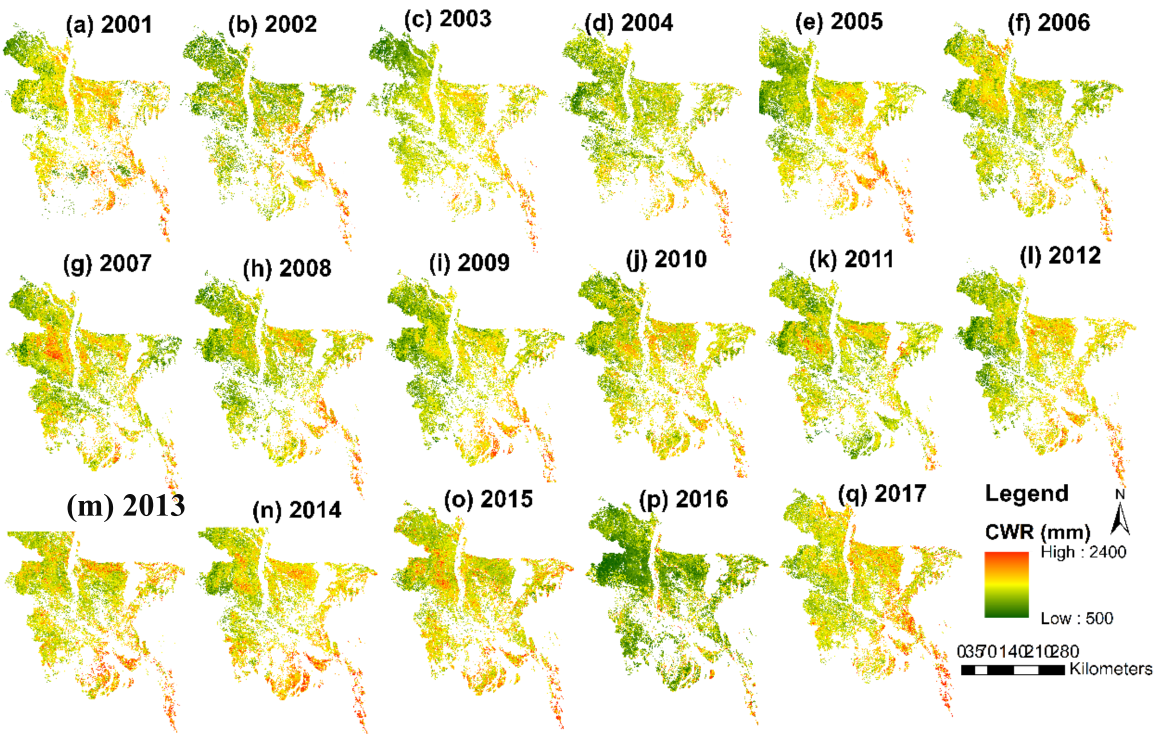
(c) 2003
(d) 2004
(e) 2005
(f) 2006
(g) 2007
(h) 2008
(i) 2009
(j) 2010
(k) 2011
(l) 2012
(m) 2013
(n) 2014
(o) 2015
(p) 2016
(q) 2017
Legend
N
CWR (mm)
High: 3600
Low : 800
0 45 90 180 270 360
Kilometers

CWR for AWD irrigated rice paddy

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(d) 2004
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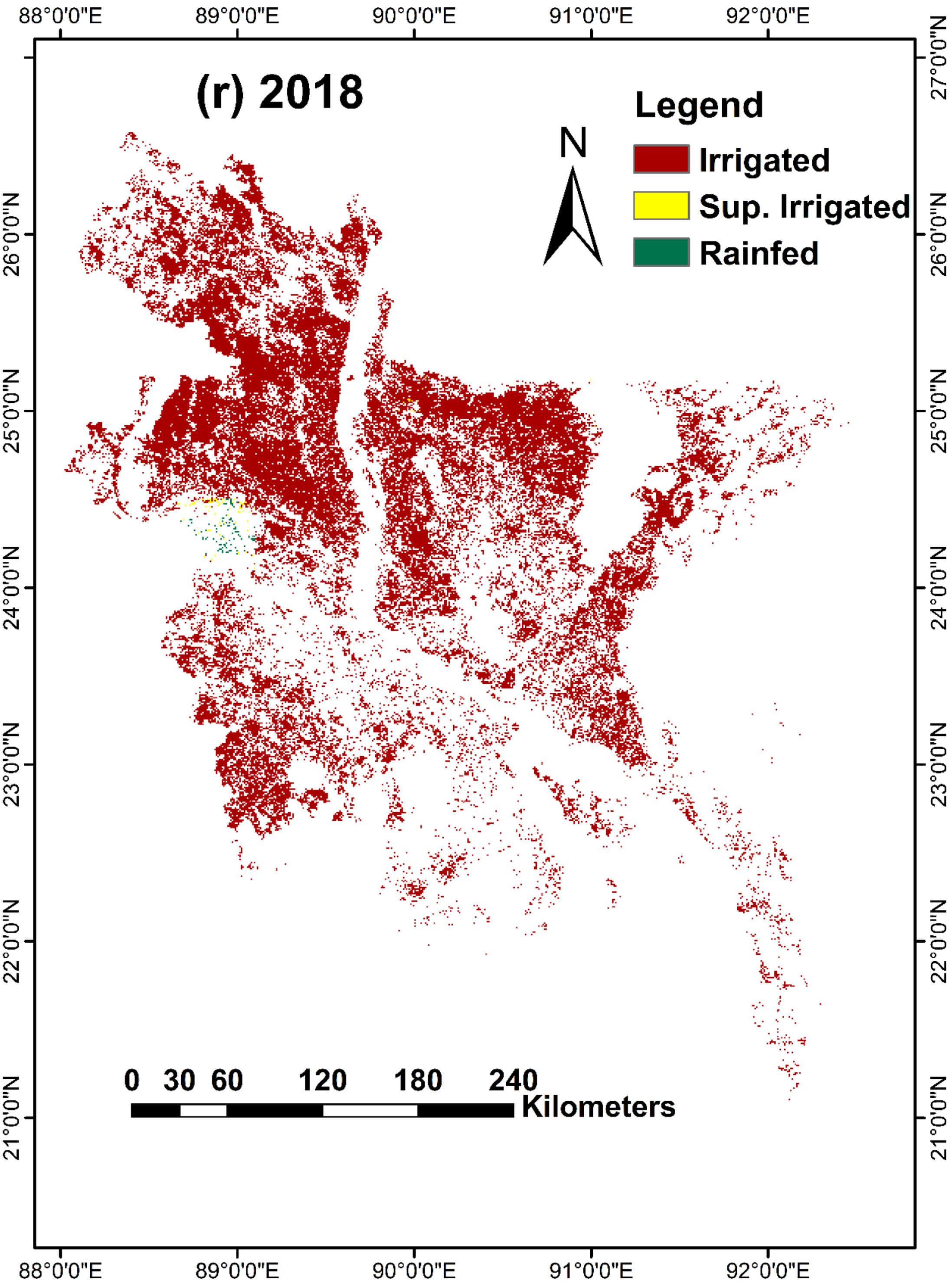
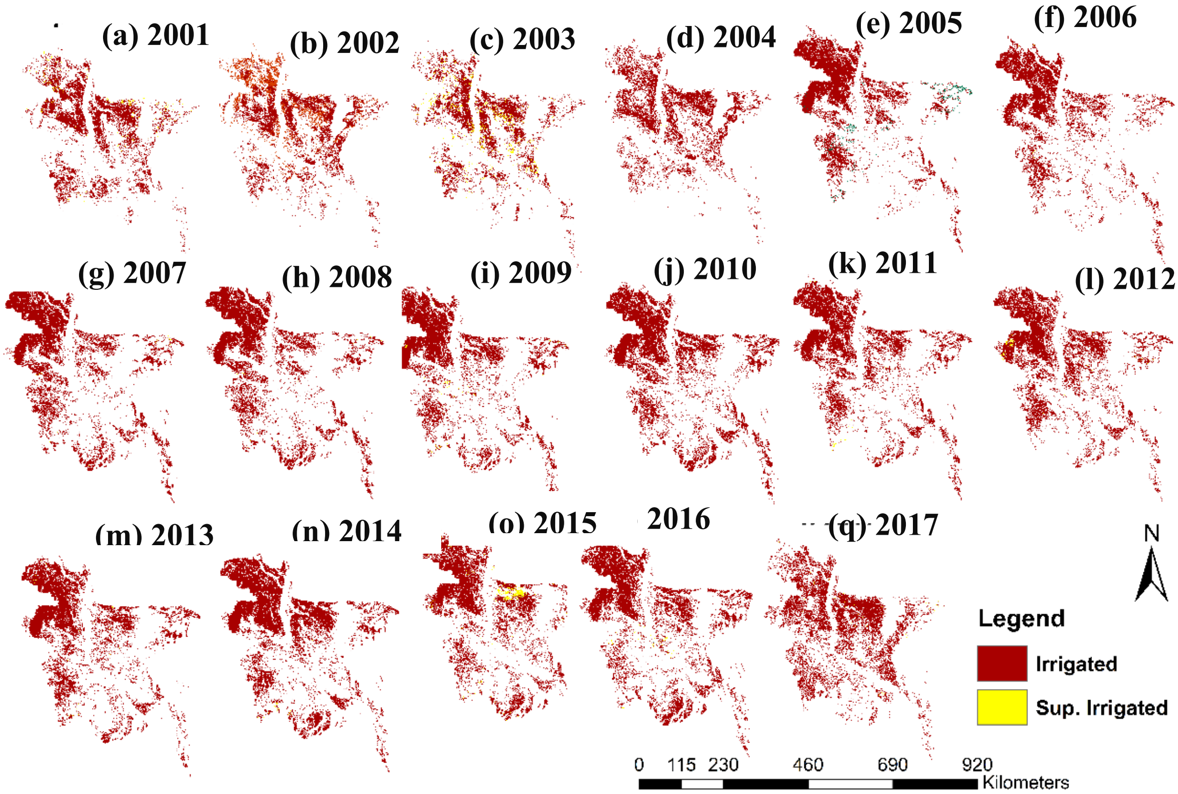
(g) 2007
(h) 2008
(i) 2009
(j) 2010
(k) 2011
(l) 2012
(m) 2013
(n) 2014
(o) 2015
(p) 2016
(q) 2017
Legend
CWR (mm)
High : 2400
Low : 500
N
Kilometers

Appendix F

Seasonal Irrigated, Supplementary Irrigated and Rainfed Rice area map from 2001 to 2018

Boro rice paddy season

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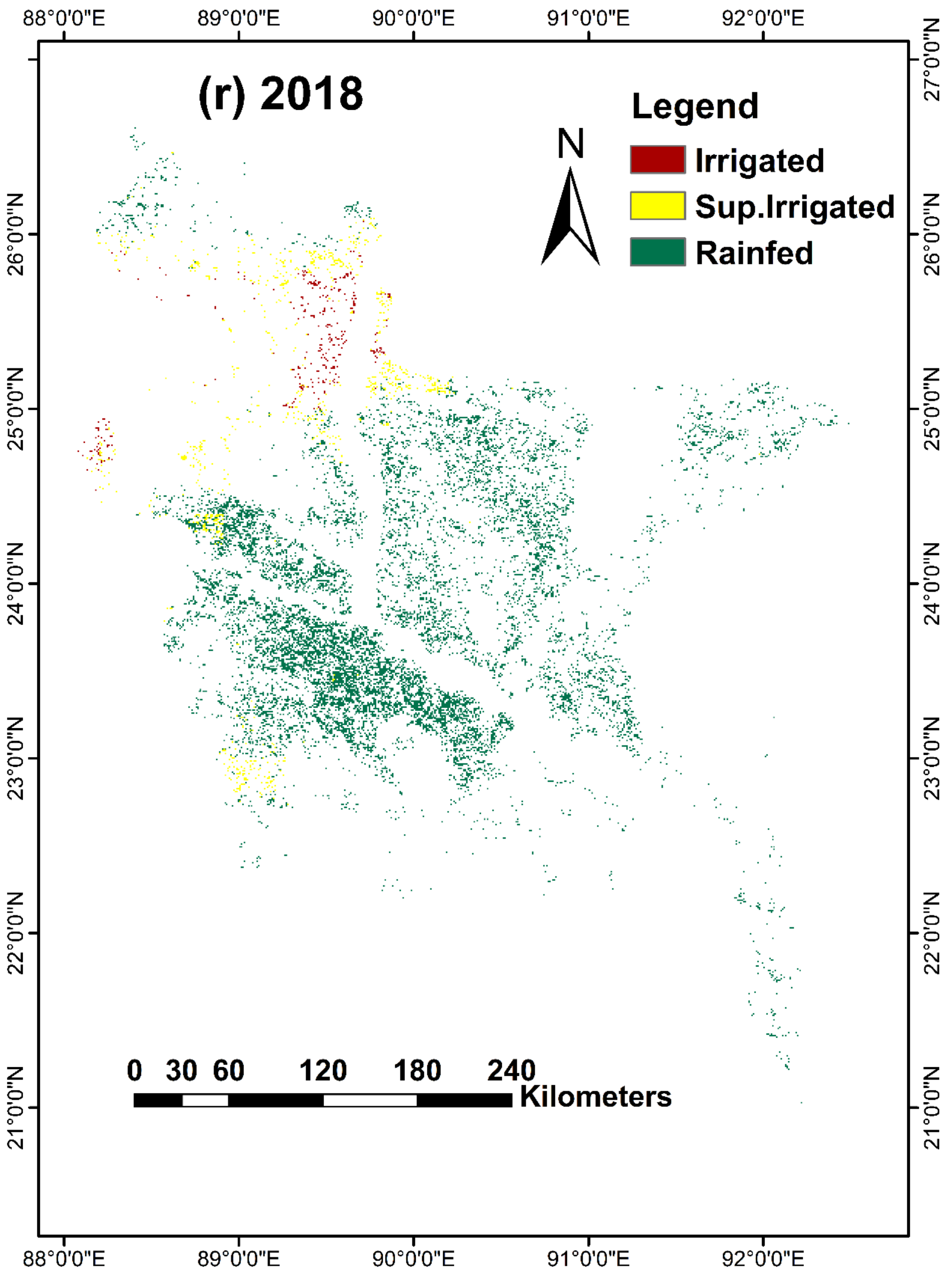
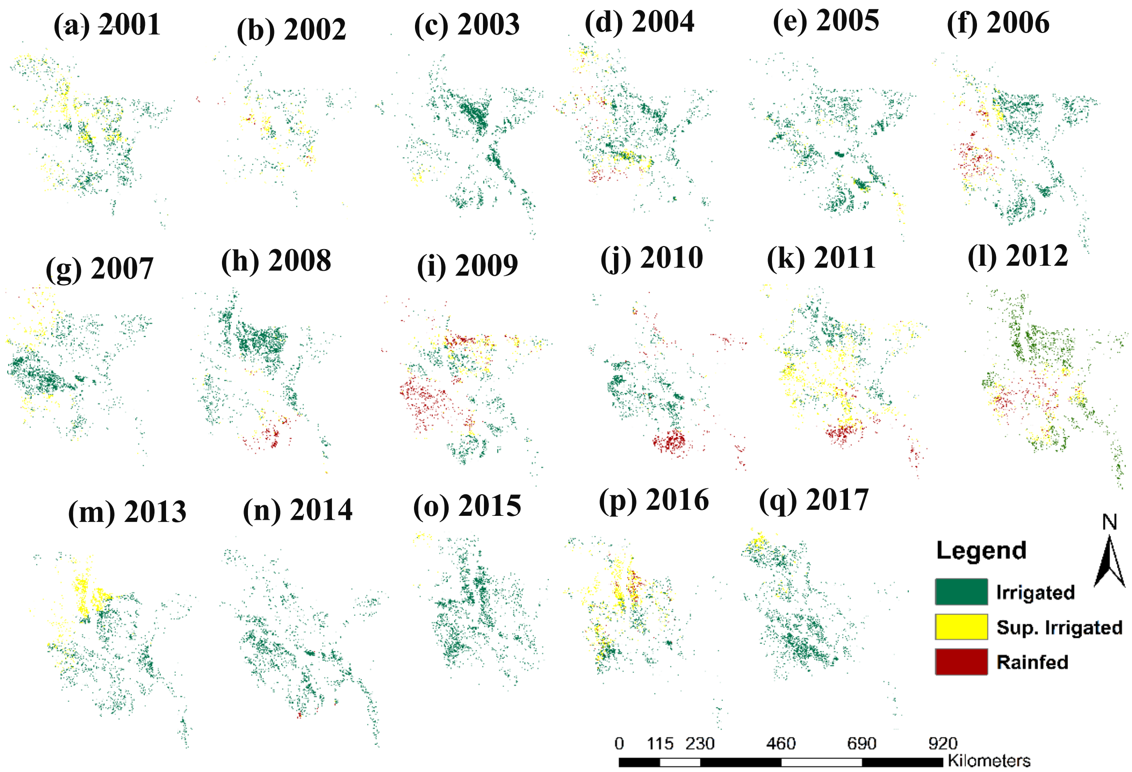
(i) 2009
(j) 2010
(k) 2011
(l) 2012
(m) 2013
(n) 2014
(o) 2015
2016
(q) 2017
N
Legend
Irrigated
Sup. Irrigated
0 115 230 460 690 920
Kilometers

Aus rice paddy season

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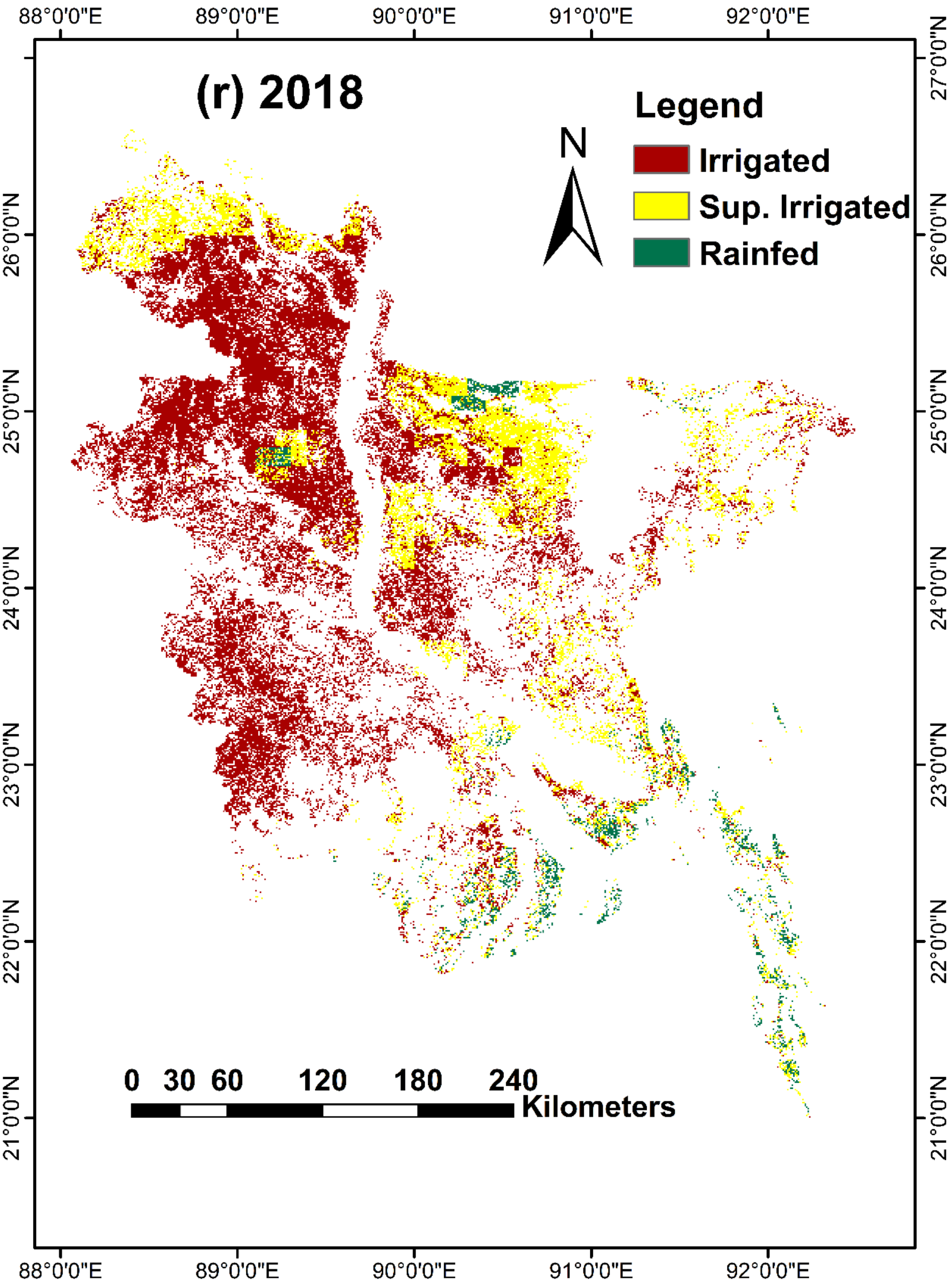
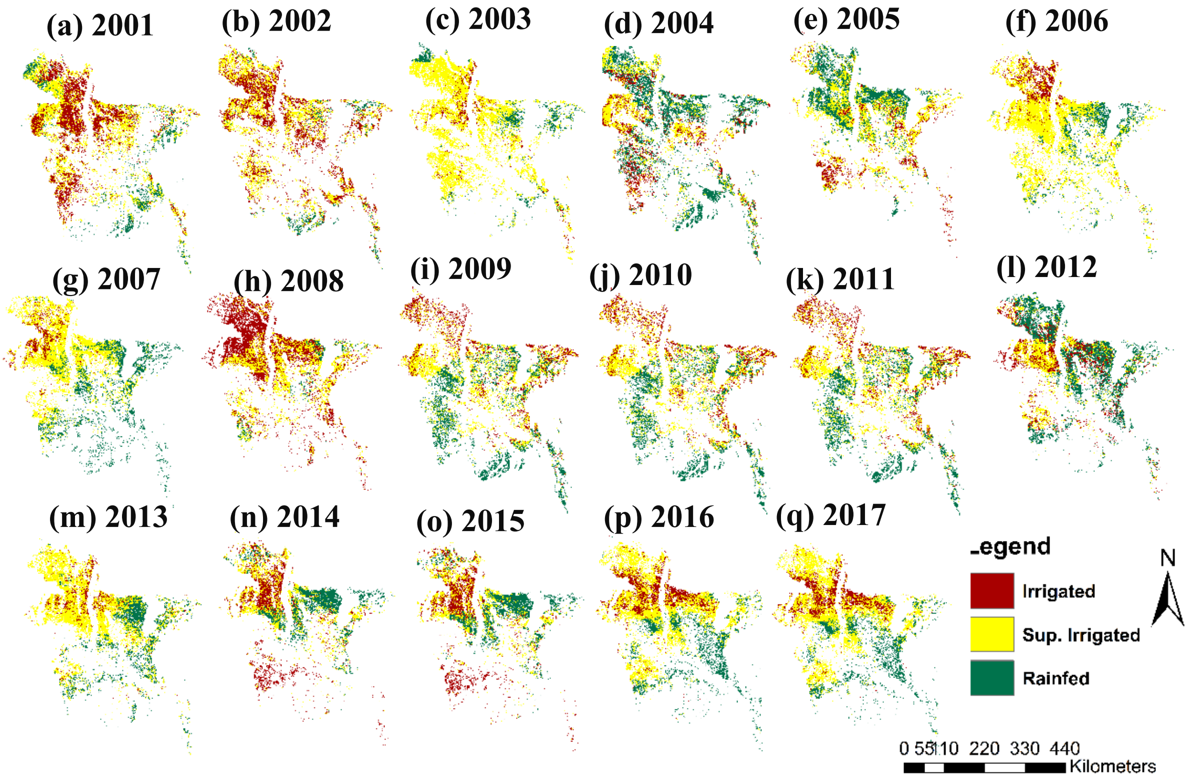
(g) 2007
(h) 2008
(i) 2009
(j) 2010
(k) 2011
(l) 2012
(m) 2013
(n) 2014
(o) 2015
(p) 2016
(q) 2017
Legend
Irrigated
Sup. Irrigated
Rainfed
N
0 115 230 460 690 920
Kilometers

Amon rice paddy season

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(f) 2006
(g) 2007
(h) 2008
(i) 2009
(j) 2010
(k) 2011
(l) 2012
(m) 2013
(n) 2014
(o) 2015
(p) 2016
(q) 2017
Legend
Irrigated
Sup. Irrigated
Rainfed
N
0 55110 220 330 440
Kilometers