ANALYSIS OF EVAPOTRNSPIRATION AND RAINFALL FOR AMAN RICE CULTIVATION IN DINAJPUR, BANGLADESH

A THESIS
BY

MAISHA FAHMIDA
Student no. 1505273
Session: 2015-2016
Semester: January-June, 2017

MASTER OF SCIENCE
IN
IRRIGATION AND WATER MANAGEMENT

DEPARTMENT OF AGRICULTURAL AND INDUSTRIAL ENGINEERING
HAJEE MOHAMMAD DANESH SCIENCE AND TECHNOLOGY UNIVERSITY, DINAJPUR

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Submitted to the Department of Agricultural and Industrial Engineering,
Hajee Mohammad Danesh Science and Technology University,
Dinajpur.

In partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE (MS)
IN
IRRIGATION AND WATER MANAGEMENT

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Approved as to the style and content by

……………………………………………..
(*Professor Dr. Mohammad Shiddiqur Rahman*)
Supervisor

……………………………………………..
(*Professor Md. Ruhul Amin*)
Co-supervisor

……………………………………………………….
(*Professor Dr. Kamal Uddin Sarker*)
Chairman
Examination Committee
And
Chairman

DEPARTMENT OF AGRICULTURAL AND INDUSTRIAL ENGINEERING
HAJEE MOHAMMAD DANESH SCIENCE AND TECHNOLOGY UNIVERSITY, DINAJPUR

JUNE, 2017

DEDICATED TO

MY BELOVED PARENTS

ACKNOWLEDGEMENTS

All praises are for Almighty Allah who has blessed the author with life, mental peace, good health and strength, and enabled her to complete the research work and writing up of this thesis.

The author would like to express her profound appreciation, sincere and heartfelt gratitude and indebtedness to her reverend Supervisor Professor Dr. Mohammad Shiddiqur Rahman, Department of Agricultural and Industrial Engineering, Hajee Mohammad Danesh Science and Technology University (HSTU),Dinajpur, for his constant and untiring supervision, immense guidance, precious advice, valuable suggestions, constructive criticism and painstaking correction throughout the study for completion of her research work and finalizing this thesis. The author also expresses her heartfelt gratitude to Co-supervisor Professor Md. Ruhul Amin, Department of Agricultural and Industrial Engineering, Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur, for his keen interest, scholastic guidance, valuable advice, constructive suggestions, active cooperation and constant encouragement throughout the research period.

The author would like to express her sincere gratitude and heartfelt indebtedness to all her respected teachers of the Department of Agricultural and Industrial Engineering and friends for their helpful suggestions and encouragement during the course of study.

Above all, the author feels proud to express her deepest sense of gratitude and heartfelt thanks to her respected parents, husband and sisters for their great sacrifices and encouragements during the student life of the author.

The Author

ABSTRACT

Long-term climatic variability influences crop evapotranspiration as well as crop production. This study was carried out to analyze the evapotranspiration and rainfall for beneficial planning of aman rice cultivation in Dinajpur, Bangladesh. This study assessed the impacts of climate change on actual evapotranspiration (ET_c) of three popular aman rice varieties i.e., BR11, BR22 and BRRI dhan49. Daily climatic data like rainfall, daily maximum and minimum temperature, maximum and minimum relative humidity, wind speed and sunshine hour for a period of 20 years (1991–2010) were collected from the Bangladesh Meteorological Department, Dhaka, Bangladesh. Reference crop evapotranspiration (ET_o) was determined by the FAO Penman-Monteith method. Actual crop evapotranspiration (ET_c) of the three rice varieties at different growth stages were determined. MAKESENS trend model was used for determining rainfall trend and ET_c trend. Weibull's method was used for probability analysis and the expected rainfall and Actual evapotranspiration (ET_c) at 75% probability level were estimated for different growth stages of those three rice varieties. It was found quite effective to predict the water availability for aman rice cultivation and to indicate the requirement of supplemental irrigation. Variation of crop efficient (K_c) and ET_o were found. ET_c varied at different growth stages over the total growing season. After probability analysis, it was clear that BR11 required supplemental irrigation of 27 mm from '25th July to 2nd September' (development stage), 19 mm from '3rd September to 7th October' (mid stage) and 9 mm from '8th October to 22th October' (late stage) in Dinajpur district, when transplanted between 15th June to 24th July. Similarly, for BR22, as it was transplanted between 30th June to 8th August, then supplemental irrigation of 49 mm and 38 mm was needed from '18th September to 22th October' (mid stage) and from '23th October to 6th November' (late stage) respectively. Finally, for BRRI dhan49, as it was transplanted between 21th June to 10th July, then supplemental irrigation of 4 mm was needed from '25th August to 28th September' (mid stage). After analyzing trend through MAKESENS trend model, it was observed that most of the rainfall curves had decreasing trend and ET_c curve had increasing trend. It will enable to optimize utilization of valuable water resources and help to create a better irrigation schedule for BR11, BR22 and BRRI dhan49 for their successful cultivation. This results can play an important role in sustainable irrigation water management under changing climate and helps to establish effective water schedule for aman rice cultivation.

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LIST OF ABBREVIATIONS

ADB = Asian Development Bank

AER = Annual Equivalent Rate

AMIS = Agriculture Market Information System

APCAS = Asia and Pacific Commission on Agricultural Statistics

BARC = Bangladesh Agricultural Research Council

BBS = Bangladesh Bureau of Statistics

BMD = Bangladesh Meteorological Department

BRRI = Bangladesh Rice Research Institute

DOE = Department of Environment

ET = Evapotranspiration

ET_0 = Reference crop evapotranspiration

ET_c = Actual Crop Evapotranspiration or water demand

FAO = Food and Agriculture Organization

GDP = Gross Domestic Product

GOB = Government of Bangladesh

IPCC = Intergovernmental Panel on Climate Change

K_{cini} = Crop coefficient at initial stage

K_{cdev} = Crop coefficient at crop development stage

K_{cmid} = Crop coefficient at mid-season stage

K_{cend} = Crop coefficient at late season stage

MAKESENS = Mann-Kendall test for trend and Sen’s slope estimates

NASA = National Aeronautics and Space Administration

PET = Potential Evapotranspiration

UNDP = United Nations Development Program

USGS = United States Geological Survey

WARPO = Water Resources Planning Organization

CHAPTER I
INTRODUCTION

1.1 Climate

Climate is the dominant pattern of weather observed over a long period of time which usually defined as the "average weather" in a place. It includes patterns of temperature, precipitation (rain or snow), humidity, wind and seasons. Climate patterns play a fundamental role in shaping natural ecosystems, and the human economies and cultures that depend on them. “Climate change” means an overall alteration of average climate conditions, on the contrary “climate variability” refers to the fluctuations of climate about the average or mean. Exquisite impacts on hydrological systems, ecosystems, agriculture and other related systems have been expected (McCarthy *et al.*, 2001). In 2011 the U.S. experienced 14 extreme weather-related events that caused loss of human life and cost the U.S. economy more than $55 billion (NASA Giddard, Department of Ecology, State of Washington). The IPCC (Intergovernmental Panel on Climate Change) reported to the United Nations that the Earth’s climate system is undoubtedly getting warmer and rising sea level will about 6-7 inches in the 20th century (IPCC, February, 2007). The average global temperature has risen about 1.4ºF (0.8ºC) since 1880, according to the new analysis (National Aeronautics and Space Administration, 2010). Climate change occurs when long-term weather patterns are altered through human activity. The average annual temperature in the Pacific Northwest rose by 1.5°F in the 20th century and is expected to rise 0.5° F per decade in the first half of the 21st century (Climate Impact Group, University of Washington). Coastal settlements in both developed and developing countries are exposed and vulnerable to climate extremes. Climate change has prolonged impacts on social and economical society. Agriculture is also an economic sector exposed and vulnerable to climate extremes. There are inconsistent patterns of change in heavy precipitation in Africa and partial lack of data; hence there is low confidence in observed precipitation trends. Heavy precipitation may induce landslides and debris flows in tropical mountain regions with potential impacts for human settlements. Due to burning of fossil fuels, eradication of forests and human activities, carbon dioxide concentration is raising in atmosphere is obstructing escape of heat radiated by the earth. In agriculture, climate change affects it in three ways by: salinity intrusion, flooding and increasing frequency of cyclone and its degree of damage. Agricultural production is decreased by the combined effects of these factors, especially in coastal areas. The most widely used indicator for climate change is temperature, both in global and regional level.

Longer growing seasons and warmer temperatures may bring benefit in cold regions may be the positive aspects including some negative impacts of reduction of water availability, greater water demand and more frequent extreme weather which put agriculture in serious risks (Eitzinger and Kubu, 2009). Kosa and Pongput (2007) reported that as much as 10% change in production will be associated with a change in growing season precipitation by one standard deviation (e.g. Millet in South Asia).

1.2 Impacts of climate change in Bangladesh

Bangladesh is a developing, low-lying, riverine country located in South Asia with a largely marshy jungle coastline of 580 on the northern littoral of the Bay of Bengal. It lies in the north-eastern part of South Asia and is situated between 88°01′ and 92°41′ East longitudes and between 20°34′ and 26°38′ North latitudes having an area of 1,47,570 km^2. This country is bounded by India in the west, north and north-east sides, Myanmar on the south-east and Bay of Bengal on the south. A great plain lies almost at sea level along the southern part of the country that rises gradually towards the north. The elevation of the land varies from 1 to 90 m above mean sea level. Bangladesh is one of the largest deltas in the world, which is highly vulnerable to Natural Disasters because of its Geographical location, flat and low-lying landscape, population density, poverty, illiteracy, lack of Institutional setup.

Climate change in Bangladesh is an extremely crucial issue and according to National Geographic (2002), Bangladesh ranks first as the nation most vulnerable to the impacts of climate change in the coming decades. The economy of Bangladesh is based on agriculture mainly, with two thirds of the population engaged (directly or indirectly) on agricultural activities; although the country is trying move towards industrialization slowly during the last one and a half decade. So, the overall impact of climate change on agricultural production would be wide spread and devastating for the country’s economy. Beside’s this, other impacts of climate change such as-extreme temperature, drought, and salinity intrusion etc. are also responsible for the declining crop yields in Bangladesh. Temperature and rainfall changes have already affected crop production in many parts of the country and the area of arable land has decreased to a great extent. The Salinity intrusion in the coastal area is creating serious implications for the coastal land that were traditionally used for rice production. Human activities increases emission of anthropogenic greenhouse gases causing climate change is a key concern for vulnerable countries including Bangladesh. According to the IPCC Fourth Assessment Report (2005), the sea-level of the Bay of Bengal is rising at a rate of 1.5 mm per year.

Heavy rainfall is characteristic of Bangladesh causing it to flood every year in lower parts. The annual rainfall in Bangladesh ranges from 2300 mm to 2600 mm but uneven distribution. Because of its location in south foothills of the Himalayas, where monsoon winds turn west and northwest, the region of Sylhet receives the greatest average precipitation. The average annual rainfall is about 2,320 mm and varies between 1,110 mm in the northwest and 5,690 mm in the northeast. FAO (2007) reported, from 1977 to 1986, annual rainfall in that region ranged between 3,280 and 4,780 mm (129.1 and 188.2 in) per year. Rashid *et al.,* (1991) found that average daily humidity ranged from March lows of between 55% and 81% to July highs of between 94% and 100%, based on readings taken at selected stations nationwide in 1986. Ali *et al.,* (2007) found that, the average annual rainfall in Bangladesh was 2486 mm and it was about 66.67% of the total year's rainfall. About 70% to 80% of the total rainfall occurs from month of June to September. The most productive dry season during November to March undergo through inadequate rainfall for crops growth. The potential increase in the global temperature with increasing emission of anthropogenic greenhouse gases, rainfall has already become fluctuating and unpredictable. Also increased the occurrence of climate-related serious issues like floods, droughts, heat waves and cyclones in future (FAO, 2006; IPCC, 2007; Ahsan *et al.,* 2011). These changes make a great concern about the drastic consequences on the agricultural crop growth and food security in most of the parts of the world. especially in developing countries (FAO, 2007; IPCC, 2007; Rouder *et al.,* 2011). Geographically, Bangladesh is located in the danger zone and the country is more vulnerable to natural disasters like cyclone and flooding every year and this study will address the coping strategy and new policies of adaptation for the vulnerable population in the coastal areas. Because of the direct and strong dependence of agricultural crop production on climate, the scientists and policy makers have recognized the sensibility of crop growth uncertain and questionable. Bangladesh is considered as one of the top most countries that is most vulnerable to climate change because of its graphical location, low elevation from sea level, density of population and low economic capacity (DOE, 2007; Paulette *et al.,* 2009; Huq and Rabbani, 2011). Temperatures in Bangladesh have increased about 1°C in May and 0.5°C in November between 1985 and 1998. An increase in average day temperature of 1°C by 2030 and 1.4°C by 2050 is predicted (FAO, 2007; IPCC, 2007). Rainfall has become day by day unpredictable, variable and displayed uneven in its distribution. Besides uncertain pattern creates extreme events such as flood, cyclone and drought resulting adverse effect on human life, animals, eco-system and crop yields especially on rice production (GOB and UNDP, 2009). The downfall of rice production is predicted by 8%-12% within 2050 (BBS, 2005; IPCC, 2007).

1.3 Rice Production in Bangladesh

Rice is the staple food for 161 million people of Bangladesh. The dominant food crop of Bangladesh is rice, accounting for about 75% of agricultural land use and 28% of GDP. It provides nearly 48% of rural employment, about two-third of total calorie supply and about one-half of the total protein intake of an average person in the country (ADB, 2014). Amount of rice production in Bangladesh: 34.5 million m ton (4th largest), yield: 4.42 tons/hectare, area covered by 11,82,000 hectare (APCAS, 2016). Based on physiography and land types, the rice-growing environment is classified into four major ecosystems: upland, irrigated, rain-fed and floating or deep-water (FAO, 2007). In rain-fed Aus and Aman, rainfall plays a very important role during April to October when about 61% of total rice grown in Bangladesh. There are three major rice crops season: Aus, Aman and Boro in Bangladesh. The cultivation of rice in Bangladesh varies according to seasonal changes in the water supply. The largest harvest is Aman, occurring in November and December and accounting for more than half of annual production. Some Aman varieties are sown in the spring through the broadcast method, matures during the summer rains. The higher yielding method involves starting the seeds in special beds and transplanting during the summer monsoon. The second harvest is Aus, involving traditional strains but more often including high-yielding, dwarf varieties. Rice for the Aus harvest is sown in March or April, better from April and May rains, matures during in the summer rain, and is harvested during the end of summer. With the increasing use of irrigation, there has been a growing focus on another rice-growing season extending during the dry season from October to March. The production of this

Boro rice, including high-yielding varieties, expanded rapidly until the mid-1980 (BBS, 2009). According to BBS (2016), total Aus production is 2328 M.Tons, Aman production is 13190 M.Tons and Boro production is 19192 M. Tons. The rice calendar varies marginally in different areas according to land elevation and soil texture. Climate often plays an important role in rice production. According to Bangladesh Rice Research Institute (BRRI, 1991), Aman is almost a completely rain-fed rice that grows in the months of monsoon, although it requires supplemental irrigation during planting and sometimes, in the flowering stage, depending on the availability of rainfall. Aman is planted in two ways: direct seeding with Aus in March and April, 2nd is transplantation between July and August. Both types are harvested from November through December (Islam *et al.,* 2004).

In North-West hydrological zone, rice is the main crop about 7.6 M ha of total cultivable land (9.03 M ha) and 5 M ha being irrigated (World Bank, 1998). Rice grown in Bangladesh in a complex maniac cycle of single-crop, double-crop and triple-crop patterns of Aus, Aman and Boro seasons.

1.4 Water demand and Evapotranspiration

According to global agriculture, water is getting scarce. Freshwater withdrawals have tripled over the last 50 years. Demand for freshwater is increasing by 64 billion cubic meters a year (1 cubic meter = 1,000 liter). Agriculture is by far the largest consumer of the Earth's available freshwater: water in rivers, lakes, groundwater and glaciers called 'blue water', seventy percent of 'blue water' withdrawals from watercourses and groundwater are for agricultural usage, three times more than 50 years ago. By 2050, the global water demand of agriculture is estimated to increase by a further 19% due to irrigational needs. Approximately 40% of the world's food is currently cultivated in irrigated areas. Especially in the densely populated regions of South East Asia, the main factor for increasing yields were huge investments in additional irrigation systems between the 1960s and 1980s (FAO Global Agriculture, 2007). Worldwide, agriculture accounts for 70% of all water consumption, compared to 20% for industry and 10% for domestic use. In industrialized nations, however, industries consume more than half of the water available for human use. Belgium, for example, uses 80% of the water available for industry (FAO, 2007). Each person's water consumption rate about 80-100 gallons of water per day (USGS, 2016). The production of biofuels has also increased sharply in recent years, with significant impact on water demand that 1,000-4,000 litres of water are needed to produce a single litre of biofuel (FAO; 2007). As agriculture sector is the largest water user, the need of water for crop growth must be known to all grower, farmers and planners. The largest sector of Bangladesh's economy is 'Agriculture', which is about 20.29% of the GDP and 47.5% of the labor sector (BBS, 2015). Agriculture is the main earning source of most of the people of Bangladesh. Modern technologies adapt new varieties and irrigation system to fulfil the food security. Impact of climate change is now the main concern for scientist to overcome production losses for the growing population.

Crop water requirements are defined here as "the depth of water needed to meet the water loss through evapotranspiration (ETcrop) of a disease-free crop, growing in large fields under non restricting soil conditions". Evaporation from natural surfaces, such as open water, bare soil or vegetative cover is a diffusive process, by which water in the form of vapour is transferred from underlying surface to the atmosphere. For successful production and better yield, grower must have to know the water requirement of that crop.

Evapotranspiration is one main factor for water balance equation of any crop (Yarahmadi, 2003). Evapotranspiration (ET) refers to water used by a crop for its growth, tissue building, cooling purposes as well as soil evaporation (Alkaisi and Broner, 2005). ET rates depend upon the factors such as temperature, humidity, solar radiation, wind speed and vegetation characteristics that is transpiring, with significant variation of vegetation types (Allen *et al.*, 1998). The reference crop evapotranspiration (ET_c) which is defined in FAO-24 as "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water." If the ET demand exceeds the available water to the plant, then transpiration may stop resulting in crop loss. Therefore, the accurate estimation of ET along with proper knowledge of precipitation and other factors, soil moisture storage capacity can improve for crop growth. Also it is important to know the future evapotranspiration rate for probable demand of water in agriculture sector.

1.5 Supplemental Irrigation (SI)

Supplemental irrigation is the opposite of full or conventional irrigation (FI). SI depends on the precipitation of a basic source of water for the crop. Supplemental irrigation (SI) can be defined as the addition of small amounts of water to essentially rain-fed crops during times when rainfall fails to provide sufficient moisture for normal plant growth, in order to improve and stabilize yields (Oweis and Hachum, 2003). SI in areas with limited water resources is based on the following three premises:

a) Water is applied to a rain-fed crop which would normally produce some yield without irrigation.
b) Since precipitation is the principal source of moisture for rain-fed crops, SI is only applied when precipitation fails to provide essential moisture for improved and stabilized production.
c) The amount and timing of SI are not scheduled to provide moisture-stress-free conditions throughout the growing season, but to ensure that the minimum amount of water required for optimal (not maximum) yield is available during the critical stages of crop growth.

1.6 Justification of the study

Water is a valuable resource in present day. The demand of water, particularly for irrigation is increasing day by day with increasing population. For calculating crop-water demand, irrigation scheduling, preparing input data to any hydrological water-balance models, and assessing and planning regional water resources and evaluating data, among various climatic factor must be known. Reference Crop Evapotranspiration, ET_o is an important key parameter. It depends upon the crop types, crop development and management practices. Water is a single most important factors that can make or break a crop. But water has to supply in crops with adequate amount and proper methods. Too much or too little water can hamper the crop growth and finally yield. Estimation of water requirement for a crop is necessary and also important to supply proper amount of water at right time, right pattern. A 1 mm loss of water through ET across 1hactare crop field is equivalent to 10 m^3 (268,000 gallons) of water (Allen *et al.*, 1998). So conjunctive use of water in crop production is very important nowadays. Many countries people are suffering from water scarcity. For upcoming climatic challenge and environmental stresses, correct measurement of water requirement, irrigation scheduling must be taken concern. On the other hand, rainfall has a great impact in rain-fed crops cultivation. Climate is becoming cruel and unpredictable causing uneven distribution of rainfall. Irrigation has a direct relationship to the crop yield; if irrigation requirement increases, the production cost also increases. Supplemental irrigation (SI), using a limited amount of water, if applied during the critical crop growth stages, can result in better improvement in yield and water use productivity. For better crop production, a good understanding of the availability, quantity and variability of water resources have to ensure. For efficiently utilizing, managing and conserving valuable resources like water, long term data collecting and analyzing is also necessary. In Dinajpur, rice production covered more than seventy percent of total production area. Huge number of auto-rice mills are established to enhance employment.

1.6 Objectives of the study

This study is done to identify the dependable rainfall and actual evapotranspiration at every stage of BR11, BR22 and BRRI dhan49 for providing accurate amount of water in Dinajpur district for future cultivation purpose. The specific objectives of the research were:

1) To determine actual crop evapotranspiration for three varieties of Aman rice at different growth stages,
2) To determine dependable rainfall and actual crop evapotranspiration by probability analysis,
3) To estimate long-term trends of rainfall and water demand for different stages of Aman rice varieties and
4) To determine stage wise supplemental irrigation for Aman rice cultivation.

CHAPTER II

REVIEW OF LITERATURE

Global climate is changing day by day and becoming biggest threats of the 21st century. Now a days environment has facing severe problem of humanity, implemented with natural ecosystem, industry and food production. Scientist has predicted from the past would result from global climate change and now occurring: loss of sea ice, accelerated sea level rise and longer, more intense heat waves (NASA, 2010). In the north-west region of Bangladesh, often suffer from heavy drought which effects agriculture, crop and food production, resources and human health. The moderate drought affected areas will be turned into severe drought prone areas within next 20-30 years (IPCC, 2007). The study deals with the impact of climate change on analysis of rainfall and evapotranspiration for valuable water resources management and crop production in Dinajpur district Bangladesh. Available literature were reviewed to find out effective information for understanding the concept of the study.

2.1 Probability analysis of dependable rainfall

Salazar *et al.,* (1974) stated that, in agriculture rainfall amount with 75% probability of occurrence (the amount equaled or exceeded 75% of the time) could be considered as dependable rainfall.

Linsley and Joseph (1975) stated that the Weibull’s method is the most commonly used method for probability analysis, in which rank of the magnitude and number of years are used.

Raghunath (1986) used the two graphical methods for probability analysis known Allen Hazzen method.

Talukder *et al.,* (1988) reported that the average annual rainfall in Bangladesh was 2080 mm. During their 16 years (1965-1980) study period, the probability of 10, 20, 40, 50, 80 and 90 %, they concluded that maximum in July at Kaptai was of the magnitude of 670, 1000, 1150, 1340, 1460 and 1560 mm and minimum in August at Ishurdi was magnitude of 215, 265, 290, 320, 335 and 350 mm at recurrence intervals considered.

Rahman and Khan (1989) suggested that a probability of 75% may be adequate for dependable precipitation and be recommended to use for the purpose of planning and design in agricultural resources. However, for moisture sensitive crops, highest 90% value and with low value crops 50% level may be appropriate.

Talukder *et al.,* (1989) analyzed eight different but evenly distributed locations in Bangladesh for estimating ET and PET for a period of 5 years (1976-1980) for the major climatological parameters like solar radiation, air temperature, relative humidity, wind speed and precipitation.

Saha *et al.,* (1990) used three different theoretical probability distributions, the Log Pearson Type-III, Log-Normal and Gumbel distribution. The annual maximum data was then plotted in the frequency curve for maximum daily rainfall data of 22 years (1964-1985) for various stations. The theoretical frequency curves were in close agreement with the observed data points, except at the highest rainfall for all the three distributions. Among the three, the Log Pearson Type-III distribution gave the best fit to the observed data.

Srivastava *et al.,* (2004) reported that for planning weather sensitive agricultural operations, probability concept was adopted to demonstrate the importance of dry and wet spells. Markov chain model was fitted to weekly rainfall data of four selected stations representing different agro climatic zones of Uttar Pradesh, India. For kharif season, initial and conditional probabilities of occurrence of dry and wet spells of different lengths were estimated at these stations, and their probabilities were calculated.

Manoroma *et al.,* (2007) analyzed 30 years of time series data on rainfall to have efficient crop production planning and analyzed the crop period for Nilgiri, Tamil Nadu, India, using co-efficient of variation and probability. Finally found that two crop are possible every year under rain-fed conditions.

Singh (2008) reported that statistical analysis of rainfall provides a better scope for planning cultivation of agricultural crops in advance. There chance of getting deficit soil moisture during critical growth stages of paddy when supplemental irrigation is required. Rabi crop found to be under moisture stress under rain-fed condition and pre-sowing irrigation is essential for good establishment.

Bhakar *et al.,* (2008) analyzed weekly and monthly rainfall for Kota, India using 35 Years (1970-2004) daily rainfall data. The variation in weekly and monthly rainfall pattern was found to be more consistent during monsoon season. For forecasting the weekly and monthly rainfall Weibull's method (extreme value type III), Normal, Log-normal and Gamma probability distribution functions were fitted. Finally Gumbel distribution was found to be fitted well for prediction of weekly and monthly maximum rainfall.

2.2 Actual crop evapotranspiration

During last 50 years or more, numerous number of researcher or scientists have developed a huge amount of empirical or semi-empirical equations. Now a days, water scarcity is increasing day by day. For higher yield and sustainable crop production, determination of actual crop evapotranspiration plays an important role.

Chakraborty and Chakraborty (1990) used data on daily rainfall over 1976-1985 for estimating rainfall pattern, conditional probability analysis and water balance analysis for the Berhampur region in Murshidabad district. They analyzed water balance (actual evapotranspiration and potential evapotranspiration ratio) for different soil types in the region with available water capacity of 200, 250 and 300 mm/m soil depth.

Tyagi *et al.,* found that through lysimeter, the average weekly ET of rice varied from 3 mm per day in the early growing period to 6.6 mm per day at milking stage. The peak ET_c was 6.61 mm per day and it occurred 11 weeks after transplanting at reproductive stage when LAI was 3.4.

Pirmoradian *et al., (*2002) determined the crop coefficient and water requirement of rice in Shiraj, Iran. They found that potential evapotranspiration (PET) estimated by FAO Penman method varied from 3.76 to 9.34 mm/day. They also found that crop coefficient of initial stage was 0.97, mid-season was 1.25 and the harvest period was 1.09.

Kar and Verma (2005) computed rice water requirement using CROPWAT 4.0 model and found: 450-550 mm for autumn rice, 600-720 mm for winter rice and 775-875 mm for summer rice in different AERs of AER 12.0 in normal year.

Kuo *et al.,* (2006) estimated irrigation water requirements with derived crop coefficients for upland and paddy crops during 1993 to 2001. They found that in the paddy fields, irrigation water requirement and deep percolation was 962 and 295 mm, respectively for the first rice crop and 1114 and 296 mm for the second rice crop.

Zhang *et al.,* (2009) examined the spatial and temporal variations from 1971 to 2004 on the Tibetan Plateau and concluded that the combined effect of the reduced wind speed and Shortened sunshine duration negated the effect of rising temperature and caused ET_{ref} to decrease in general.

Liu *et al.,* (2011) quantified the impacts of climate factor using a derivation-based approach through linear regression of ET_{ref} and E_{pan} on the observed changes in pan evaporation (E_{pan}) on the Tibetan Plateau.

Kader (2012) found that the actual crop evapotranspiration of BRRI dhan28 during the growing season varied from 357 to 430, 343 to 414, 327 to 410 and 314 to 493 mm in Rajshahi, Bogra, Rangpur and Dinajpur, respectively and for BRRI dhan29, the variations of ET_c in the corresponding districts were from 367 to 444 mm, 369 to 45 mm, 349 to 410 mm and 333 to 425 mm. He detected that there was a decreasing trend of ETc in Bogra, Rangpur and Dinajpur, but an increasing trend in Rajshahi due to change in climate over time.

Karim *et al.,* (2013) estimated Reference evapotranspiration (ET_0) both monthly and seasonal periods of 1971-2010. Study revealed that ET_0 decreased from January to April and increased from July to December. Decrease of evapotranspiration during November and December might hamper the crop production.

2.3 Supplemental Irrigation (SI)

Peterson *et al.,* (1995) analyzed rainfall and evapotranspiration data to determine the rainfall excess and deficit periods in order to aid crop planning and water management practices. They mentioned that rainfall at 70% probability and evaporation at 30% probability of occurrence could be used for the estimation of excess or deficit periods in the Bihar plateau, India.

Szilagyi *et al.,* (2001) examined that evapotranspiration to increase with increases in temperature, and increasing evapotranspiration is necessary for increases in precipitation and cloudiness.

Ohmura and Wild (2002) found on the grounds that the decreasing pan evaporation must be caused by decreasing solar irradiance, or global dimming, and thus evidence of decreasing landscape evaporation.

Rockstrom *et al.*, (2003) conducted an experiment on supplemental irrigation for dry-spell mitigation of rain-fed agriculture in the Sahel. The on-farm experiment involved five repetitions of two levels of nutrient application (non- fertilized and fertilized) and two levels of supplemental irrigation (non-irrigated and irrigated) including: farmers' traditional practices, supplemental irrigation, fertilizer application and supplemental irrigation combined with fertilization. This paper presented field results from three rainy seasons (1998-2000), receiving a cumulative seasonal rainfall ranging from 418-617 mm. Supplemental irrigation ranging from 60-90 mm per season was applied based on actual occurrence of dry-spell induced crop water stress.

Islam *et al.* (2004) conducted a study on supplemental irrigation as a safeguard technique for successful cultivation of monsoon rice (Transplanted aman) in Bangladesh. The study was conducted in Monsoon (Transplanted aman) at BRRI farm, Joydebpur, from 1978-1987, to determine the impact and viability of supplemental irrigation. The results of 8 years of experimentation indicate that the impact of supplemental irrigation mainly depends on rainfall distribution patterns and the last precipitation of the season. Generally, the late transplanted crops suffer from moisture stress when the last rainfall occurred in the first week of October. Under the situation, supplemental irrigation of 60 mm could produce about 58% more yield, and the consequent benefit cost ratio of supplemental irrigation was 5.3 to 14.5, which is highly profitable.

Sen (2016) analyzed supplemental irrigation needed for BRRI dhan33 in Rangpur were 17mm and 27 mm for mid and late stage and 22 mm and 12 mm in Rajshahi and Bogra districts respectively. Similarly for BRRI dhan34, supplemental irrigation needed 66 mm and 18 mm in Bogra and Rangpur district.

2.4 Impact of climate change on crop-water use

Marks *et al.*, (1993) found that the predicted future climatic conditions would significantly increase potential evapotranspiration, causing a 20% reduction in runoff relative to input precipitation and a 58% reduction in soil moisture storage in Columbia River Basin, USA. The distribution and composition of forests in the northwest would change markedly and water resources would become more limited.

Hatch *et al.,* (1999) assessed irrigation requirements in Georgia, USA, using a climate scenario derived from HadCM2 model. This scenario produced increased rainfall in most stations, which together with a shorter growing season and the assumed effect of CO2 enrichment resulted in a decrease in irrigation demand.

Nielsen *et al.,* (2001) studied the impact of climate change on crop-water demand and crop suitability in the Okanagan Valley, British Columbia, Canada. They estimated that crop-water demand would increase by 37% between the present day and the 2070–2099 scenarios. They indicated that drawing water from the main channel and lake system would likely have sufficient water to meet increased demand but some districts using tributary water may not meet the demand. They found that growing season would lengthen by 1.5–1.7 months by 2070–2099.

Cesar *et al.,* (2003) evaluated the potential consequences of climate change and variability on the agriculture, water resources as well as other economic and natural resource sectors in the United States. They evaluated climate change impacts on crop yields and ecosystem processes by scenarios of the HadCM2, GCM and EPIC agro system model.

Yao *et al.*, (2007) assessed the impact of climate change on irrigated rice yield using B2 climatic change scenario from the Regional Climate Model and CERES-rice model during 2071–2090 in the main rice ecological zones of China. They explored that B2 climate scenario would have a negative impact on rice yield at most rice stations and have negative impact at Fuzhou and *K*unming. They concluded that low yield and high variances of rice yield could pose a threat to rice yield at most selected stations in the main areas of China.

Iqual *et al.*, (2009) examined that long term changes in means and standard deviations of the climatic variables have differential impacts on the productivity of rice and thus the overall impact of climate change on agriculture is not unambiguous.

Ali, *et al.,* (2012) reported that the crop yield is negatively impacted by rise in temperature, erratic rainfall, flooding, salinity, etc. and among which water logging and drainage congestion are the major problems.

Most of the studies on climatic impacts on agriculture and its resource focused on developed nations under mid-latitudinal climatic conditions. So, studies dealing with analysis of rainfall and actual evapotranspiration of aman rice in Bangladesh are needed.

CHAPTER III

METHODOLOGY

Scientific methods and procedures, used for collection and analysis of data are very important in any scientific investigation and require a very careful consideration. In this study, a series of activities were done. The methods, procedures and essential information, followed in conducting this study are enumerated as under.

3.1 Site description

3.1.1 Location of the study

There are eight Hydrological Regions in Bangladesh. These are North West (NW), North Central (NC), North East (NE), South East (SE), South Central (SC), South West (SW), Eastern Hills (EH), and the active floodplains and char lands of the main rivers and estuaries. There are sixteen districts in North West hydrological region, but only Dinajpur was selected for this study because it has weather station and large area under rice cultivation. Dinajpur is high land and main source of irrigation is ground water. Dinajpur is the north western district of Rangpur division. Total area of Dinajpur is 3439.98 sq. km, located between $25^{0}10'$ and $26^{0}04'$ north latitudes and in between $88^{0}23'$ and $89^{0}18'$ east longitudes. Total population of Dinajpur is 26,42,850. For optimum use of valuable and limited water resources, this study is done.

3.1.2 North-West Hydrological Region (Dinajpur)

3.1.2.1 Administrative Unit

The North-West Hydrological Region consists of two divisions: Rajshahi and Rangpur. Rangpur division has an area of 16,185.01 sq km. It consists of Rangpur, Dinajpur, Kurigram, Gaibandha, Nilphamari, Panchagarh, Thakurgaon and Lalmonirhat. There are 58 upazilla under these eight districts. Rangpur is the northern most division of Bangladesh and has a population of 1,57,87,758 which is about 9.87% of the total population of Bangladesh (BBS, 2015). Dinajpur is situated in the western part of Rangpur division. Dinajpur is located in tropical monsoon climate. A dry winter starts from November and continues up to February. Summer comes from middle of March and continues up to mid of June. Weather is very hot in this region. Rainfall is generally heavy during July and August (BBS, 2009).

3.1.2.2 Agronomical condition

The soil in this region is clay, silty clay loam, loam, sandy loam and sand. Most of the soil is loamy in texture. Main crops in Dinajpur are: paddy, wheat, jute, sugarcane, oil seed and onion. Main fruits are mango, jackfruit, litchi, black berry, coconut and papaya. Irrigation is not always essential for aman rice cultivation because of availability of rainfall in that season (BBS, 2015).

Figure 3.1: Study area showing in the map of Bangladesh

3.2 Data collection

3.2.1 Agro-climatic data

Daily agro-climatic data like rainfall, maximum and minimum temperatures, maximum and minimum relative humidity, wind speed and sunshine duration of Dinajpur district for a period of 20 years (1991-2010) were collected from the Bangladesh Meteorological Department (BMD) situated at Agargaon, Dhaka.

3.2.2 Crop data

Several varieties of rice are cultivated in three seasons in the North-West Hydrological Region, especially in Dinajpur district. Three popular Aman rice varieties; BR11, BR22 and BRRI dhan49 which covered 29%, 4.9% and 33% of the total rice production area of Dinajpur were selected for this study. Crop coefficients of these rice varieties in different seasons were selected and adjusted from 1991 to 2010 in Dinajpur district. The name of the variety, year of their release, growing period, time of seed sowing, seedling age and growing period of each variety (Table 3.1) were collected from Bangladesh Rice Research Institute (2006). A staggered seed sowing (50% area for first seed sowing and 50% area for second seed sowing) was considered. Lengths of growth stages of the rice varieties in aman season are given in Table 3.2.

Table 3.1 Different rice varieties, year of release, time of transplanting and growing period

Season	Variety	Release year	Transplantation time	Height (cm)	Harvest time	Growing period, day
Aman	**BR11**	1980	15th June-14th July	115	25th October-29th November	145
	BR22	1988	30th June- 8th August	105	30th November-15th December	150
	BRRI dhan 49	2008	21th June – 10th July	100	15th November-30th November	135

Table 3.2: Different growth stages of BR11, BR 22 and BRRI dhan 49.

Season	Variety	Transplant Time	Duration of rice growth stages			
			Initial stage	Development stage	Mid-season stage	Late stage season
Aman	**BR11**	1st transplant	15th June-24th July	25th July-2nd September	3rd September-7th October	8th October-6th November
		2nd transplant	25th June-3rd August	4th August-12th September	13th September-17th October	18th October-16th November
	BR22	1st transplant	30th June-8th August	9th August-17th September	18th September-22th October	23th October-26th November
		2nd transplant	16th July- 24th August	25th August-3rd October	4th October-7th November	8th November- 12th December
	BRRI dhan 49	1st transplant	21th June-10th July	11th July-24th August	25th August-28th September	29th September- 2nd November
		2nd transplant	4th July- 23th July	24th July-6th September	7th September-11th October	12th October-15th November

3.2.3 Estimation of missing data

Some of the climatic data were found partially missing for the selected study area. These missing data were considered to be identical with neighboring locations and calculated on the basis of Arithmetic Mean method. The missing data were computed by simple arithmetic average of the index stations by

$$P_x = \frac{\mathrm{P1} + \mathrm{P2} + \dots\dots\dots + P_n}{\mathrm{n}} \qquad (3.1)$$

Where,

P_X = data of missing station;

P1, P2….. P_n = data of index stations and

n= number of index stations.

3.3 Determination of reference crop evapotranspiration (ET_o)

There are various types of methods used for calculation of reference crop evapotranspiration (ET_o). The Penman-Monteith method is recommended as the sole standard method of determination of ET_o by FAO (Allen *et al.,* 1998). The classic Penman-Monteith method combines both energy and mass balances to model reference evapotranspiration. It is based on fundamental physical principles, which guarantee the universal validity of the method. The reference surface is assumed to be a flat surface that is completely covered by a grass with an assumed uniform height of 0.12 m and an albedo of 0.23 under enough soil water supplies (Allen *et al.,* 1998). The formula for reference evapotranspiration is given by,

$$ET_o = \frac{0.408\ (R_n - G) + \gamma \frac{900}{T+273} u_2\ (e_s - e_a)}{\Delta + \gamma\ (1 + 0.34 u_2)} \qquad (3.2)$$

Where,

ET_o= reference crop evapotranspiration, mm/day;
R_n =net radiation at the crop surface, MJ/m^2/day;
G= soil heat flux density, MJ/m^2/day;
T= air temperature at 2 m height, ^oC;
u_2= wind speed at 2 m height, m/sec;
e_s= saturation vapor pressure, kPa;
e_a= actual vapor pressure; kPa;
Δ = slope of vapor pressure curve, kPa$^{/o}$C and
γ = psychometric constant, kPa$^{/o}$C.
(e_s - e_a)= saturation vapor pressure deficit, kPa;

It is noted that the reference crop evapotranspiration (ET_o), which is controlled by climatic parameters but independent of crop type, was determined for different periods of time matching with the growth stages of BR11, BR 22 and BRRI dhan49.

3.4 Adjustment of crop coefficients

Crop coefficient (K_c) is a ratio of actual crop evapotranspiration to the reference crop evapotranspiration. The growing period of rice has four distinct growth stages: initial, crop development, mid-season and late season. The length of the initial period is highly dependent on the crop, the crop variety, the planting date and the climate. The initial stage runs from planting to the period when approximately 10% ground cover is developed. The crop development stage runs from 10% ground cover to effective full cover. The mid-season stage runs from effective full cover to the start of maturity and the late season stage runs from the start of maturity to harvest or full senescence. There are two approaches for calculating crop coefficient under optimum soil moisture conditions (Allen *et al.,* 1998). These are: single crop coefficient approach and dual crop coefficient approach. The single crop coefficient approach is used for most applications related to irrigation planning, design and management. The dual crop coefficient approach is relevant in real time irrigation scheduling, water applications, water quality modeling and research. In this study, crop coefficient of rice was adjusted by the single crop coefficient approach. The crop coefficient, K_c, of rice was taken as 1.05 for initial stage, 1.20 for mid-season stage and 0.90-060 for late season stage ((FAO, 2006). Following Allen *et al.,* (1998), K_c for initial stage was considered as 1.05 for both rice varieties. K_c of the mid-season stage (1.20) was adjusted by considering minimum relative humidity, wind speed and crop height. The equation for adjustment is:

$$K_{cmid} = 1.20 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)](\frac{h}{3})^{0.3} \qquad (3.3)$$

Where,

K_{cmid} = crop coefficient of mid-season stage;

RH_{min} = mean daily minimum relative humidity during the mid-season growth stage (%);

u_2 = mean daily wind speed at 2 m height over grass during the late-season growth stage (m/s) and

h = the mean plant height during the mid-season stage (m);

The effect of the difference in aerodynamic properties between the grass reference surface and agricultural crops is not only crop specific but also varies with the climatic conditions and crop height. More arid climates and conditions of greater wind speed will have higher values for K_{cmid}.

The crop coefficient at the end of the late season growth stage reflects crop and water management practices particular to those crops. Rice crops are allowed to senescence and dry out in the field before harvest. So, irrigation was ceased fifteen days before harvest and during the late season stage. The equation for adjustment is:

$$K_{cend} = 0.90 + [0.04(u_2 - 2) - 0.004(RH_{min} - 45)]\,(h/3)^{0.3} \quad (3.4)$$

Where,

K_{cend} = crop coefficient of late-season stage,
RH_{min}= mean daily minimum relative humidity during the late-season growth stage (%),
u_2= mean daily wind speed at 2 m height over grass during the late-season growth stage (m/s) and
h= the mean plant height during the late-season stage (m).

The crop coefficient of the development stage of rice was derived by empirical equation considering constant crop coefficient values during the initial and mid-season stages. This empirical equation is:

$$K_{cdev} = K_{cprev} + \left[\frac{\{i - \sum L_{prev}\}}{L_{stage}}\right] \times (K_{cnext} - K_{cprev}) \quad (3.5)$$

Where,

K_{cdev} = crop coefficient of rice at cr8op development stage, i is the day number Within the growing season (1....... length of the growing season),
L_{stage} = length of the stage under consideration (day),
$\sum L_{prev}$ =sum of lengths of all previous stages (day),
K_{cnext} =crop coefficient at the beginning of next stage and

K_{cprev} =crop coefficient at the end of previous stage.

3.5 Actual evapotranspiration of rice

In the crop coefficient approach, crop evapotranspiration is calculated by multiplying ET_o by K_c that is actual crop evapotranspiration (FAO Irrigation and Drainage Paper No. 56, 2006).

$$ET_{crop} = K_c \times ET_o \quad (3.6)$$

Where,

ET_{crop} = water demand/ actual evapotranspiration (mm/day);
ET_o = reference crop evapotranspiration at different growing stages of rice (mm/day);
K_c = crop coefficient at different growing stages.

3.6 Probability analysis of rainfall and actual evapotranspiration data

‘Weibull's ranking method’ was used for probability analysis of Dinajpur for 20 years data (1991-2010). According to this method, yearly rainfall and actual evapotranspiration data were arranged in descending order. Probability was calculated as follows:

$$P=\frac{m}{N+1}\times 100 \tag{3.7}$$

Where,
N = total number of data and
m =order or rank of the observation from the highest value.

The probabilities thus found were plotted on log-normal probability paper. Rainfall and actual evapotranspiration were plotted against the corresponding probability on the log normal probability paper and the probability curves were drawn. These plotted values on the probability paper were found approximately normal. The expected rainfall and actual evapotranspiration at probability level of 75% was estimated for different growth stages of BR11, BR22 and BRRI dhan49 from 1991 to 2010 for Dinajpur district.

3.7 Supplemental irrigation

Supplemental irrigation (SI) at different growth stages of rice in aman season under Dinajpur districts was calculated by:

SI = Actual evapotranspiration- Rainfall

When rainfall was not sufficient and actual evapotranspiration was high then supplemental irrigation was essential for successful aman rice production.

3.8 Trend analysis

3.8.1 MAKESENS trend model

The MA*K*ESENS is a software computer model, which was developed using Microsoft Excel 97, and macros were coded with Microsoft Visual Basic (Salmi *et al.,* 2002). It performs two types of statistical analysis. It first tests any presence of monotonic increasing or decreasing trend with nonparametric Mann-*K*endall test and then estimates slope of a linear trend with the nonparametric sen's method.

3.8.2 Trend of rainfall

The trends of rainfall during different stages of three rice varieties-BR11, BR22 and BRRI dhan49 in Dinajpur district was calculated and estimated by MAKESENS trend model.

3.8.3 Trend of actual crop evapotranspiration

The trends of rainfall during different stages of three rice varieties-BR11, BR22 and BRRI dhan49 in Dinajpur district were estimated by MAKESENS trend model.

CHAPTER IV

RESULTS AND DISCUSSION

The results obtained in this study have been presented and interpreted in this chapter under relevant headings and sub-headings.

4.1 Variation of crop coefficient, K_c

4.1.1 BR11

The crop coefficients K_c of BR11 for Dinajpur district are presented in Table 4.1. K_c values for different growth stage varied in different years and with the time of seed sowing. It was observed that the adjusted crop coefficients at mid-season stage and late season stage of these rice varieties were higher in some years and lower in other years than considered values. The higher values of crop coefficient were due to lower values of minimum relative humidity and higher wind speed. The lower values of K_c were due to higher values of minimum relative humidity and lower values of wind speed. From Table 4.1 it was revealed that crop coefficients of BR11 varied from 1.00 to 1.03 in the crop development stage, 1.11 to 1.13 in the mid-season stage and 0.82 to 0.86 in the late season stage in the first seed sowing.

In the second seed sowing, K_c varied from 1.00 to 1.02 in the crop development stage, 1.11 to 1.15 in the mid-season stage and 0.83 to 0.88 in the late season stage. The results also revealed that the adjusted crop coefficients of mid-season stage and late season stage of the three rice varieties were lower than the assumed values due to lower wind speed and higher minimum relative humidity (Allen *et al.*, 1998).

Table 4.1: Crop coefficient (K_c) of BR11

Year	K_c at different growth stages of BR11							
	1st transplant				2nd transplant			
	Initial	**Crop Development**	**Mid-Season**	**Late Season**	**Initial**	**Crop Development**	**Mid-Season**	**Late Season**
1991	1.05	1.03	1.11	0.86	1.05	1.02	1.12	0.88
1992	1.05	1.00	1.14	0.85	1.05	1.01	1.13	0.87
1993	1.05	1.02	1.12	0.84	1.05	1.02	1.12	0.84
1994	1.05	1.01	1.13	0.85	1.05	1.00	1.14	0.86
1995	1.05	1.02	1.11	0.83	1.05	1.02	1.11	0.84
1996	1.05	1.02	1.11	0.84	1.05	1.02	1.11	0.85
1997	1.05	1.02	1.11	0.85	1.05	1.02	1.11	0.86
1998	1.05	1.02	1.11	0.82	1.05	1.02	1.12	0.84
1999	1.05	1.02	1.11	0.83	1.05	1.02	1.11	0.84
2000	1.05	1.02	1.12	0.86	1.05	1.01	1.13	0.85
2001	1.05	1.02	1.11	0.84	1.05	1.02	1.12	0.86
2002	1.05	1.00	1.14	0.86	1.05	1.00	1.14	0.87
2003	1.05	1.02	1.12	0.83	1.05	1.01	1.12	0.84
2004	1.05	1.02	1.11	0.86	1.05	1.02	1.11	0.88
2005	1.05	1.02	1.12	0.83	1.05	1.01	1.13	0.84
2006	1.05	1.01	1.13	0.86	1.05	1.00	1.14	0.86
2007	1.05	1.02	1.12	0.84	1.05	1.01	1.13	0.86
2008	1.05	1.02	1.12	0.83	1.05	1.02	1.12	0.85
2009	1.05	1.02	1.12	0.86	1.05	1.02	1.12	0.87
2010	1.05	1.02	1.12	0.85	1.05	1.02	1.12	0.87

4.1.2 BR22

The crop coefficients K_c, of BR22 for Dinajpur district are presented in Table 4.2. K_c values for different growth stage varied in different years and with the time of seed sowing. Crop coefficients, K_c of BR22 varied from 1.01 to 1.02 in the crop development stage, 1.11 to 1.14 in mid stage and 0.84 to 0.89 in late stage. In the second seed sowing, K_c varied from 1.00 to 1.03 in the crop development stage, 1.12 to 1.16 in the mid-season stage and 0.84 to 0.89 in the late season stage.

Table 4.2: Crop coefficient (K_c) of BR22

Year	K_c at different growth stages of BR22							
	1st transplant				2nd transplant			
	Initial	Crop Development	Mid-Season	Late Season	Initial	Crop Development	Mid-Season	Late Season
1991	1.05	1.01	1.13	0.88	1.05	1.00	1.16	0.89
1992	1.05	1.01	1.13	0.88	1.05	1.00	1.15	0.88
1993	1.05	1.02	1.12	0.85	1.05	1.01	1.14	0.87
1994	1.05	1.01	1.14	0.88	1.05	1.01	1.15	0.88
1995	1.05	1.02	1.11	0.85	1.05	1.01	1.13	0.84
1996	1.05	1.02	1.11	0.85	1.05	1.01	1.13	0.87
1997	1.05	1.02	1.12	0.86	1.05	1.02	1.15	0.85
1998	1.05	1.02	1.11	0.85	1.05	1.01	1.12	0.85
1999	1.05	1.02	1.11	0.86	1.05	1.02	1.12	0.88
2000	1.05	1.01	1.14	0.85	1.05	1.00	1.16	0.86
2001	1.05	1.02	1.12	0.86	1.05	1.01	1.13	0.86
2002	1.05	1.01	1.14	0.88	1.05	1.00	1.16	0.89
2003	1.05	1.02	1.12	0.85	1.05	1.01	1.13	0.87
2004	1.05	1.02	1.12	0.88	1.05	1.00	1.15	0.89
2005	1.05	1.02	1.11	0.86	1.05	1.01	1.12	0.86
2006	1.05	1.01	1.14	0.87	1.05	1.00	1.15	0.87
2007	1.05	1.01	1.13	0.88	1.05	1.00	1.14	0.89
2008	1.05	1.02	1.12	0.86	1.05	1.01	1.13	0.86
2009	1.05	1.01	1.13	0.87	1.05	1.00	1.15	0.86
2010	1.05	1.02	1.12	0.87	1.05	1.00	1.15	0.87

4.1.3 BRRI dhan49

The highest K_c of BRRI dhan49 were obtained due to lower values of minimum relative humidity and higher values of wind speed. The lowest crop coefficients of both rice varieties were obtained due to higher values of minimum relative humidity and lower values of wind speed in the development, mid-season and late season stages in the first and second seed sowings. The crop coefficient for BRRI dhan49 varied from 1.05 to 1.06 in the crop development stage, 1.12 to 1.13 in the mid-season stage and 0.83 to 0.85 in the late season stage in the first seed sowing. In the second seed sowing, K_c of BRRI dhan49 varied from 1.04 to 1.06 in the crop development stage, 1.12 to 1.13 in the mid-season stage and 0.85 to 0.86 in the late season stage**.** Allen *et al.,* (1998), reported that wind variation alter aerodynamic resistance of a crop. Aerodynamic properties are greater for many agricultural crops as compared to grass reference. Crop coefficients for many crops increase as wind speed increases and as relative humidity decreases.

Table 4.3: **Crop coefficient (K_c) of BRRI dhan49**

Year	K_c at different growth stages of BRRI dhan49							
	1st transplant				2nd transplant			
	Initial	Crop Development	Mid-Season	Late Season	Initial	Crop Development	Mid-Season	Late Season
2008	1.05	1.05	1.12	0.83	1.05	1.06	1.13	0.85
2009	1.05	1.05	1.13	0.85	1.05	1.04	1.12	0.86
2010	1.05	1.06	1.12	0.84	1.05	1.06	1.12	0.86

4.2 Actual evapotranspiration of rice

4.2.1 BR11

Actual evapotranspiration of BR11 of different growth stages for two transplanting times in Dinajpur district are given in Table 4.4. Actual evapotranspiration this rice variety varied due to crop coefficient, reference crop evapotranspiration, length of growing stages and total growing season. From Table 4.4, actual evapotranspiration of BR11 at the 1st transplant time varied from 45 to 83 mm in initial stage, 134 to 180 mm in crop development stage, 120 to 154 mm in mid stage and 36 to 58 mm in late stage. In case of 2nd transplant time it varied from 43 to 73 mm in initial stage, 133 to 178 mm in crop development stage, 116 to 145 mm in mid stage and 33 to 72 mm in late stage.

Table 4.4: Actual Evapotranspiration (ET_c) of BR11

Year	ET_c (mm) at different growth stages of BR11							
	1st transplant				2nd transplant			
	Initial	Crop Development	Mid-Season	Late Season	Initial	Crop Development	Mid-Season	Late Season
1991	66	166	122	58	66	148	133	58
1992	54	165	150	39	64	168	135	44
1993	61	152	136	45	66	146	132	41
1994	45	172	147	45	64	165	145	42
1995	65	161	124	40	66	158	123	38
1996	51	151	144	36	53	164	128	39
1997	60	159	128	45	70	147	132	41
1998	46	134	142	37	53	133	144	33
1999	58	144	128	37	66	137	125	36
2000	70	157	134	45	66	150	139	40
2001	66	170	124	42	62	159	132	44
2002	53	157	154	44	45	173	141	44
2003	72	173	140	38	69	174	123	36
2004	50	175	120	38	72	178	116	43
2005	57	147	141	36	68	136	136	34
2006	68	180	138	45	69	174	138	42
2007	46	144	132	37	43	142	145	40
2008	48	155	142	44	62	150	131	38
2009	83	173	142	43	62	143	138	42
2010	53	163	132	38	65	151	126	72

4.2.2 BR22

The higher actual crop evapotranspiration was obtained due to the higher values of reference crop evapotranspiration and crop coefficient and the lower actual crop evapotranspiration was obtained due to the lower values of reference crop evapotranspiration and crop coefficient in the growth stages except initial stage. From Table 4.5, actual crop evapotranspiration of BR22 at the 1st transplant time varied from 40 to 77 mm in initial stage, 127 to 179 mm in crop development stage, 116 to 140 mm in mid stage and 33 to 47 mm in late stage. In case of 2nd transplant time it varied from 41 to 77 mm in initial stage, 126 to 179 mm in crop development stage, 112 to 146 mm in mid stage and 28 to 38 mm in late stage.

Table 4.5: Actual Evapotranspiration (ET_c) of BR22

Year	ET_c (mm) at different growth stages of BR22							
	1st transplant				2nd transplant			
	Initial	Crop Development	Mid Season	Late Season	Initial	Crop Development	Mid Season	Late Season
1991	61	144	140	42	70	132	133	37
1992	60	169	134	43	69	152	134	37
1993	40	152	129	40	65	134	130	30
1994	67	166	140	34	61	162	122	37
1995	61	159	118	42	56	139	136	33
1996	56	154	130	47	62	151	128	34
1997	67	139	139	41	57	136	139	32
1998	58	133	132	44	47	142	132	32
1999	75	127	131	39	41	132	122	38
2000	64	147	138	39	58	142	135	30
2001	65	150	134	40	75	136	123	37
2002	61	168	135	46	52	163	146	36
2003	71	168	123	33	65	154	112	32
2004	75	149	116	42	74	126	121	35
2005	69	142	119	41	46	151	118	34
2006	66	179	137	37	77	144	132	28
2007	57	131	134	41	56	130	126	37
2008	70	149	134	37	56	145	125	36
2009	50	147	137	39	50	153	128	29
2010	77	141	126	41	51	41	123	34

4.2.3 BRRI dhan49

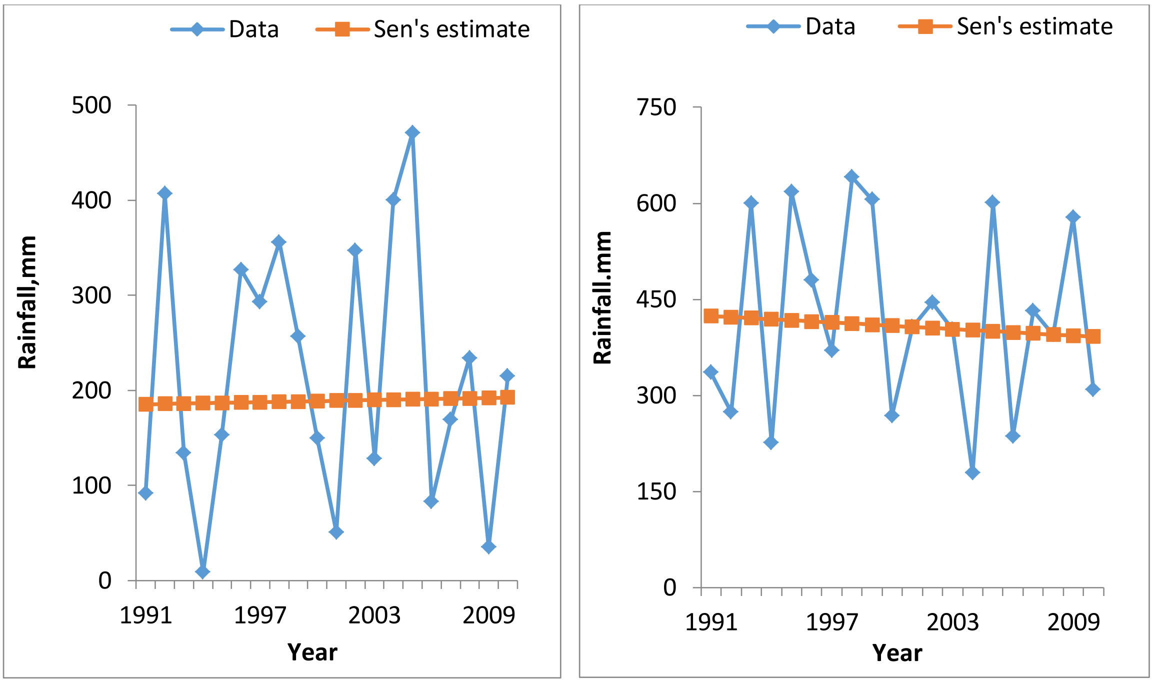
From 4.6, actual crop evapotranspiration of BRRI dhan49 at the 1st transplant time varied from 55 to 66 mm in initial stage, 172 to 185 mm in crop development stage, 131 to 148 mm in mid stage and 37 to 42 mm in late stage. In the 2nd transplant time, it varied from 50 to 82 mm in initial stage, 163 to 189 mm in crop development stage, 128 to 142 mm in mid stage and 38 to 46 mm in late stage.

Table 4.6: Actual Evapotranspiration (ET_c) of BRRI dhan49

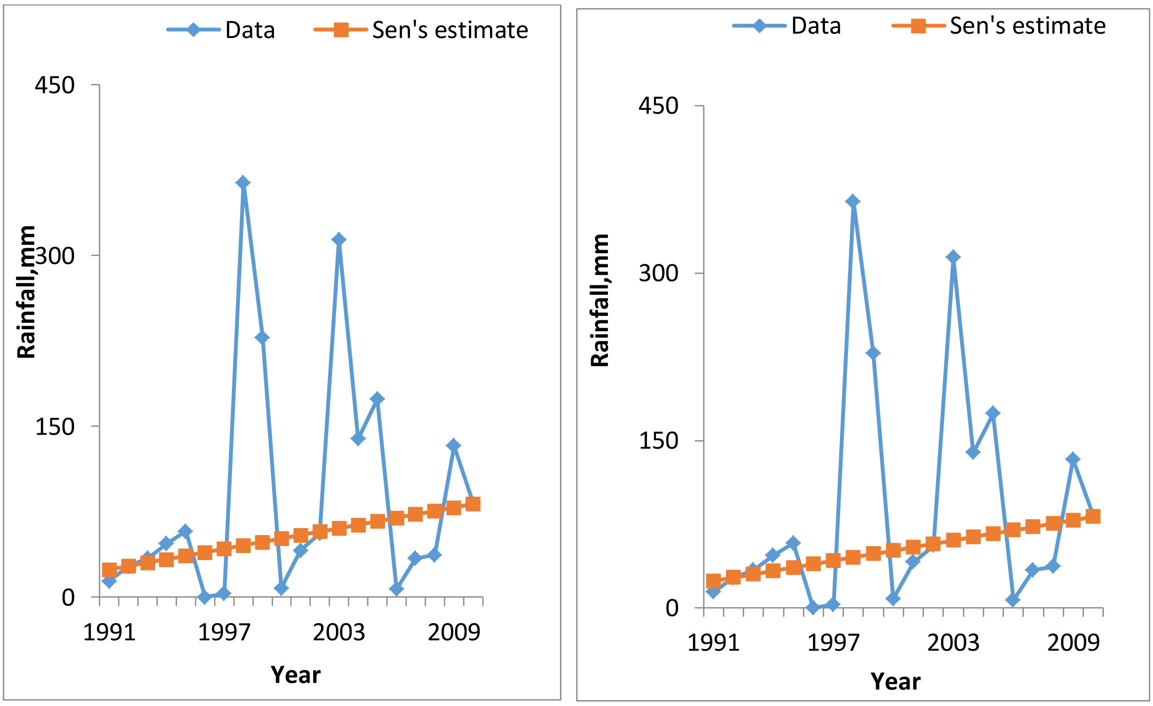
Year	ET_c (mm) at different growth stages of BRRI dhan49							
	1st transplant				2nd transplant			
	Initial	Crop Development	Mid Season	Late Season	Initial	Crop Development	Mid Season	Late Season
2008	66	172	131	40	50	175	142	45
2009	55	182	148	42	82	163	138	46
2010	57	185	138	37	51	189	128	38

4.3 Trend of rainfall and its variability

From Figure 4.1, In Dinajpur for BR11, there was an increasing trend of rainfall except in development stage for 1st transplanting time, but for 2nd transplanting time from figure 4.2 there was a decreasing trend of rainfall in different stages except initial stage. From Figure 4.3, there was a decreasing trend in development and mid stage for BR22 1st transplanting time. In case of 2nd transplanting time, there was an increasing trend except development stage in figure 4.4. In figure 4.5, for 1st transplanting time for BRRI dhan49, there was decreasing trend of rainfall except initial stage for 1st transplanting time and from figure 4.6, a decreasing trend except late stage for 2nd transplanting time.

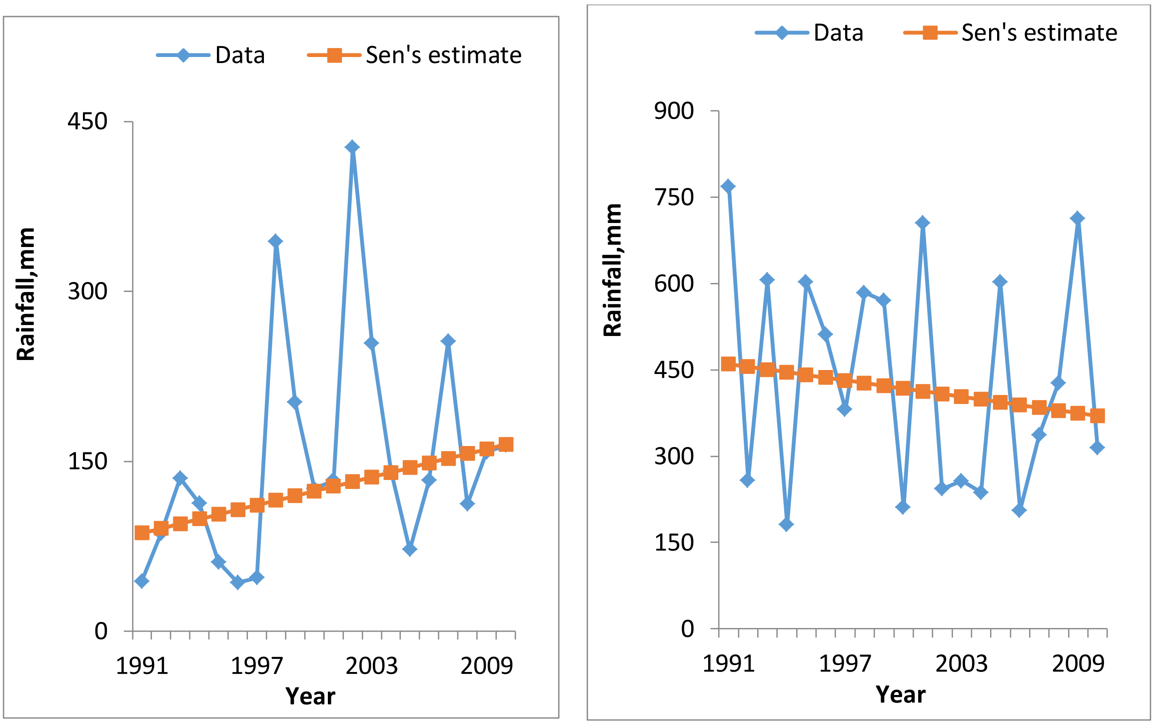


a. **Initial stage** **b. Development stage**

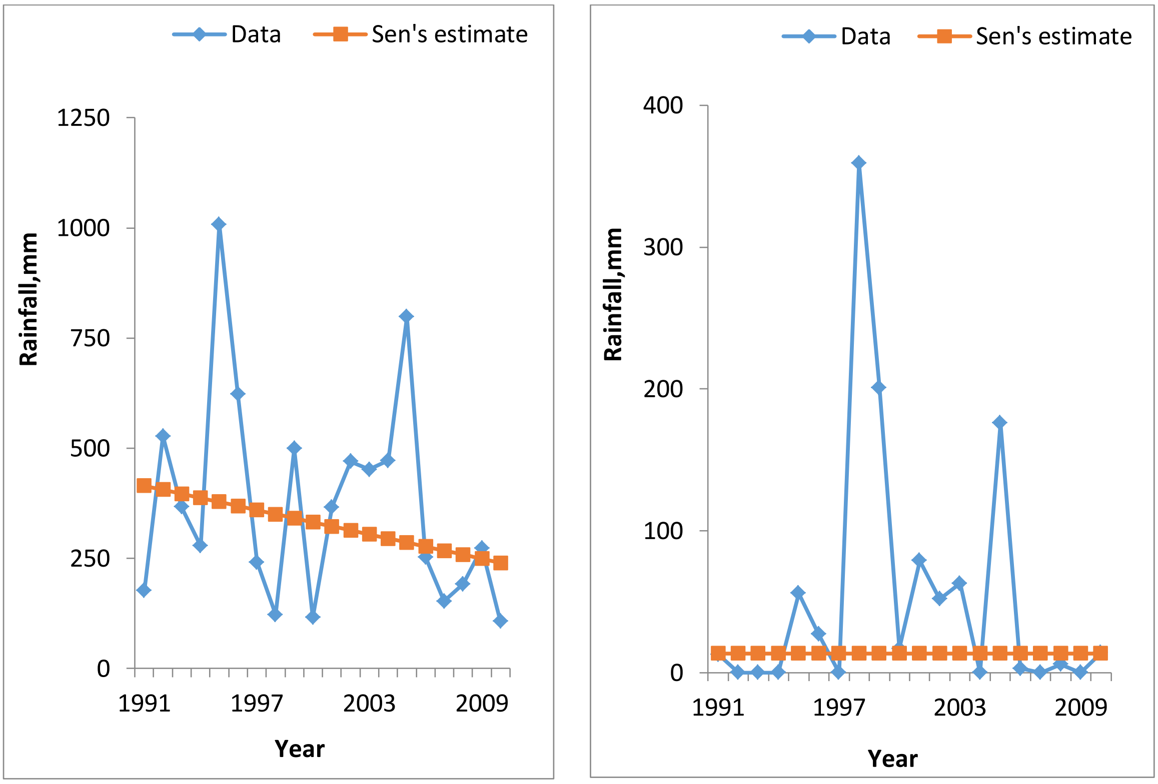


c. **Mid stage** **d. Late stage**

Figure 4.1: Trend of rainfall during the initial (a), development (b), mid (c) and late stages (d) of BR11 for 1st transplanting time

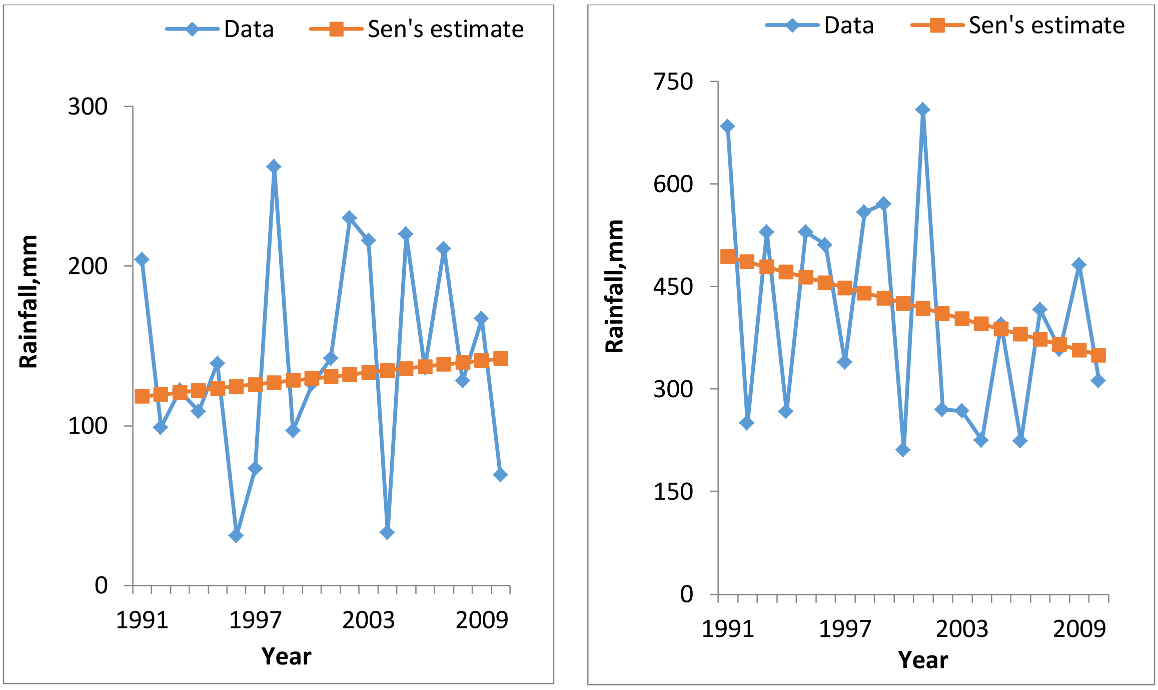


a. Initial stage **b. Development stage**



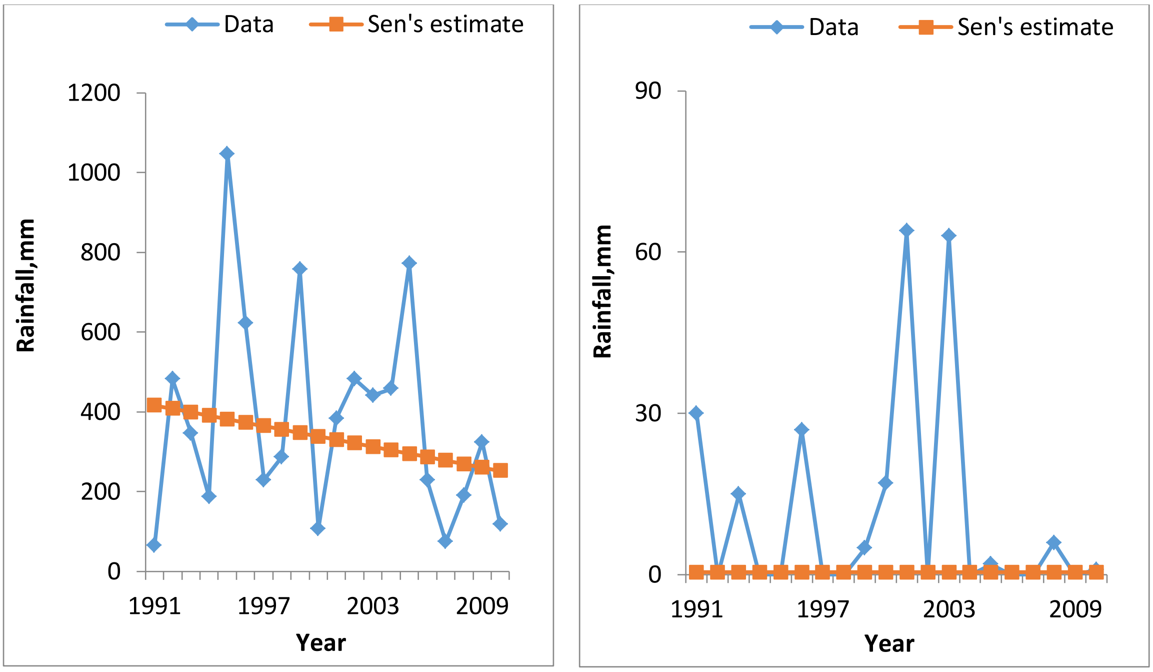
c. Mid stage **d. Late stage**

Figure 4.2: Trend of rainfall during the initial (a), development (b), mid (c) and late stages (d) of BR11 for 2nd transplanting time



a. **Initial stage**

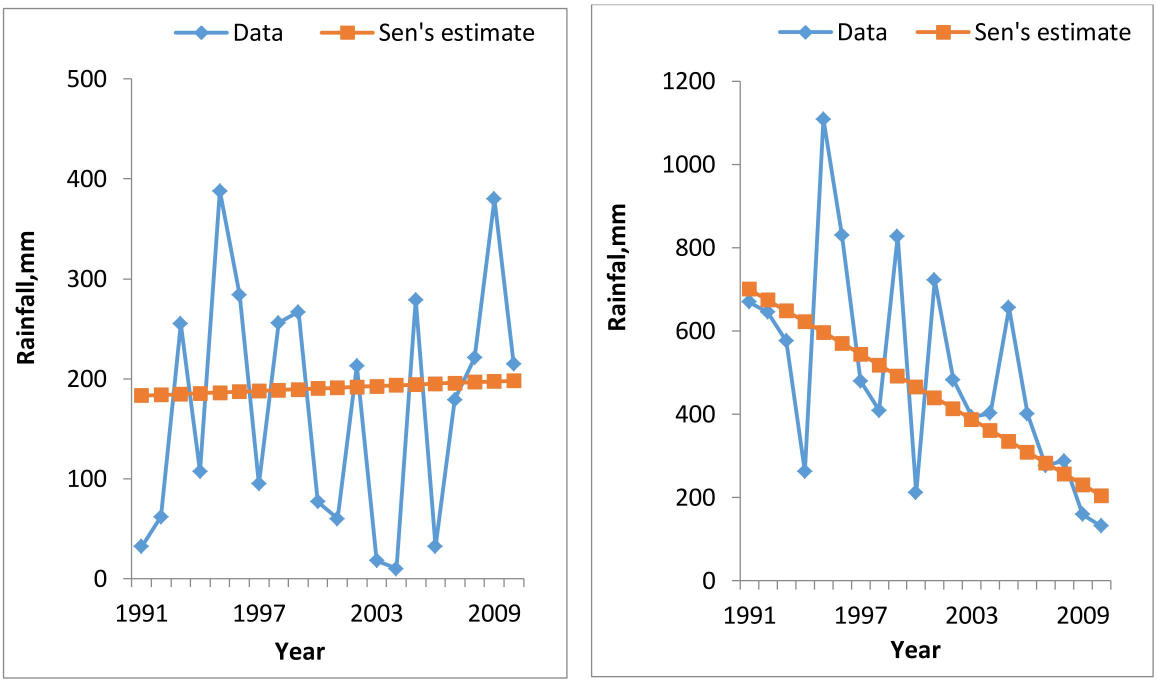
b. Development stage



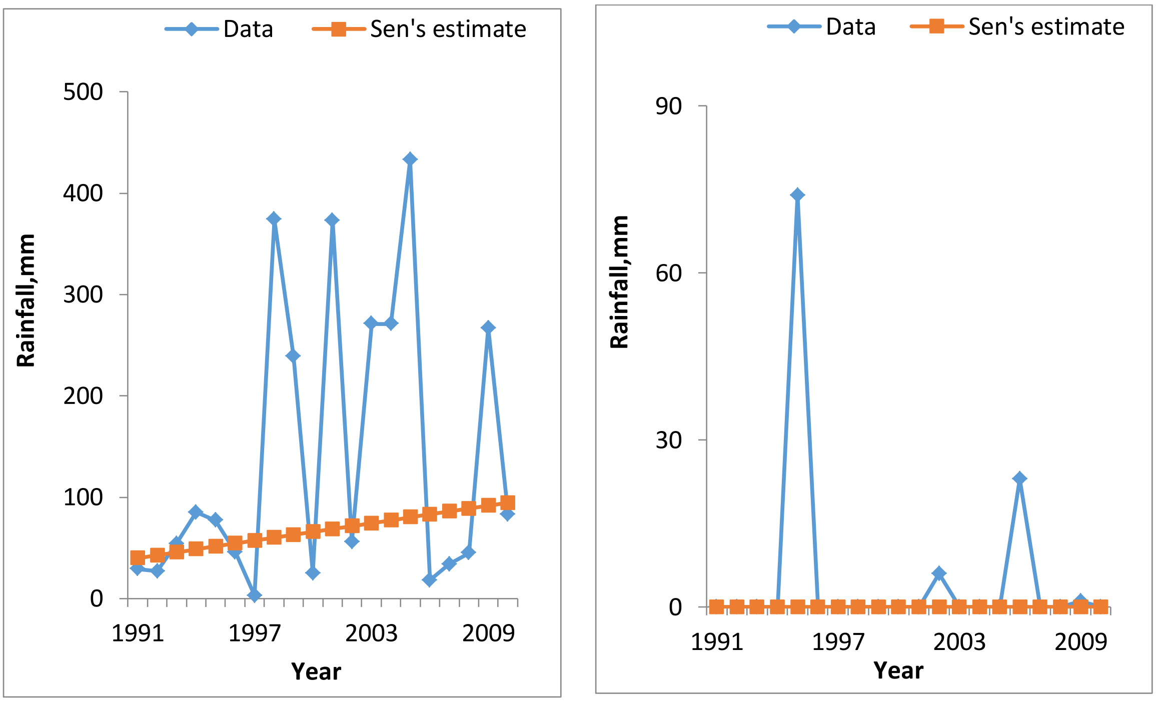
c. **Mid stage**

d. Late stage

Figure 4.3: Trend of rainfall during the initial (a), development (b), mid (c) and late stages (d) of BR22 for 1st transplanting time

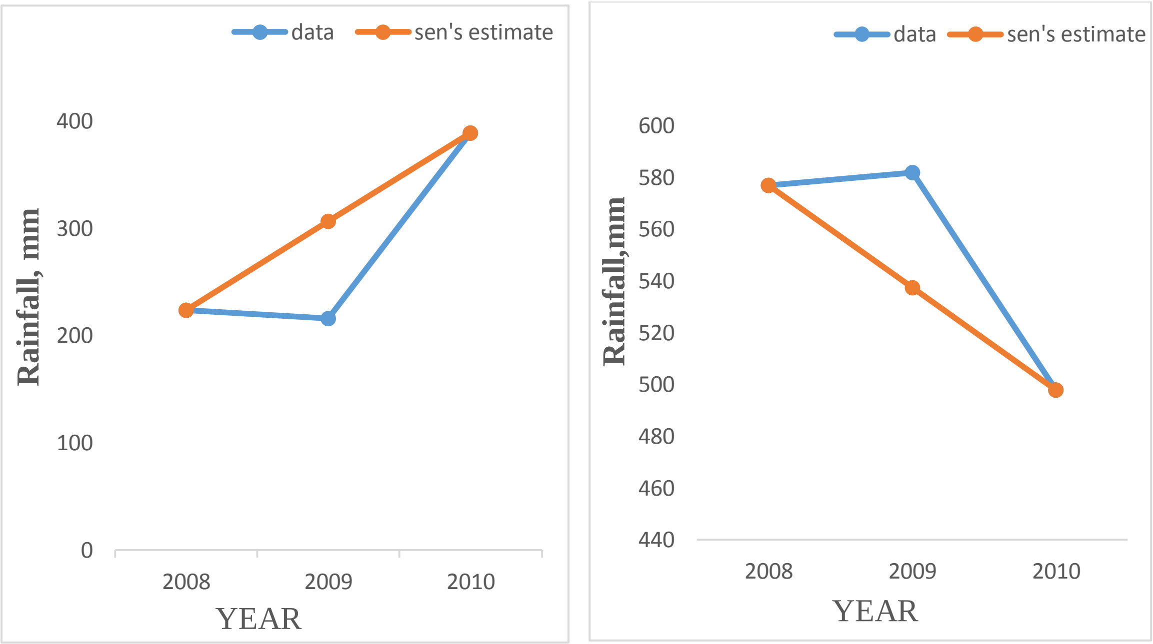


a. Initial stage **b. Development stage**

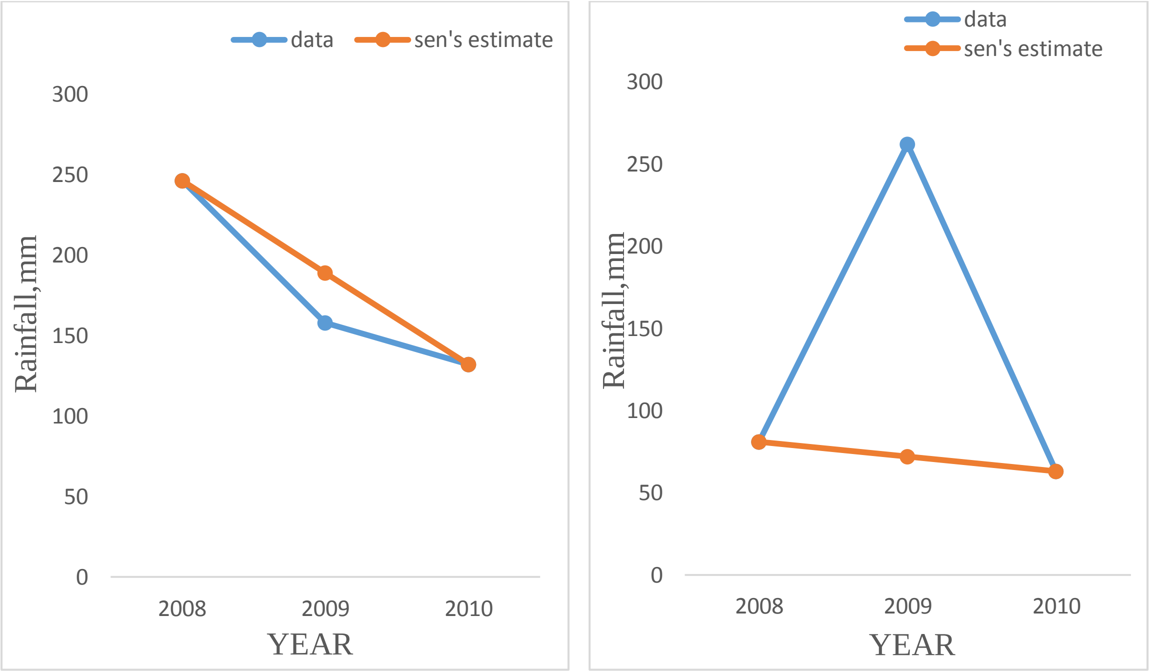


c. Mid stage **d. Late stage**

Figure 4.4: Trend of rainfall during the initial (a), development (b), mid (c) and late stages (d) of BR22 for 2nd transplanting time

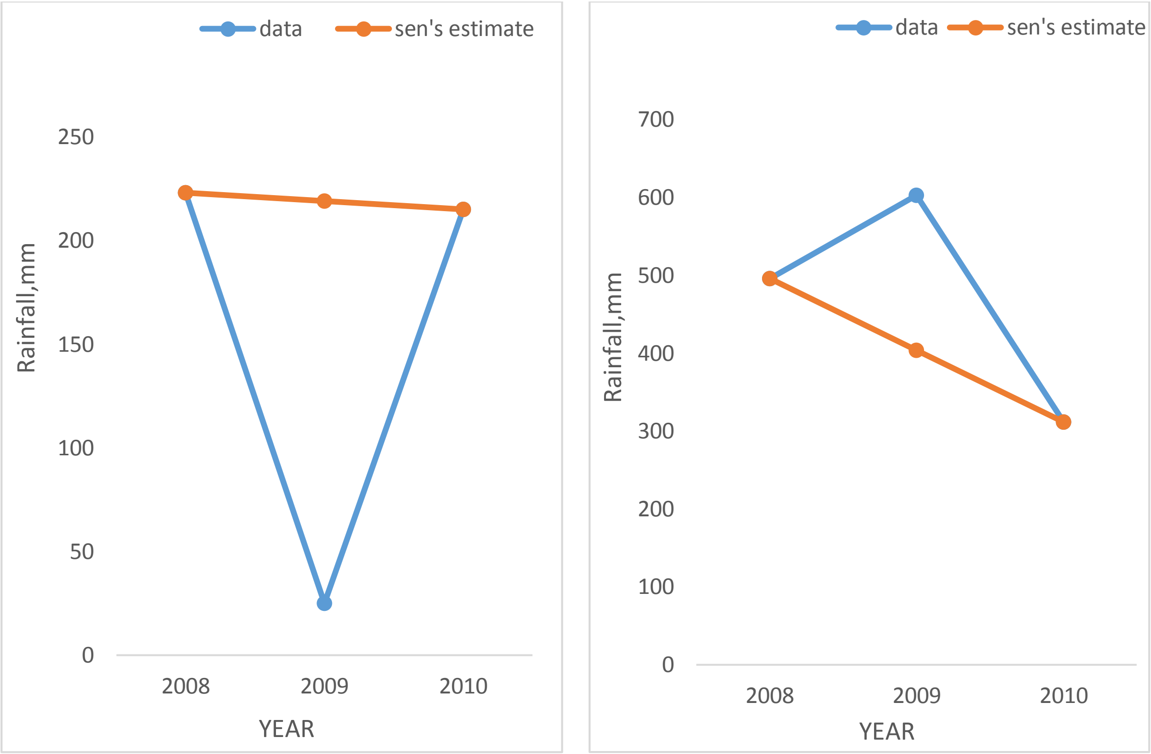


a. Initial stage **b. Development stage**



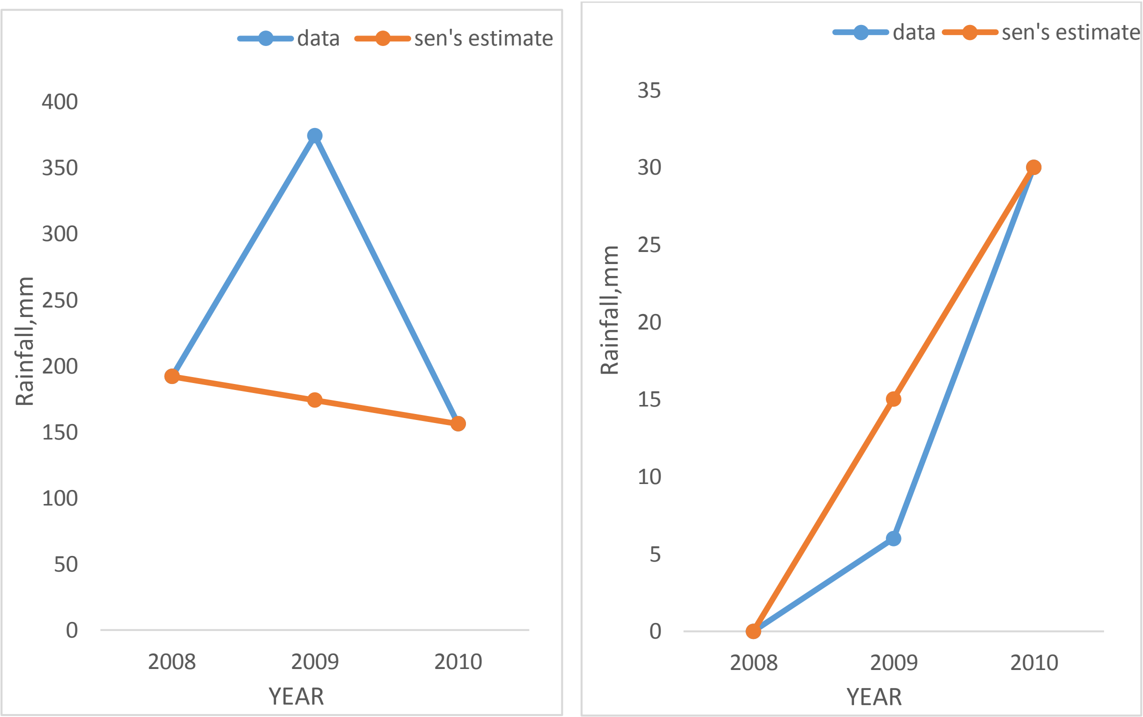
c. Mid stage **d. Late stage**

Figure 4.5: Trend of rainfall during the initial (a), development (b), mid (c) and late stages (d) of BR22 for 2nd transplanting time



a. **Initial stage**

b. Development stage



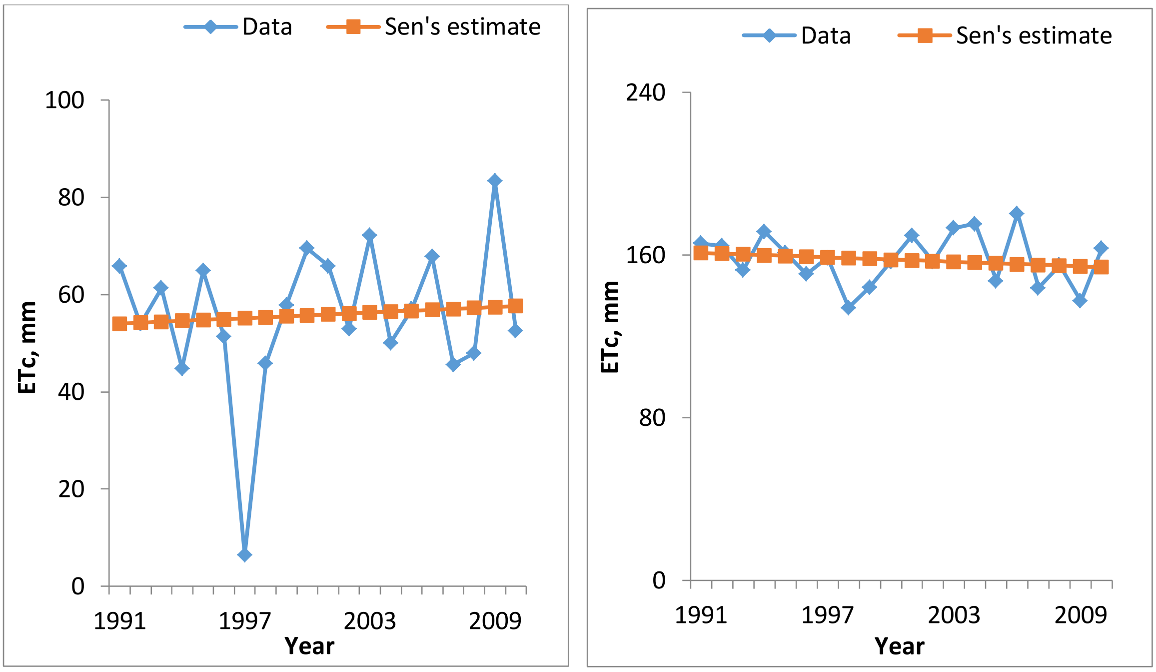
c. **Mid stage**

d. Late stage

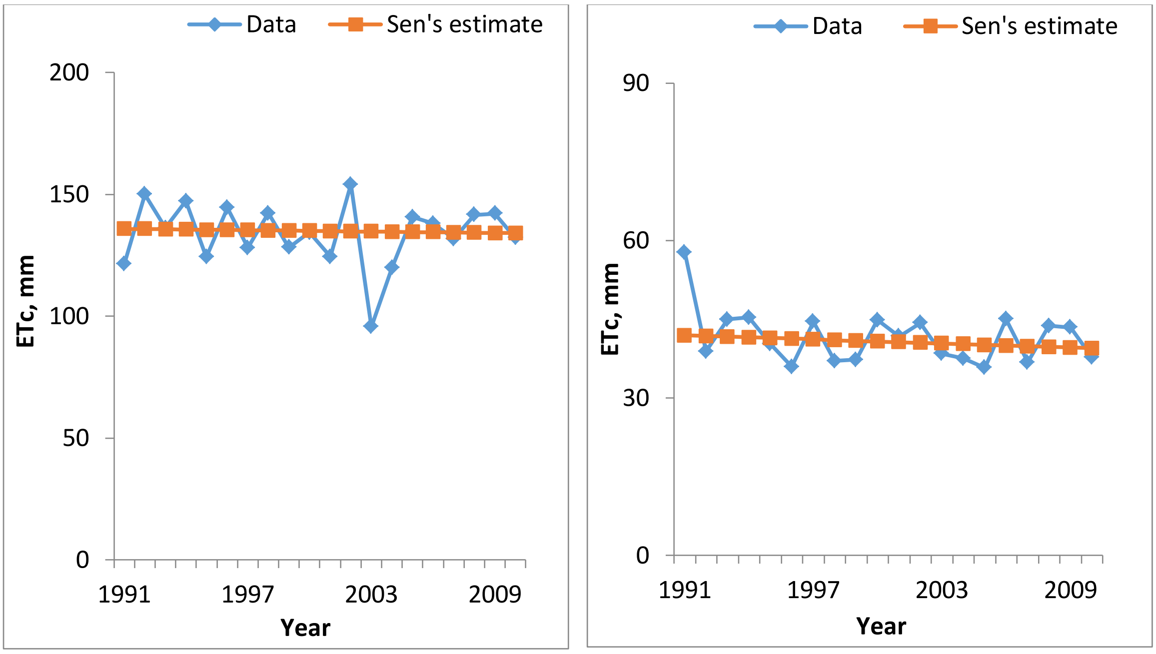
Figure 4.6: Trend of rainfall during the initial (a), development (b), mid (c) and late stages (d) of BRRI dhan49 for 2nd transplanting time

4.4 Trend of actual evapotranspiration (ET_c) and its variability

From Figure 4.7, In Dinajpur for BR11, there was an increasing trend of water demand for 1st transplanting time. For 2nd transplanting time there was an increasing trend of rainfall except development stage from Figure 4.8 Similarly for BR22, there was increasing trend of total water demand for 1st transplanting time and 2nd transplanting time except development and late stage from Figure 4.9. In case of BRRI dhan 49, an increasing trend of total water demand was found except initial and late stage from figure 4.10.

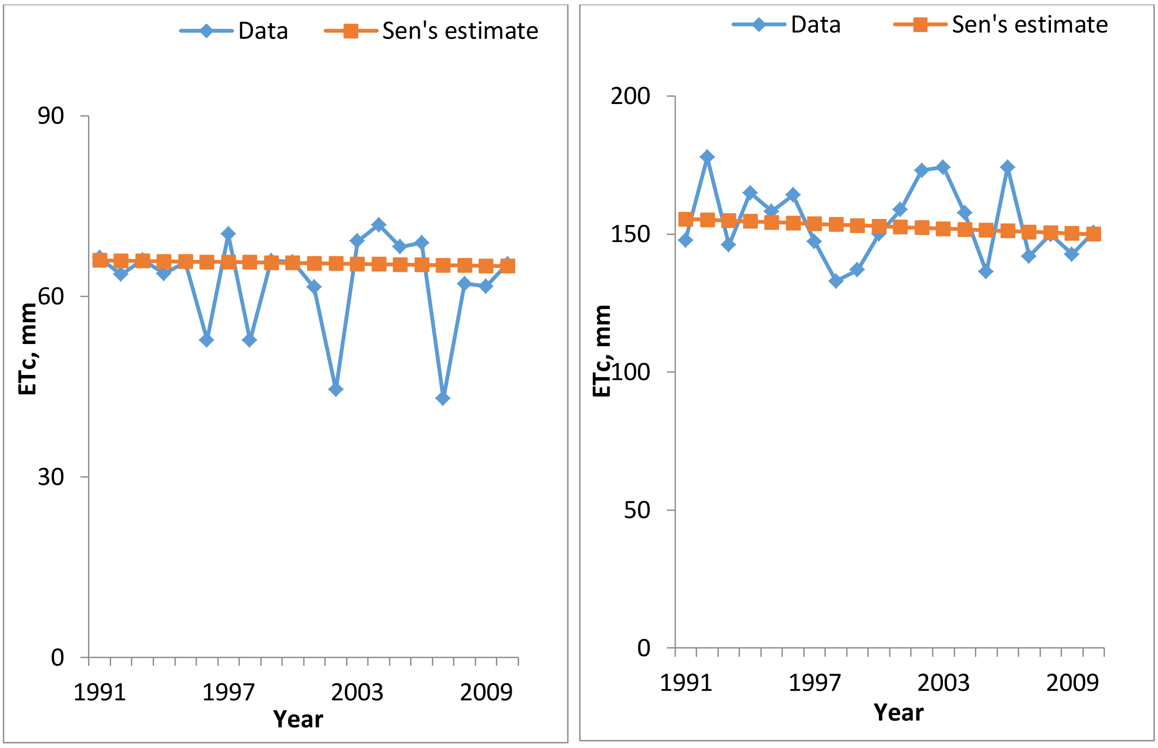


a. Initial stage **b. Development stage**

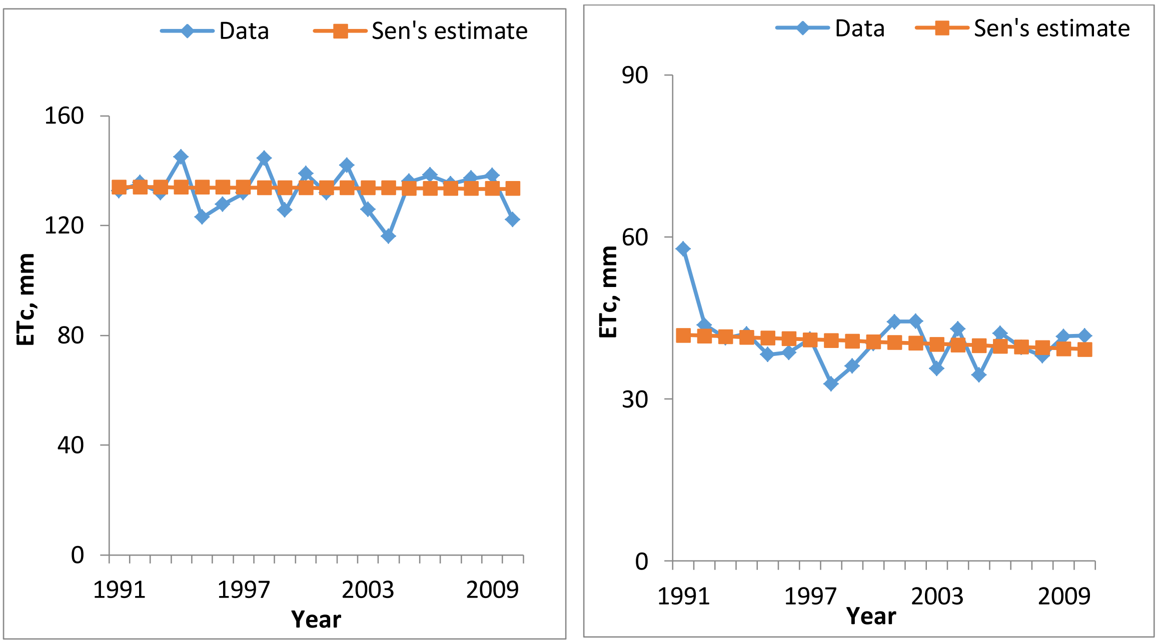


c. Mid stage **d. Late stage**

Figure 4.7: Trend of ET_c during the initial (a), development (b), mid (c) and late stages (d) of BR11 for 1^{st} transplanting time

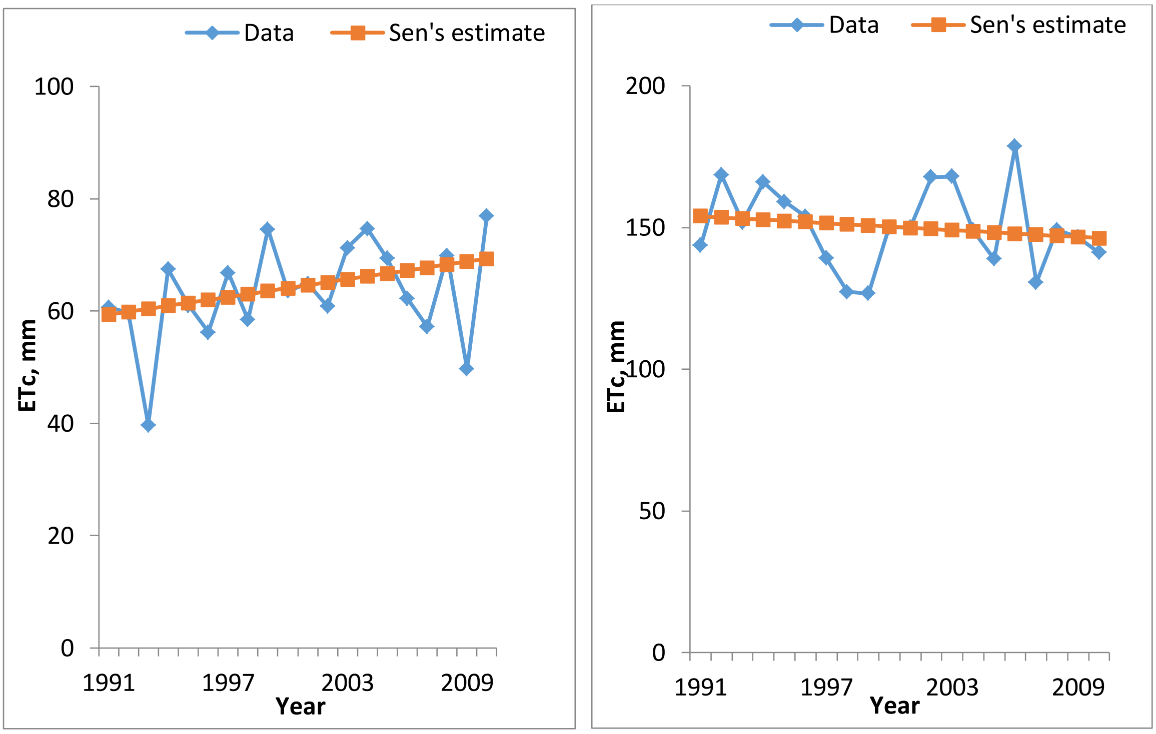


a. Initial stage **b. Development stage**

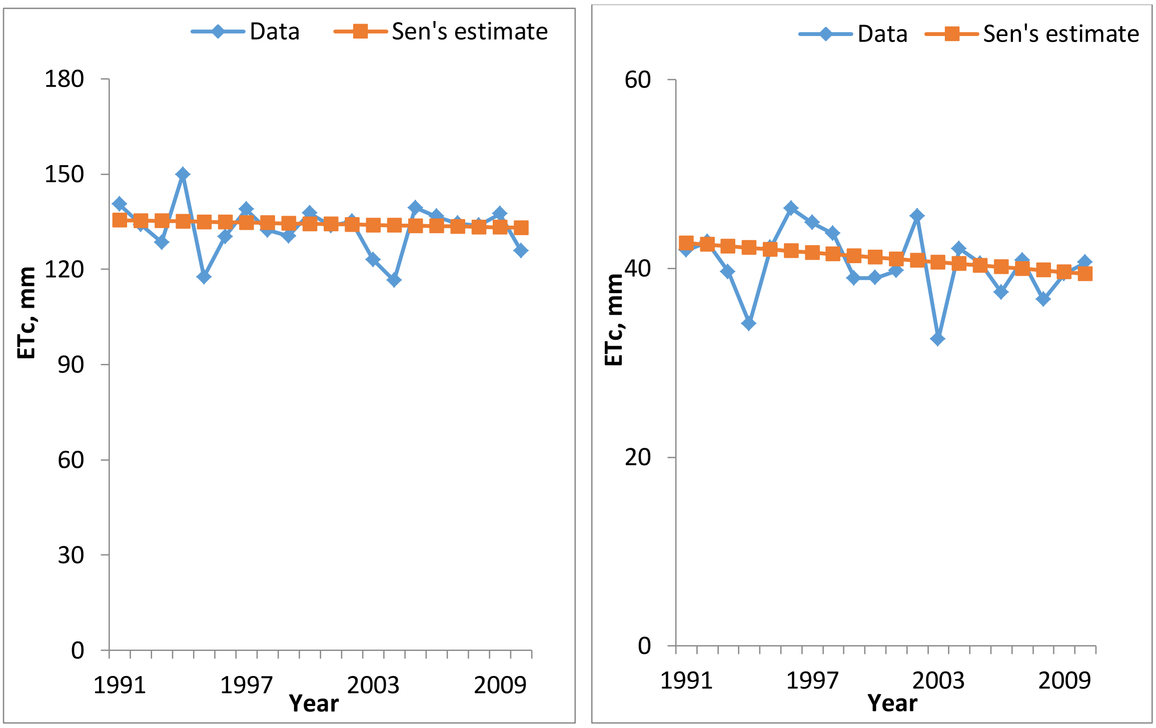


c. Mid stage **d. Late stage**

Figure 4.8: Trend of ET_c during the initial (a), development (b), mid (c) and late stages (d) of BR11for 2^{nd} transplanting time

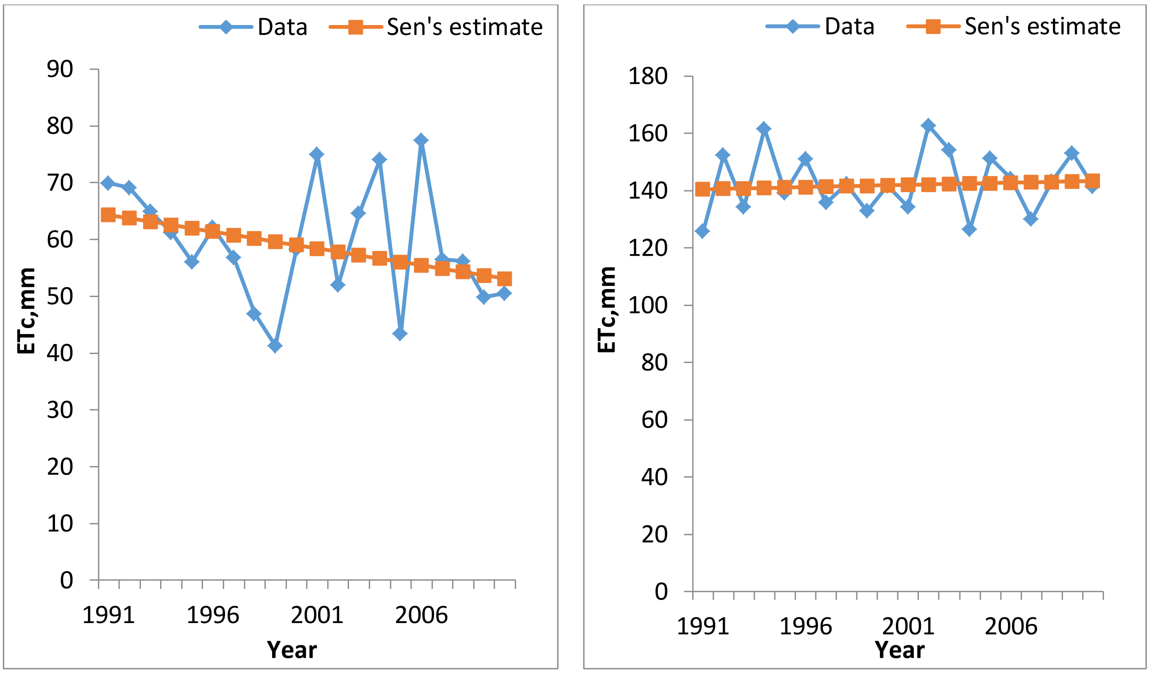


a. Initial stage **b. Development stage**

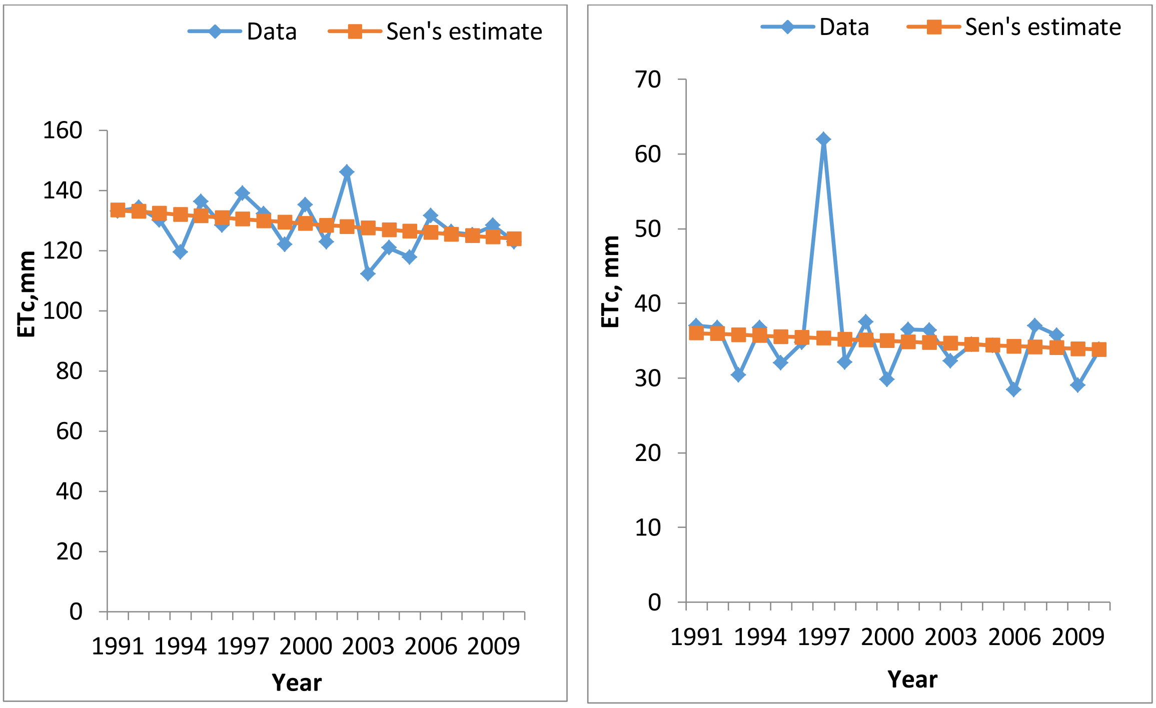


c. Mid stage **d. Late stage**

Figure 4.9: Trend of ET_c during the initial (a), development (b), mid (c) and late stages (d) of BR22 for 1st transplanting time.

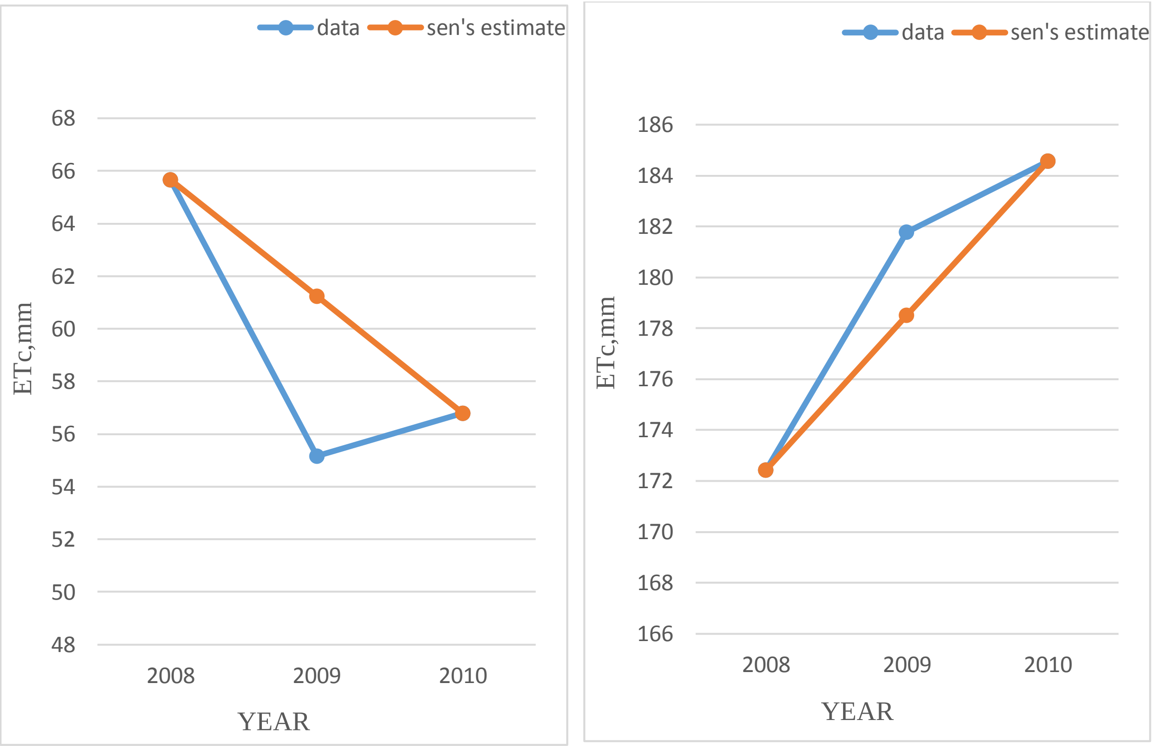


a. Initial stage **b. Development stage**

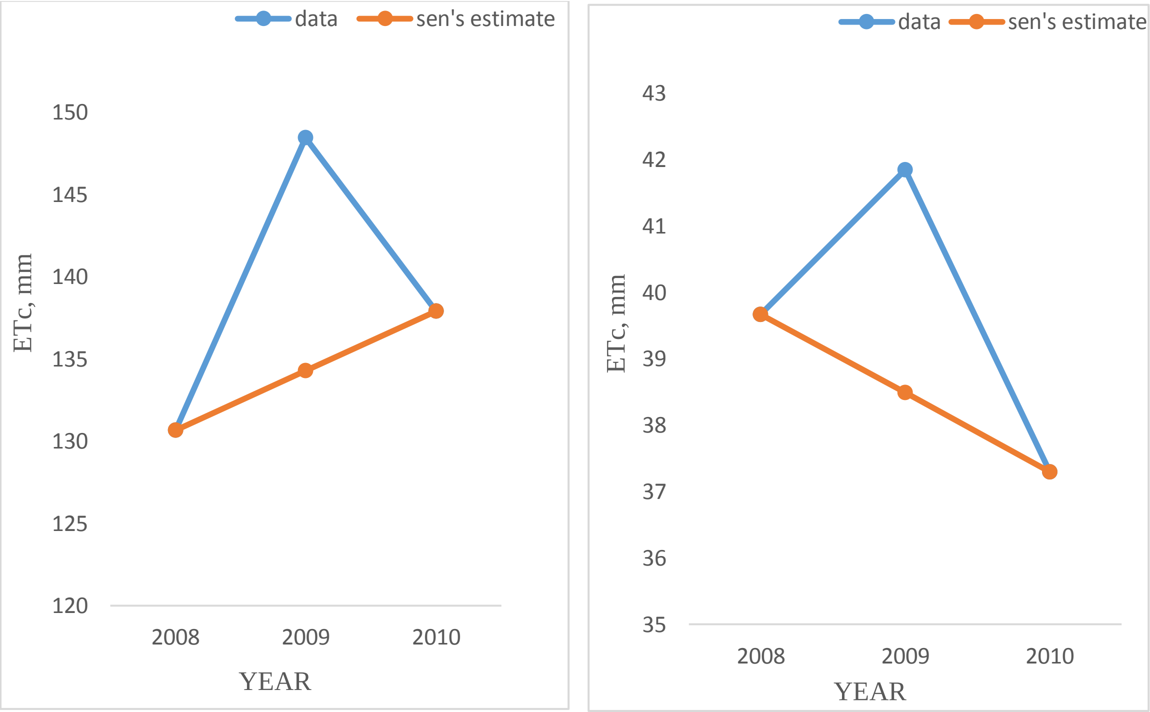


c. Mid stage **d. Late stage**

Figure 4.10: Trend of ET_c during the initial (a), development (b), mid (c) and late stages (d) of BR22 for2nd transplanting time.

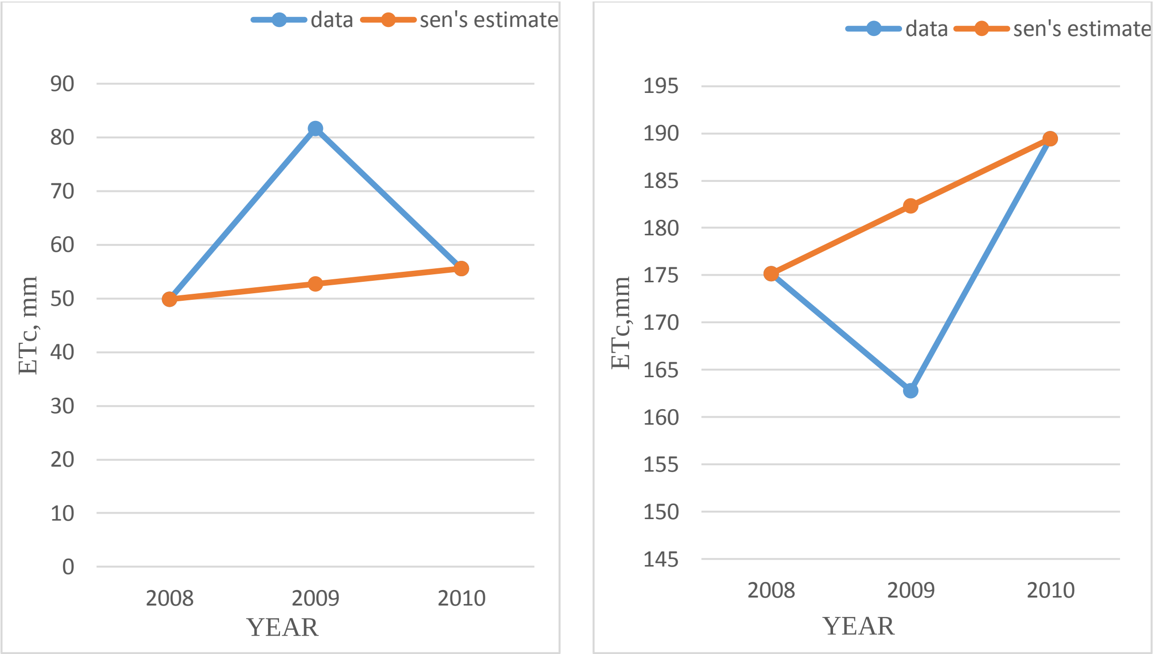


a. Initial stage **b. Development stage**



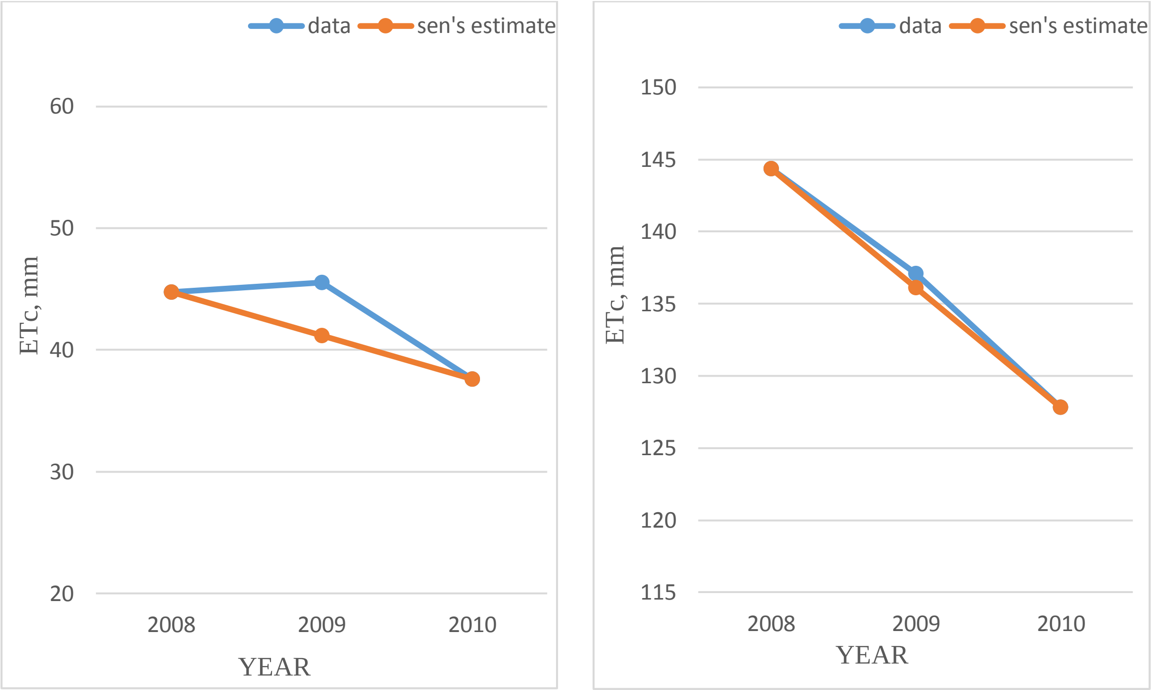
c. Mid stage **d. Late stage**

Figure 4.11: Trend of ET_c during the initial (a), development (b), mid (c) and late stages (d) of BRRI dhan49 for 1st transplanting time.



a. Initial stage

b. Development stage



c. Mid stage

d. Late stage

Figure 4.12: Trend of ET_c during the initial (a), development (b), mid (c) and late stages (d) of BRRI dhan49 for 2^{nd} transplanting time.

4.5 Probability of rainfall and actual crop evapotranspiration

Table 4.7, 4.8 and Table 4.9 show the supplemental irrigation need at different growing stages of BR11, BR22 and BRRI dhan49, respectively. For BR11 (Table 4.7), supplemental irrigation was needed during the development stage, mid stage and late stage for 1st transplanting time and for 2nd transplanting time, supplemental irrigation needed in mid stage and late stage respectively. Similarly, for BR22 (Table 4.8), supplemental irrigation need was detected as mid stage and late stage for 1st transplanting time (Figure 4.6) and for 2nd transplanting time (Figure 4.8). For BRRI dhan49, supplemental irrigation was needed in mid and late stage.

Figure 4.13 and 4.14 shows the level of dependable rainfall and ET_c at 75% probability for BR11 for 1st and 2nd transplanting time. Similarly 4.15 and 4.16 shows the data of BR22 for 1st and 2nd transplanting time and figure 4.17 & 4.18 shows respectively for BRRI dhan49.

About 80% of the total rainfall occurred during the monsoon period. The monsoon season starts mainly in June and continues up to October. Hence, it is observed that water deficiency occurred after October in the mid and late stages mainly. Proper arrangement of supplemental irrigation can bring successful rice production.

Table 4.7: Supplemental irrigation for BR11 in Dinajpur District (Dependable Rainfall and ET_c at 75% probability level)

Stages	1st transplanting time				2nd transplanting time			
	Rainfall (mm)	ET_c (mm)	Supplemental Irrigation (mm)	Remarks	Rainfall (mm)	ET_c (mm)	Supplemental Irrigation (mm)	Remarks
Establishment Stage	94	49	_	No need of irrigation	66	62	_	No need of irrigation
Development stage	120	147	27	Irrigation is needed	160	141	_	No need of irrigation
Mid stage	108	127	19	Irrigation is needed	57	120	63	Irrigation is needed
Late stage	120	37	9	Irrigation is needed	0	39	39	Irrigation is needed

Table 4.8: Supplemental irrigation for BR22 in Dinajpur District (Rainfall and ET_c at 75% probability level)

Stages	1st transplanting time				2nd transplanting time			
	Rainfall (mm)	ET_c (mm)	Supplemental Irrigation (mm)	Remarks	Rainfall (mm)	ET_c (mm)	Supplemental Irrigation (mm)	Remarks
Establishment Stage	105	59	_	No need of irrigation	60	51	_	No need of irrigation
Development stage	140	126	_	No need of irrigation	160	128	_	No need of irrigation
Mid stage	70	119	49	Irrigation is needed	40	118	78	Irrigation is needed
Late stage	0	38	38	Irrigation is needed	0	33	33	Irrigation is needed

Table 4.9: Supplemental irrigation for BRRI dhan49 in Dinajpur District (dependable Rainfall and ETc at 75% probability level)

Stages	1st transplanting time				2nd transplanting time			
	Rainfall (mm)	ET_c (mm)	Supplemental Irrigation (mm)	Remarks	Rainfall (mm)	ET_c (mm)	Supplemental Irrigation (mm)	Remarks
Establishment Stage	216	55	_	No need of irrigation	25	50	25	Irrigation is needed
Development stage	295	153	_	No need of irrigation	272	150	_	No need of irrigation
Mid stage	121	125	4	Irrigation is needed	90	127	37	Irrigation is needed
Late stage	63	37	_	No need of irrigation	0	38	38	Irrigation is needed

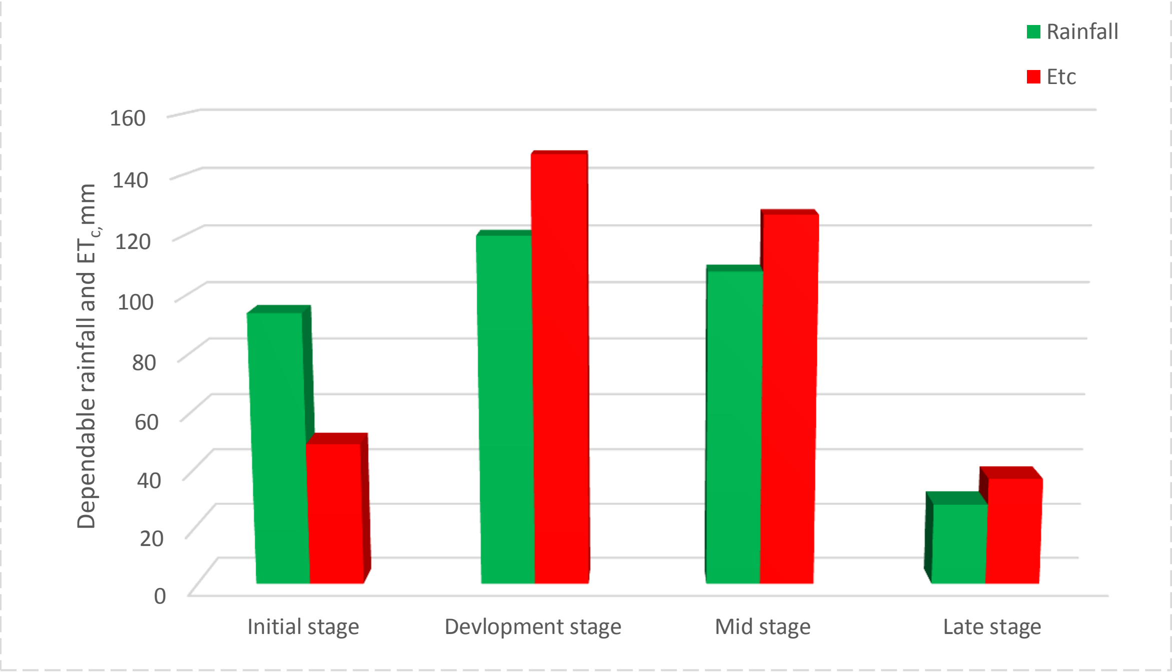


Figure 4.13: Dependable rainfall at 75% probability as compared to ET$_c$ at initial, development, mid and late stages of BR11 for 1st transplanting.

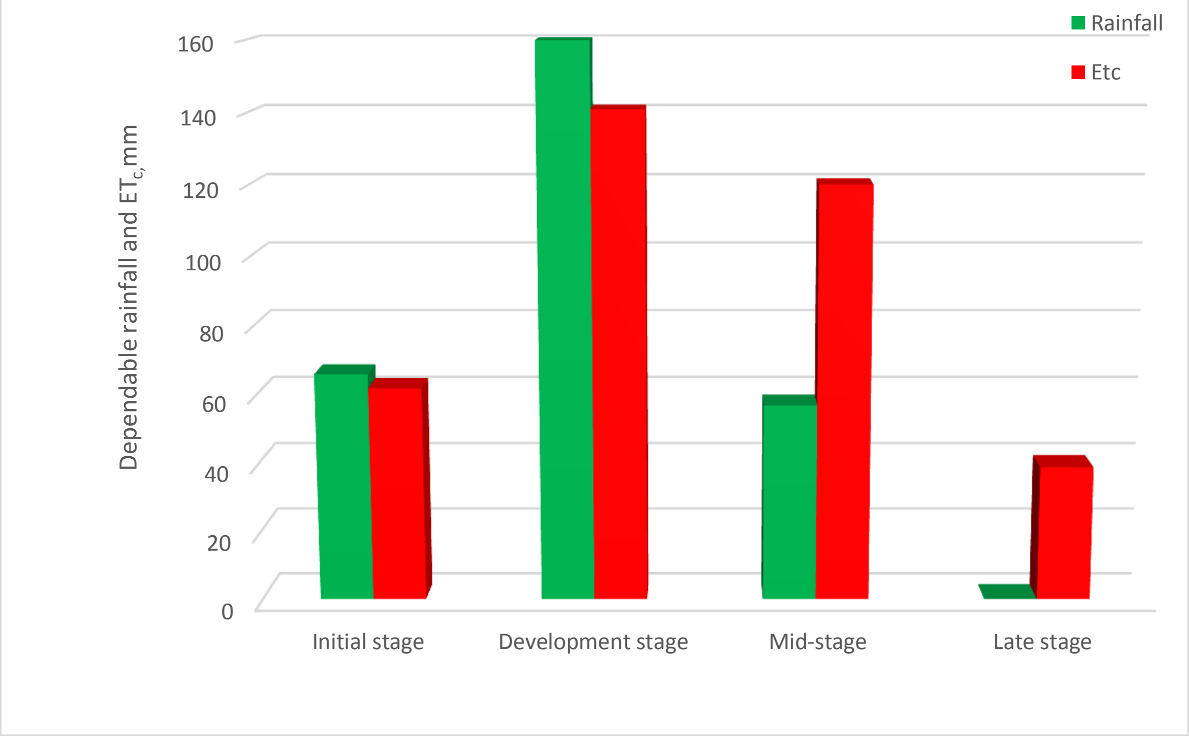


Figure 4.14: Dependable rainfall at 75% probability as compared to ET$_c$ at initial, development, mid and late stages of BR11 for 2nd transplanting time.

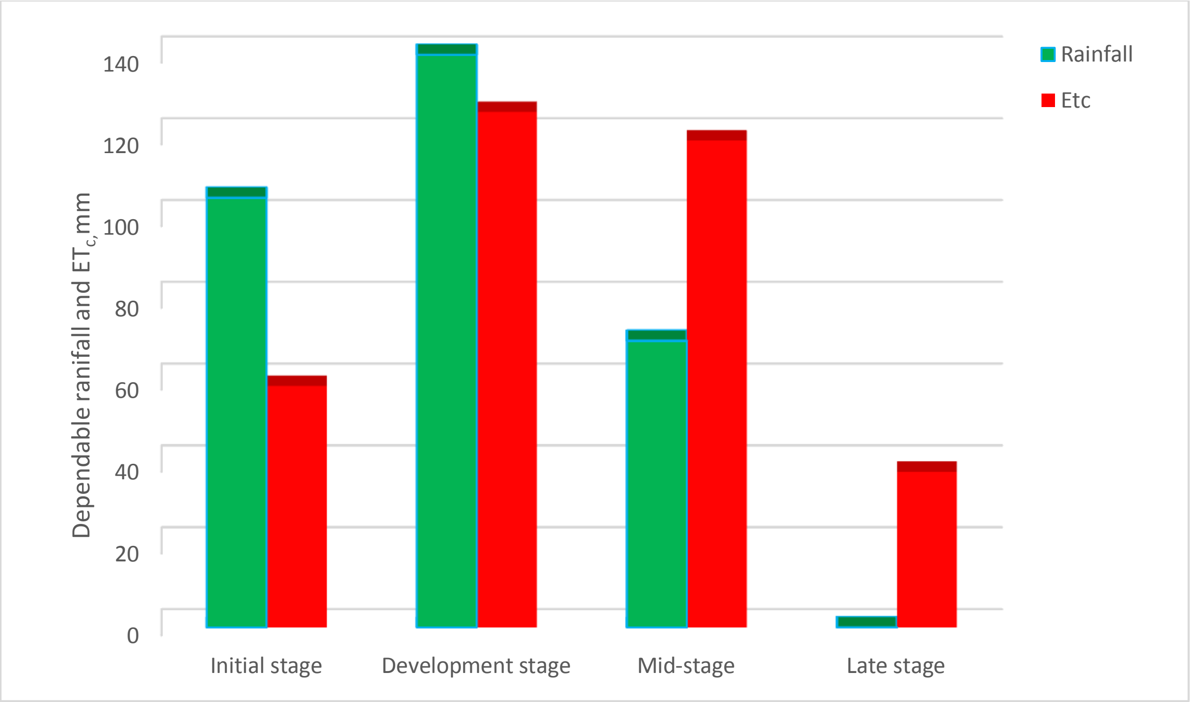


Figure 4.15 Dependable rainfall at 75% probability as compared to ET$_c$ at initial, development, mid and late stages of BR22 for 1st transplanting time

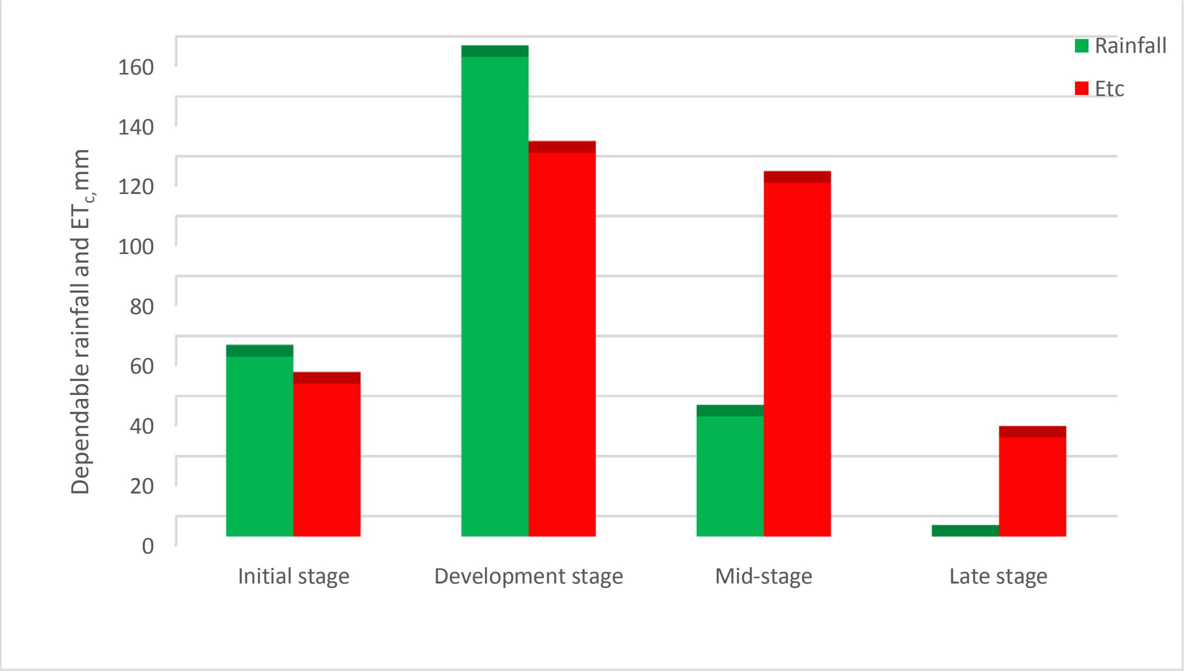


Figure 4.16: Dependable rainfall at 75% probability as compared to ET$_c$ at initial, development, mid and late stages of BR22 for 2nd transplanting time.

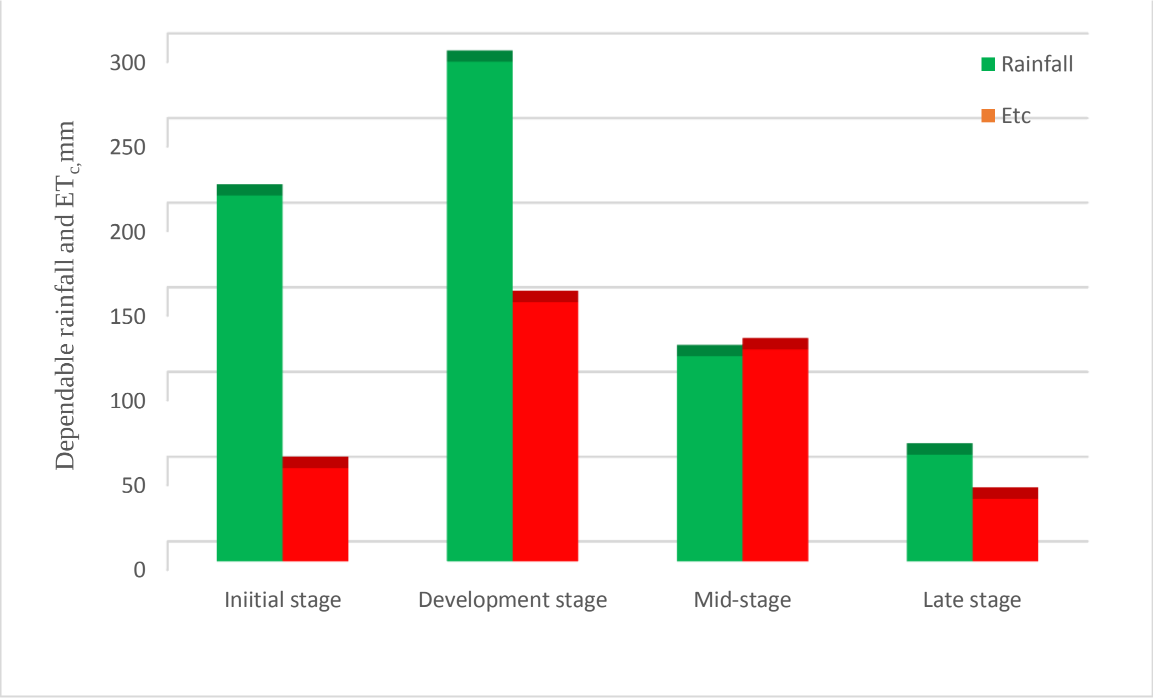


Figure 4.17 Dependable rainfall at 75% probability as compared to ET$_c$ at initial, development, mid and late stages of BRRI dhan49 for 1st transplanting time

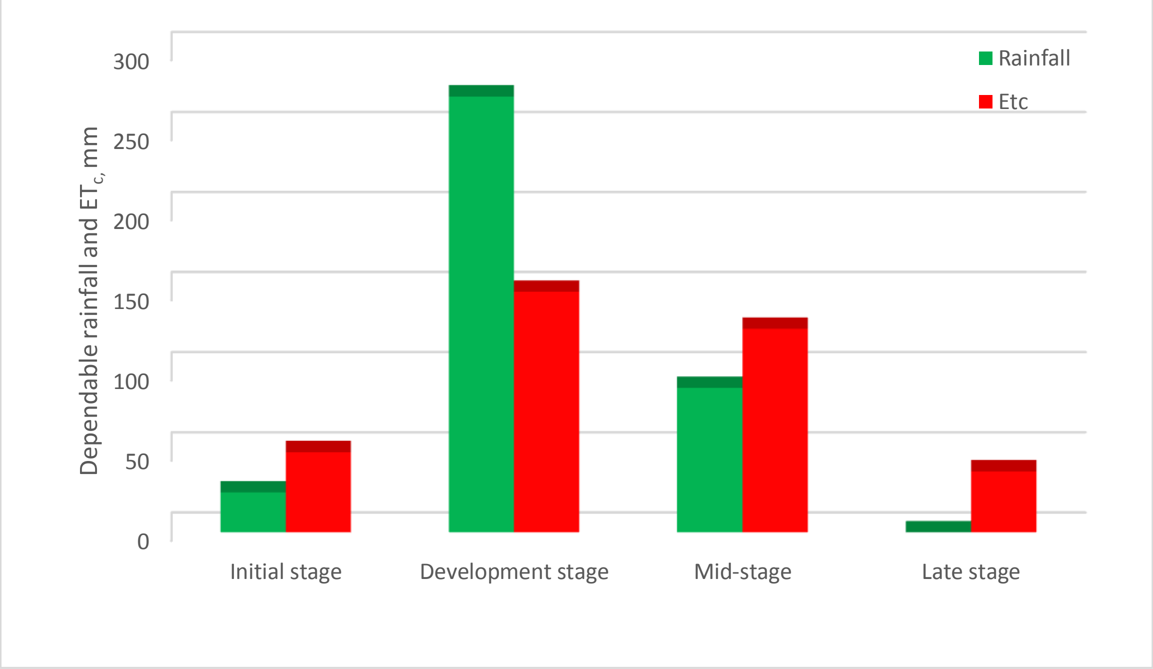


Figure 4.18 Dependable rainfall at 75% probability as compared to ET$_c$ at initial, development, mid and late stages of BRRI dhan49 for 2nd transplanting time

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Actual crop evapotranspiration and rainfall were analyzed for Dinajpur district for three popular rice varieties. Finally found that supplemental irrigation was needed for these rain-fed rice varieties or not. Major conclusions were drawn on the basis of findings of this study:

i. Adjusted crop coefficients of BR11, BR22 and BRRI dhan49 at different growth Stages in different years and sowing times varied due to the changes of relative humidity and wind speed.

ii. Actual crop evapotranspiration of BR11 for 1st transplant time varied from 359 to 441 mm and 363 to 503 mm in Dinajpur districts. For BR22, actual crop evapotranspiration for 1st transplanting varied from 361 to 463 mm and 333 to 393 mm for 2nd transplanting time. The variations of ETc for 1st transplant time were from 409 to 427 mm and 406 to 429 mm for 2nd transplanting time for BRRI dhan 49 in Dinajpur district, respectively. Actual crop evapotranspiration varied due to variation of crop coefficient and reference crop evapotranspiration.

iii. In Dinajpur district, there was mostly decreasing trend of rainfall for two transplanting times for unpredictable climatic change.

iv. Water demand of three rice varieties had decreasing trend for two transplanting time due to decreasing rate of reference crop evapotranspiration and crop coefficient.

v. For BR11, supplemental irrigation was needed in development, mid and late stage in 1st transplanting, but for 2nd transplanting time, supplemental irrigation was needed in mid and late stages. For BR22, supplemental irrigation was needed mainly in mid and late stages for 1st and 2nd transplanting. Finally, for BRRI dhan49, supplemental irrigation was needed in mid and late stages Dinajpur district.

5.2 Recommendations

Based on the result of this study, research should be undertaken:

i. To estimate the ET_0 with different method for long period of time.

ii. To estimation of ET_c and supplemental irrigation with different computer based models.

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APPENDICES

Appendix I Monthly average rainfall in Dinajpur District (mm)

Year	January	February	March	April	May	June	July	August	September	October	November	December
1990	0.00	0.00	0.00	0.64	3.5	10.26	11.55	15.79	5.63	2.21	0.00	0.00
1991	0.00	0.00	1.22	2.06	3.9	12.24	18.6	12.3	22.4	1.14	0.32	0.00
1992	0.48	1.12	2.02	0.17	11.3	14.35	17.25	2.45	0.67	0.54	4.20	0.00
1993	0.00	0.00	4.6	9.02	14.3	16.5	13.26	18.22	17.02	4.26	0.08	0.00
1994	0.06	1.10	1.06	0.00	2.98	9.50	15.22	17.25	34.2	2.54	2.40	0.00
1995	0.06	1.30	1.12	0.00	4.22	9.56	15.06	16.11	34.2	1.19	2.47	0.00
1996	0.92	0.64	0.00	0.96	3.16	10.67	13.8	11.3	24.6	2.41	0.00	0.00
1997	0.78	2.10	0.98	2.21	2.90	12.32	14.87	8.64	9.63	0.09	0.00	0.00
1998	0.64	0.60	0.77	4.93	4.94	9.60	18.25	17.67	10.57	9.30	0.00	0.00
1999	0.00	0.00	0.00	2.26	11.38	9.40	13.00	16.6	17.02	8.64	0.17	0.00
2000	0.00	1.03	0.03	4.90	10.48	13.3	6.35	6.53	6.29	0.81	0.00	0.00
2001	0.00	0.00	0.00	0.16	1.76	19.10	10.25	15.4	12.32	1.76	0.00	0.00
2002	0.20	0.25	0.42	5.60	3.35	21.93	25.64	7.93	16.02	1.86	0.03	0.00
2003	0.35	1.21	1.70	3.50	4.74	11.23	17.26	6.35	7.67	12.25	0.00	0.00
2004	0.22	0.00	0.38	5.40	8.96	17.23	19.41	4.12	8.43	10.64	0.00	0.02
2005	0.29	0.54	1.19	2.97	8.22	15.8	16.35	16.02	7.40	24.34	0.00	0.00
2006	0.00	0.00	0.02	2.23	8.35	8.10	8.02	4.06	11.33	0.67	0.73	0.20
2007	0.00	0.00	0.02	1.10	3.90	15.8	12.93	7.67	7.80	1.64	0.00	0.00
2008	1.06	0.2	0.61	0.9	7.09	12.1	14.09	12.4	8.64	1.42	0.00	0.00
2009	0.00	0.00	0.32	1.37	11.9	15.23	9.06	15.19	4.27	8.04	0.20	0.00
2010	0.00	0.00	0.00	2.80	6.64	17.17	11.48	9.35	3.57	2.64	1.00	0.00

Appendix II Monthly average minimum relative humidity in Dinajpur District (Percent)

Year	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1990	53.09	43.53	42.00	58.00	66.19	71.93	75.25	70.32	72.13	67.42	46.6	41.29
1991	57.21	42.26	32.09	48.17	63.66	70.89	72.74	74.56	69.65	58.29	57.17	43.10
1992	48.74	32.29	42.19	47.65	65.26	71.62	70.54	72.94	63.41	40.41	55.66	47.09
1993	61.90	43.17	37.7	49.5	68.29	72.83	70.74	76.87	74.00	64.61	56.44	45.82
1994	55.32	41.17	35.29	51.26	71.35	69.67	73.69	75.31	67.97	59.67	46.37	48.87
1995	54.36	41.39	43.36	50.27	65.69	65.49	65.93	67.74	70.16	69.37	45.67	50.16
1996	54.77	43.34	37.36	60.58	70.26	74.5	72.47	72.73	65.06	52.97	49.96	49.3
1997	52.03	41.19	36.90	37.14	61.22	69.47	72.29	71.69	71.09	63.64	51.37	48.33
1998	63.77	41.29	45.74	59.95	62.77	70.13	77.67	79.25	71.53	69.59	57.3	52.06
1999	54.29	43.17	40.06	57.22	70.67	71.53	70.93	70.63	72.36	56.49	58.03	64.29
2000	56.22	45.37	41.41	56.79	71.79	71.16	71.45	70.79	73.3	58.45	57.03	44.74
2001	52.36	49.36	42.19	57.37	65.79	70.94	72.46	70.76	63.49	63.29	46.69	49.67
2002	57.03	48.19	44.90	57.14	61.22	68.47	70.29	75.69	65.09	69.46	51.37	50.44
2003	63.80	53.79	52.41	61.03	59.45	71.46	69.45	69.37	70.76	67.90	53.20	53.19
2004	58.21	49.26	46.09	60.17	62.66	70.89	72.94	71.56	69.69	70.29	56.17	46.10
2005	53.46	47.36	50.19	59.37	61.77	71.94	70.46	72.76	62.69	64.29	49.69	47.67
2006	47.29	35.5	36.19	55.03	51.13	67.97	73.37	67.04	70.70	61.35	45.20	47.96
2007	52.35	45.17	49.06	53.16	57.96	72.16	71.93	73.77	67.70	64.19	49.93	66.29
2008	55.33	49.17	48.06	52.16	58.67	71.16	70.93	73.87	66.70	645.39	47.93	61.39
2009	60.22	40.96	38.22	50.9	60.41	63.03	67.93	73.41	65.47	56.48	49.4	55.83
2010	43.61	50.6	62.8	66.2	68.54	69.09	69.43	58.83	54.67	35.19	59.39	43.60

Appendix III Monthly average wind speed in Dinajpur District (m/s)

Year	January	February	March	April	May	June	July	August	September	October	November	December
1990	1.75	2.15	2.32	2.95	2.53	2.89	3.06	2.59	3.01	3.11	2.26	2.04
1991	2.01	2.20	1.99	2.64	2.12	2.70	2.14	1.69	2.30	1.99	2.01	1.80
1992	1.88	2.01	2.20	1.97	2.01	1.69	1.99	1.70	2.45	2.12	1.96	2.19
1993	2.59	2.62	2.71	3.68	2.57	2.39	2.49	2.16	2.07	2.23	2.10	1.05
1994	1.84	2.3	2.99	3.00	2.61	2.62	2.30	1.90	1.09	1.72	1.85	2.02
1995	2.08	2.71	2.90	2.97	2.71	1.69	1.69	1.78	2.45	2.12	2.60	2.19
1996	1.78	2.156	2.33	2.75	2.50	2.879	3.16	2.59	3.91	3.71	2.16	1.94
1997	1.57	1.98	2.33	1.92	2.07	2.23	2.23	1.88	1.69	1.35	1.54	1.61
1998	2.49	2.49	2.01	2.32	2.35	2.08	2.47	1.92	1.97	1.97	2.49	1.79
1999	2.10	2.77	2.97	2.93	2.71	1.67	1.63	1.88	2.45	2.72	2.68	2.09
2000	2.10	2.31	2.06	2.37	1.95	1.99	2.21	1.91	1.87	1.94	1.63	1.35
2001	1.36	1.73	1.64	1.8	2.33	1.87	1.95	1.45	1.66	1.22	1.44	1.34
2002	1.44	1.49	1.92	2.42	2.55	2.17	1.57	1.91	1.91	1.49	1.48	1.69
2003	2.20	2.63	1.89	2.64	2.62	2.78	2.17	1.69	2.37	1.99	2.11	1.87
2004	1.91	1.95	2.32	2.06	2.03	2.07	2.02	1.99	1.87	1.77	1.72	1.63
2005	2.84	2.36	2.90	2.70	2.63	2.20	2.30	1.90	1.79	1.79	1.55	1.92
2006	2.21	2.27	2.39	2.44	2.32	1.90	2.16	1.69	2.10	1.99	2.11	1.85
2007	2.45	2.80	2.91	3.70	2.54	2.43	2.37	3.17	1.70	1.44	0.97	1.06
2008	1.67	1.39	1.92	2.10	1.99	2.03	1.52	1.70	1.70	1.40	1.50	1.20
2009	1.36	1.77	1.63	1.80	2.13	1.67	1.94	1.43	1.36	1.22	1.40	1.30
2010	1.47	1.39	1.91	2.02	2.05	2.17	1.47	1.92	1.91	1.47	1.43	1.39

Appendix IV Monthly average reference crop evapotranspiration (ET_o), mm/day

Year	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1990	1.91	2.74	3.71	4.20	4.52	4.20	3.60	4.23	3.72	2.81	2.93	2.24
1991	2.04	3.05	4.21	4.91	3.83	4.00	3.96	3.93	3.07	3.38	2.75	1.95
1992	2.01	2.67	4.87	5.44	4.61	4.48	3.46	4.09	3.80	3.31	2.75	2.00
1993	1.72	2.77	4.09	4.70	4.09	4.23	4.31	3.57	3.45	3.44	3.02	2.06
1994	2.00	2.80	4.23	5.08	4.90	3.84	4.44	4.23	3.84	3.40	3.10	2.04
1995	2.16	2.71	4.31	5.22	5.04	3.59	4.00	4.02	3.76	3.41	2.94	2.12
1996	2.13	3.09	4.67	5.31	4.66	3.63	3.34	3.93	3.61	3.34	2.91	2.02
1997	2.02	2.82	4.64	5.16	5.07	4.33	3.93	3.79	3.20	3.45	2.62	2.14
1998	1.60	3.00	4.23	4.42	4.82	3.96	3.35	3.25	3.65	3.10	2.56	2.01
1999	2.24	3.31	4.51	4.28	4.17	3.99	3.55	3.38	3.28	3.18	2.73	2.10
2000	1.87	2.24	3.42	4.36	4.64	3.82	4.06	3.75	3.33	3.47	2.53	2.17
2001	1.63	2.30	3.40	4.60	4.71	4.56	4.32	4.45	4.46	3.07	2.67	2.27
2002	1.80	2.41	3.60	4.09	4.26	3.75	4.62	3.10	3.99	3.90	2.51	2.07
2003	1.62	2.26	3.47	3.99	4.63	3.53	4.29	4.34	3.69	2.87	2.37	2.18
2004	1.71	2.32	3.91	3.51	4.55	3.74	3.51	4.29	3.10	3.04	2.42	2.16
2005	1.69	2.93	3.8	4.26	4.10	4.16	3.84	3.18	3.94	2.89	2.12	2.1
2006	1.54	2.55	3.97	3.97	3.46	3.79	4.23	4.52	3.55	3.48	2.18	2.01
2007	1.98	2.48	3.87	4.16	5.12	3.96	3.47	3.78	3.19	3.27	2.74	1.79
2008	1.89	2.57	3.71	4.61	4.71	4.09	3.65	3.67	3.67	3.25	2.75	1.64
2009	1.64	3.00	3.67	4.37	4.37	4.46	4.29	3.37	3.79	3.29	2.37	1.74
2010	1.75	2.93	4.00	4.22	4.69	3.59	3.89	3.88	3.48	3.15	2.60	1.60

Specific calculation

Adjustment of crop coefficient of initial stage is:

$K_{initial}$= 1.05

The equation for adjustment of crop coefficient of mid-season stage is:

K_{cmid}= $1.20+ [0.04(u_2-2)-0.004(RH_{min}- 45)](\frac{h}{3})^{0.3}$

$= 1.20+ [0.04(2-2)-0.004(76- 45)](\frac{1.15}{3})^{0.3}$

$=1.11$

Where,

K_{cmid} = crop coefficient of mid-season stage;

RH_{min}= mean daily minimum relative humidity during the mid-season growth stage (%) =76%

u_2 = mean daily wind speed at 2 m height over grass during the late-season growth stage (m/s) =2m/s

h = the mean plant height during the mid-season stage (m) =1.15m

The equation for adjustment of crop coefficient of late-season stage is:

K_{cend}= $0.90+ [0.04(u_2-2)-0.004(RH_{min}- 45)]\ (h/3)^{0.3}$

$=0.90+ [0.04(2-2)-0.004(58- 45)]\ (1.15/3)^{0.3}$

$=0.86$

Where,

K_{cend} = crop coefficient of late-season stage,

RH_{min}= mean daily minimum relative humidity during the late-season growth stage (%)=58%

u_2= mean daily wind speed at 2 m height over grass during the late-season growth stage (m/s) =2m/s

h= the mean plant height during the late-season stage (m) =1.15m

This empirical equation for crop coefficient at crop development stage is:

K_{cdev}= $K_{cprev}+ [\frac{\{i-\sum L_{prev}\}}{L_{stage}}] \times (K_{cnext} - K_{cprev})$

$=105+ [\frac{\{1-40\}}{40}] \times (1.12 - 1.05)$

$=1.01$

Where,

K_{cdev} = crop coefficient of rice at crop development stage, i is the day number Within the growing season (1....... length of the growing season),

L_{stage} = length of the stage under consideration (day) =40

$\sum L_{prev}$ =sum of lengths of all previous stages (day) =40

K_{cnext} =crop coefficient at the beginning of next stage =1.12 and

K_{cprev} =crop coefficient at the end of previous stage=1.05

Actual evapotranspiration of rice:

$ET_{crop} = K_c \times ET_o$

$=1.05\times62.86$

$=66mm$

Where,

ET_{crop} = water demand/ actual evapotranspiration (mm/day);
ET_o = reference crop evapotranspiration at different growing stages of rice (mm/day) =62.86mm/day
K_c = crop coefficient at different growing stages=1.05