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MONSOONAL RAINFALL VARIABILITY, WATER STRESS, AND RAINFED RICE PRODUCTIVITY IN BANGLADESH

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By

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MONSOONAL RAINFALL VARIABILITY, WATER STRESS, AND RAINFED RICE PRODUCTIVITY IN BANGLADESH

A Dissertation APPROVED FOR THE DEPARTMENT OF GEOGRAPHY

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ABSTRACT

Agricultural practice in Bangladesh is largely dependent on the monsoonal rainfall. Historical data show that Bangladesh experienced severe droughts and floods during monsoon months. Crop losses were reported under both of these extreme conditions. Intra-seasonal monsoonal rainfall variations also significantly affect rainfed rice productivity. Due to the immense importance of rainfed rice in annual crop production, it is essential to minimize crop and economic losses. Thus, studies of the monsoon's impacts on rice productivity can provide significant information for crop planners and decision makers who are interested in devising strategies to minimize losses.

This project investigates intra-seasonal monsoonal rainfall variations and their impacts on the potential rainfed rice productivity in Bangladesh. A crop growth simulation model, the CERES-Rice, is applied to 16 meteorological stations located in the major rice growing regions and for eight transplanting dates to understand the dynamic relationships between the variable monsoonal rainfall and the rainfed rice and determine optimum transplanting date(s). The model applications reveal that rice yield decrease as the transplanting dates were moved well into the monsoon. The rate of decrease in yield is notable until July 15; thereafter, a very high decrease in yield occurs. Baseline estimates show, on the average, for a July 15 transplanting date, yield loss is 20.9% compared to a June 1 transplanting date. On the other hand, for an August 15 transplanting date, yield loss is 73.7% on the average compared to July 15 transplanting date. It is found that flowering/heading and maturing stage water stress play key role in determining yield. Further analyses show combined effect of water stress on yield during these two stages is more severe compared to one of these stages. This study reports that early transplanting may ensure the availability sufficient soil water during flowering/heading and maturing stages and thus reduce crop loss. Moreover, applications of a decision making technique suggests that a 'future year' like 1986 would be quite good for Bangladeshi farmers. Overall, the findings of this study will enable crop planners and policy and decision makers to develop more effective plans to mitigate crop losses due to extreme climatic conditions.

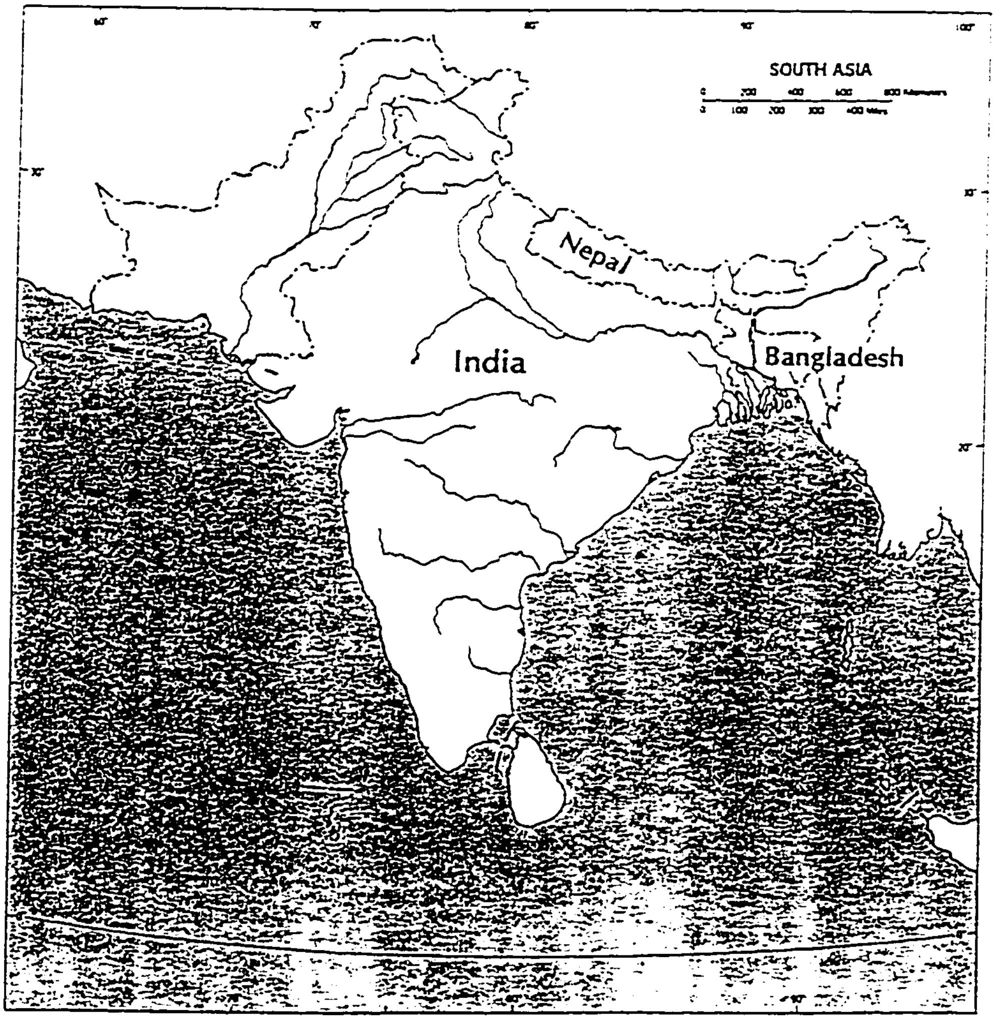
CHAPETR 1

INTRODUCTION

Agriculture is a way of life in South Asia. Survival of the economies in this region largely depends on a stable agricultural sector. Intricate relationships between the societies of this region and agricultural activities can be found in Bangladesh. The agriculture sector in Bangladesh contributes 44% of the national Gross Domestic Product (GDP) and employs 56.5% of the total employed labor force (Kurian, 1992). It is important to note that rice is the staple food in Bangladesh, like many other regions of South Asia, and obviously a very large section of the economy is involved in rice production. Furthermore, rainfed '*aman*' rice, among a number of other varieties of seasonal rice, constitutes more than 50% of the total rice production in Bangladesh (Bangladesh Bureau of Statistics, 1989).

Rainfed rice production is largely dependent on the inter- and intra-annual behavior of the weather and climate, especially on the summer monsoon which is the predominant supplier of water. Seasonal rainfall totals, however, are not as critical to the development of rice plants as is the timing of rainfall. Furthermore, rice is dependent on rainwater for puddling during its initial growth stage whereas clear, dry conditions are required for optimal development during rice maturing and harvesting. In other words, inter- and intra-seasonal variations in monsoonal rainfall present significant uncertainty and risk in crop productivity. These uncertainties and associated crop losses could be reduced by accurate forecasting and precise management decisions. It is important to note that long-lead time seasonal forecasting is not reliable (Johnson, 1998). However, studies of the past seasonal rainfall variations and their impacts on the crop growth and crop productivity can play a significant role in devising field-level management plans that may notably reduce crop losses in the future.

Moreover, in the absence of reliable long-lead time forecasting and in the event of abnormal weather conditions in the middle of the growing season, farmers need to make short-term adjustments to minimize crop loss. Study of past weather variations and their impacts on potential crop productivity will help to devise proper strategies which can be activated in the future during abnormal weather conditions to minimize losses. The present research project investigates intra-seasonal rainfall variations during the summer monsoon season in Bangladesh and their impacts on the rainfed *aman* rice plant growth and potential yield. A crop growth simulation model, the CERES-Rice (Ritchie *et al.*, 1987; and Tsuji *et al.*, 1994), is applied to 16 stations distributed over major rice growing regions of Bangladesh (Figures 1.1, and 1.2). These stations represent various precipitation regimes and soil characteristics and thus can be assumed as representative of 16 rice growing regions. This application helps to understand the relationship between the changes in the summer monsoon, soil water availability, and rice plant growth and productivity. The monsoons for 1975 through 1987 are



Adopted from: deBlij and Muller (1994)

Figure 1.1. Bangladesh and South Asia.

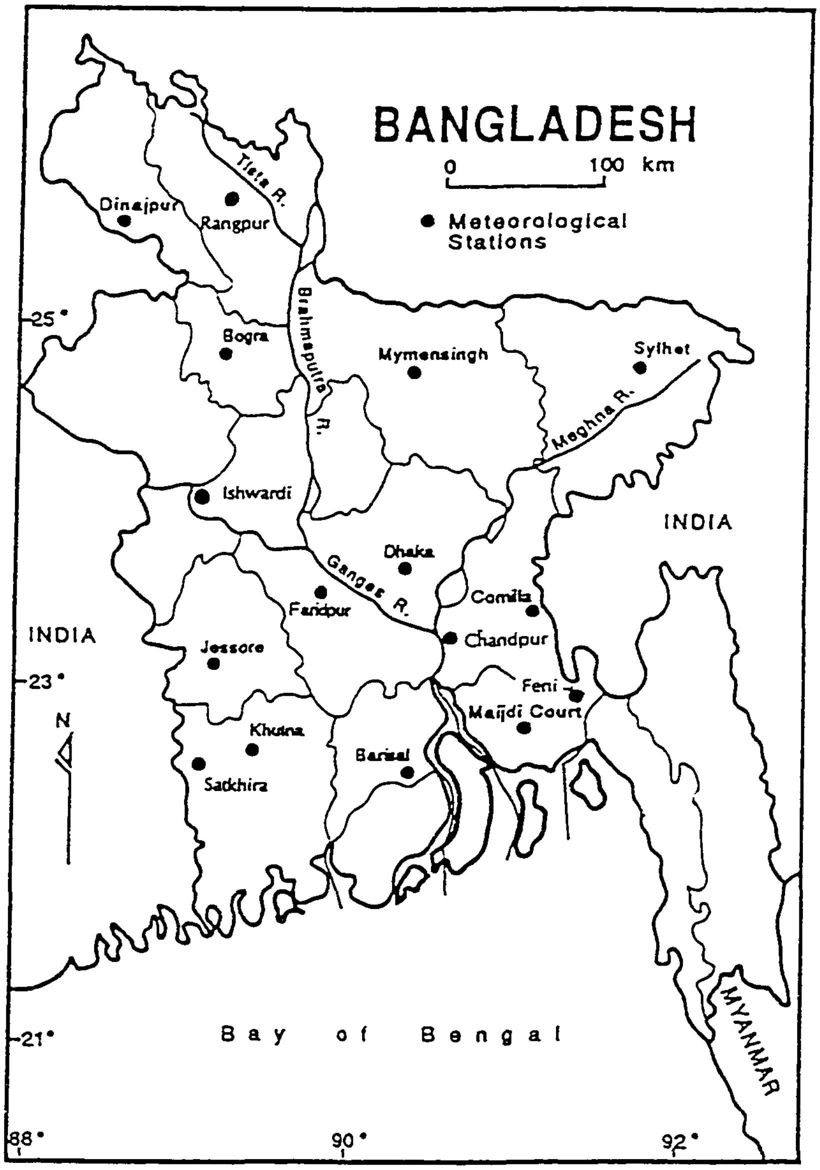


Figure 1.2. Location of Meteorological Stations in Bangladesh.

used as scenarios (thus 13 scenarios) to determine loss per scenario for each station. In addition, long-term crop productivity estimates allow one to identify climatically vulnerable rainfed rice growing regions in Bangladesh. A number of planting dates are proposed in response to the abnormal conditions that would minimize crop loss. These planting dates will allow farmers of Bangladesh to use their resources more efficiently. It is important to note that this research project adopts Kates' (1985) framework for climate impacts studies (Figure 1.3a-b). A flow chart of the major components of this study is shown in Figure 1.4.

1.1. Objectives

Abnormal rainfall and associated drought and flooding causes substantial crop losses in Bangladesh (*cf.*, Sah, 1987). The effect of abnormal rainfall on rice productivity becomes acute due to intra-seasonal variations. Thus, the determination of optimum planting dates is essential to optimize water availability, and hence to reduce crop loss due to abnormal monsoonal conditions.

In light of the above discussion, this study:

a) investigates the impacts of intra-seasonal variations of monsoonal rainfall on the potential rainfed rice productivity in Bangladesh (the model assumes recommended supply of fertilizer and saturated soil at the time of transplant),

b) investigates the role of end-of-the-growing-season (end-of-season) water stress on yield,

c) determines optimum planting dates for the reduction of crop losses under various abnormal conditions,

d) identifies climatically vulnerable rainfed rice growing sites, and

e) contributes in decision-making and resource re-allocation under variable weather and climate conditions.

It is important to note that the model assumes The Bangladesh Rice Research Institute (BRRI) recommended supply of fertilizer and saturated soil at the time of transplanting.

1.2. Significance of the study

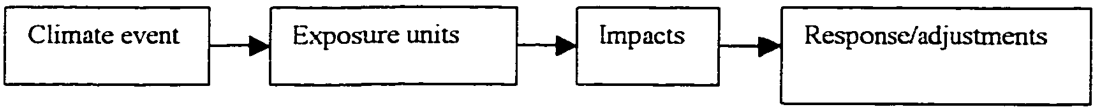
1.2.1. Optimizing end-of-season yield by improved crop management.

Population pressure and demand of grain is a major concern for both scientists and society (Brown, 1997; Yoshino, 1998). It has been noted that technologically we have reached the plateau of crop productivity (Brown, 1997; Mann, 1999). In other words, limit of potential yield due to technological advances has been reached. However, due to environmental, technological, and economic constraints, many rice growing regions of the world are unable to attain their potential yield. Average yields in these regions reflect this situation (Brown, 1997). Hence, opportunity exists for increasing the average yield by improving crop management. Brown (1997: 20) noted that Bangladesh could be one of the few countries where the "greatest remaining potential appears to lie".

1.2.2. Impact analysis for short- and long-term adjustments. Abnormal behavior of weather and climate and their impact on the biophysical environment and, subsequently, on the socio-economic structure is a major concern for policy and decision makers. Climate impact analysis allows one to understand the nature and scale of effects of extreme weather and climate conditions on the biophysical environment. In addition, it allows decision makers to devise procedures to cope with extreme conditions and minimize crop and associated economic losses (*cf.*, Kunkel *et al.*, 1995). Thus, the impacts of abnormal monsoonal conditions on rice plant growth and productivity and the identification of optimum management practice scenarios can help decision and policy makers devise potential loss minimizing plans for Bangladesh.

1.2.3. Physical relationship between rice crop productivity and climate during the monsoon season. There is a significant lack of scientific work exploring interactions between the inter- and intra-seasonal monsoonal rainfall variations and rice productivity. Hence, the current study has been designed to monsoonal variations and rice crop productivity. Furthermore, there has been a major thrust in recent years towards understanding the planet earth as a system (Ghassam and Dozier, 1994). This new approach is providing the basis for a significant number of interdisciplinary research projects. Application of the CERES-Rice model (instead of purely statistical indices) for variable monsoon

a)



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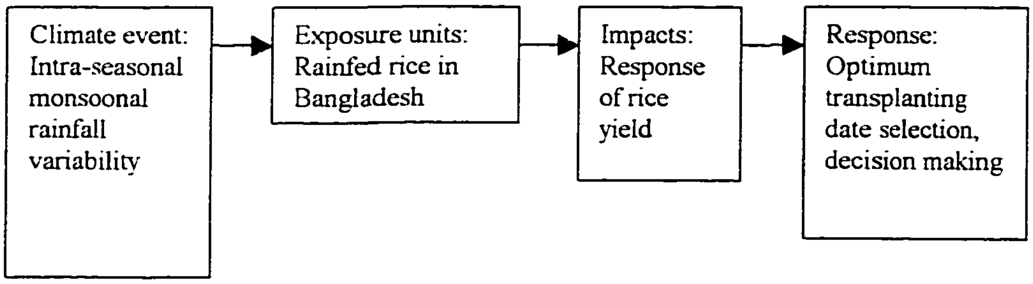


Figure 1.3. Kates' (1985) framework for climate impacts studies (a); Kates' framework and components as adapted to the study of Bangladesh (b).

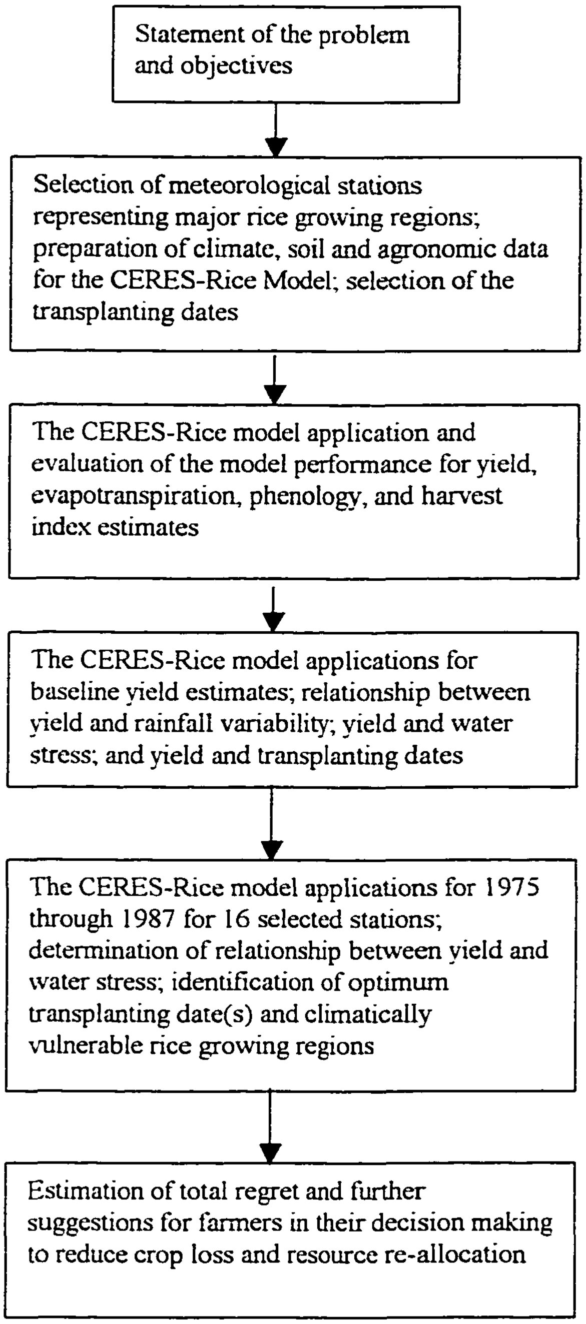


Figure 1.4. Flow chart of various components for the Bangladesh study.

scenarios represents a step in this direction.

1.2.4. Model applications for rainfed conditions. A large number of modeling studies have focused on the impacts of weather variability on dry season irrigated rice. Moreover, by providing optimum management, it is possible to reduce losses of irrigated rice (as a result of temperature variability) to a minimum level. Hayes *et al.* (1982a) noted that with an optimum supply of water, 85% of maximum yield still can be attained under abnormal weather and soil conditions. It is also known that the timing of the availability of water is crucial for optimum rice yield. Application of the models for irrigated rice growing under optimum management did not permitted us to study the impacts of growing season rainfall variations on rice plant growth and productivity. Hence, this current application of the CERES-Rice model for rainfed rice during monsoon season will fill the void in the scientific literature related to rainfall variations and productivity.

It is important to note that despite the availability of a 'state-of-the-art' CERES-Rice model, it has never been applied extensively to estimate rainfed rice productivity in a dynamic environment such as the Indian summer monsoon. However, its application has been demonstrated in a limited way by Karim *et al.* (1996) and Hussain (1995). Karim *et al.* (1996) applied the CERES-Rice model for 2xCO_2 conditions to estimate rice yield while Hussain (1995) applied it for a few selected stations to determine impacts of various levels of fertilizer applications. These studies used daily weather data interpolated from the monthly means as inputs to the model.

1.2.5. Regional-scale estimation of rice yield. Terjung *et al.* (1985) correctly noted that there is a significant scarcity in regional scale systematic studies that estimated yield. Many systematic studies estimating crop productivity, evapotranspiration, and irrigation water requirements are actually site-specific. The estimation of yield and related parameters for 16 sites can be used in future as a baseline to identify climatically vulnerable rice growing regions in Bangladesh.

CHAPTER 2

BACKGROUND

2.1. The agro-ecological setting of rice farming in Bangladesh

Bangladesh is a deltaic country located in eastern South Asia and at the confluence of the three great rivers---- the Ganges, the Brahmaputra, and the Meghna. The annual monsoon rain supplies ample surface water during the summer monsoon months (June-October) through the hundreds of rivers and channels of Bangladesh. The storage of groundwater gets renewed every year by the monsoon rains and provides a very large potential source of irrigation water along with the surface water sources during the non-monsoon months. Currently, only 25% of the potential ground water is utilized in Bangladesh for irrigation (Rogers *et al.*, 1989).

Farming in Bangladesh is largely subsistence in character. A survey by the Bangladesh Bureau of Statistics (BBS) showed that the net cultivated area for all crops in Bangladesh during 1984-85 was 8.64 million hectares and the total cultivated area was 13.15 million hectares (BBS, 1989). About 90% of the land use in Bangladesh is under the category of farming, and 78% of the cultivated land is used for rice production (Choudhuri, 1988). As in many other South and Southeast Asian nations, rice is the staple food in densely populated (785 person km^{-2}) Bangladesh; food production and rice production are synonymous.

Bangladesh's loamy alluvial soils are suitable for puddling, which is essential for rice cultivation. The hydroclimatic environment determines the availability of water during different growth stages of various rice crops. Soil fertility gets renewed every year largely by nutrients carried by flood waters from the over-flowing rivers during the monsoon. Bangladesh produces three major rice crops-- the *aus*, the *aman*, and the *boro*, each with different lengths of growing seasons and growing-season climate conditions (Table 2.1).

Table 2.1. Important features of climate of Bangladesh during the three rice crop growing seasons.

Rice cropping seasons	T_{max} °C	T_{min} °C	S_{rad} MJ m^{-2} day^{-1}	Precipitation mm
Aus (Mar-Aug)	34-31	16-26	14-23	1200-3100
Aman (July-Nov)	34-28	26-16	14-19	1250-3000
Boro (Dec-May/June)	24-34	10-26	14-23	250-550

Note: T_{max} = mean maximum air temperature; T_{min} = mean minimum air temperature; S_{rad} = solar radiation. Range of values for T_{max}, T_{min}, and S_{rad} represent respective increase and decrease as rice growing season progresses. Precipitation shows seasonal total (mm) with regional variation.

The *aus*, the *aman*, and the *boro* rice growing seasons are nearly synchronized with the three different climatic seasons namely, the spring (March-May), the summer monsoon (June-October), and the dry winter (November-February), respectively. Thus, rice production and yield in Bangladesh is largely dependent on the intra- and inter- seasonal behavior of the climate. For example, in 1987 and in 1988 the aus and the aman yields were greatly affected by severe flooding. The boro rice yield was also affected by severe drought in 1989.

It is important to note that the *aus*, the *aman*, and the *boro* rice crops constitute nearly 20%, 54%, and 26%, respectively, of the total annual rice production (BBS, 1989). The farmers of Bangladesh typically cultivate the *aus* rice crop on the highest agricultural lands (3.1-5.0 meters above sea level), the *aman* on the medium high (1.1-3.0 meters above sea level) agricultural lands, and the *boro* on the lowest (0.0-1.0 meter above sea level) agricultural lands.

2.2. Importance of rice in Bangladesh's agriculture and socio-economic structure

Hossain (1984) reported that the *aus*, the *aman*, and the *boro* production increased, on average, 2.4%, 1.3%, 8.8%, respectively, per year between 1949 to 1984. In other words, in spite of the annual floodings during the summer monsoon and weather anomalies during the pre- and post-monsoon seasons, rice production has increased moderately over the last four decades. This progress has been achieved due to the rapid adaptation of high yielding varieties (HYV) of rice by Bangladeshi farmers, increased use of fertilizer and pesticide, and increasingly accessible irrigation facilities for the dry winter season and hot and dry pre-monsoon months. In 1976-77 1,216,000 hectares of agricultural lands were provided with irrigation water by using both modern and traditional methods. In 1980-81 1,639,000 hectares of agricultural land were supplied with irrigation water and in 1984-85, this figure rose to 2,074,000 hectares. Furthermore, in 1962-63, 27,000 metric tons (2.5 kg ha^{-1}) of synthetic fertilizer were applied to agricultural lands of Bangladesh. In 1975-76 this figure increased to 216,000 metric tons (15 kg ha^{-1}); in 1980-81 to 420,000 metric tons (32 kg ha^{-1}), and in 1983-84 to 544,00 metric tons (36 kg ha^{-1}) (Choudhuri, 1988).

However, successes in the agricultural sector over the last four decades in Bangladesh are not sufficient to sustain the fragile economy where the population growth rate is 2.5% per year (Kurian, 1992). Increasing grain production is barely maintaining, an equilibrium situation between life and death for most of this immense population (125 million). It is important to note that the rate of increase in yield in Bangladesh is relatively low compared to the other major rice-growing countries. Over the last four decades, per hectare rice yield in Bangladesh has increased 50% compared to 150%, 105%, 82% in Indonesia, India, and Pakistan, respectively. Meanwhile, the world rate has been about 120% (The Bangladesh Observer, 1988).

In addition to this grim picture, crop failure due to climatic fluctuations can wreak havoc on the economy. For example, rice farming provides employment for a large portion of the population in Bangladesh. Employment is higher in the rural rice farms during land preparation and harvesting stages. Hence, crop loss means less employment during harvesting seasons (Rahman, 1981). In addition, drought or unseasonable heavy rainfall and resultant flooding during land preparation stages forces farmers not to sow certain seasonal rice varieties and this results in cutback of potential employment opportunities.

Another issue related to the rice economy of Bangladesh is the question of availability and intake of food and the nutritional status of the population. Abdullah (1989) found that household food consumption increases significantly during post harvest seasons and this results in improvement in the nutritional status of the population. Since rice constitutes the major share of food intake and nutrition, it is important to maintain high rice yields and to keep production steady (which is largely dependent on climate and other environmental and socio-economic factors). Furthermore, the level of production and yield of rice influence the buying capacity of families and food security. The World Bank (1986) noted that the immediate availability and ability to buy food are the key components of food security. One of the important steps to satisfy the above requirements would be the fulfillment of market demands by increased food production and efficient supply to the market. This will keep the price stable, which is very important for millions of poor families. Mellor (1990) found that India's top 5% population of income distribution spends over two and a half times more money per capita annually on food grain purchasing for household consumption compared to the lowest 2%. It is important to note that the upper income classes allocate only 15% of their total expenditures to food grains while the lower income classes spend 54% of their total expenditures for the same purpose. From personal experience, the situation in Bangladesh is not very different from that in India.

Mellor (1990) also noted that the price of food increases rapidly when production declines. As a result the lowest income families experience a decline in real income since they spend larger shares of their income for buying food. On other hand, the upper income families experience an increase of income with rapidly rising food price as they largely control food markets and spend much less of a portion of their income to buy food compared to low income families. This situation readily creates a threat to the food security and causes social unrest.

Kurian (1992) reported that 86 percent of the population in Bangladesh lives below the poverty line. Thus, food security and steady food production is critical in keeping the already fragile socio-economic structure together. Since rice is the staple food and the dominant source of nutrition, it is crucial to have an adequate production and supply of rice in Bangladesh to maintain food security. In the context of these intense socio-economic pressures, it is very important to determine the affects of climatic fluctuations on the rainfed *aman* rice yield in a multiple cropping environment to minimize losses in the future. As noted previously, the CERES-Rice model is applied here to estimate the impacts of intra-seasonal rainfall variations on the *aman* rice productivity. The CERES-Rice model has been successfully applied to other important crop-growing region of the world (*cf.*, Rosenzweig and Parry, 1994).

2.3. Monsoonal rainfall variations and rice production

Climate plays a vital role in determining crop production and optimum yield (Lockwood, 1985; Sakamoto *et al.*, 1980). Sah (1987) estimated that South Asia produces 65 percent of its grain output during the summer monsoon and that success is critically dependent on the timing of the onset of the monsoon and its associated heavy rainfall. Seven rain-less days during the early part of the summer monsoon season after transplanting of rice seedlings can cause severe moisture stress which could potentially destroy up to 60% of the rice crop. This type of loss occurs frequently in different parts of the South Asian subcontinent. By contrast, an early arrival of the summer monsoon and the associated heavy rainfall also can be detrimental to young seedlings because they are still unable to cope with the deep flood water. Moreover, a late departure of the monsoon can significantly disrupt the maturing and harvesting and results in reduced yield.

Shukla (1987) examined dates for the onset of the monsoon over southern India (the state of Kerala) from 1901 through 1978 and found the onset ranges from May 11 to June 18 (a 38 day period). Moreover, he found that fluctuations in the arrival date of the monsoon of even a week can have an important effect on rice productivity. Similarly, departure dates for the monsoon vary from September 25 to October 20 (25 days) and also have important effects on rice yields (Das *et al.*, 1987; 1988; Ramasastry *et al.*, 1983; 1984; 1985; 1986). These detrimental effects include wet fields and cloudy skies (increased pest infestations) which are harmful for maturing and harvesting stages.

Mowla (1978) showed the relationship between annual rainfall and rice production and loss between 1951-1974 in Bangladesh. He found that the increases and decreases of seasonal rainfall significantly influence rice production.

Tanaka (1978) noted that anomalous (both high and low) rainfall with a standard deviation of +1.5 or -1.5 from normal was a cause of the bad harvests in Bangladesh. He explained the relationship between the large-scale atmospheric fluctuations and their impact on rainfall and rice yield in monsoon Asia by studying the correlation of rainfall between different parts of monsoon Asia and developing a Seasonal Monsoon Index based on these correlation coefficients for June, July and August. This index estimates the pattern of correlation coefficient variation among different regions. The correlation of the Seasonal Monsoon Index with national rice yield showed that Bangladesh, India, and Thailand were significantly influenced by large-scale precipitation fluctuations. Garnett and Khandekar (1992) presented a statistical analysis of the relationships between anomalies in large-scale atmospheric circulation, the Indian Monsoon, and worldwide grain yield including India. They found that an ENSO event results in low grain yield in India and Australia and high grain yield in North America due to unfavorable and favorable weather conditions, respectively.

Interestingly, these studies of Mowla (1978), Tanaka (1978), and Garnett and Khandekar (1992) have exclusively used seasonal total rainfall to estimate rice productivity and excluded the intra-seasonal variability of the monsoon. Such simple indices fail to include the dynamic relationship between the monsoon and rice plant growth. In addition, rapid changes in land-surface conditions associated with the precipitation amount, intensity and temporal distribution and their impacts on the soil-plant relationship are not represented properly in such simple analyses. For example, Krishnamurti *et al.* (1989) showed that during 1987, the monsoon arrived late and early-season precipitation was below normal. But later, part of the monsoon of 1987 was marked by excessive rainfall (seasonal total rainfall was record breaking for most of the northeastern region of South Asia) which caused one of the worst flooding events in the recent history of northeastern India and Bangladesh. In situations such as this, intra-seasonal rainfall variability, rather than just the seasonal total (and indices based on seasonal total rainfall), would help to understand the relationships between rice crop growth and weather. As a result, this study investigates the impacts of intra-seasonal rainfall variations and their impacts on rainfed rice yield. The CERES-Rice model application also shows whether variable intra-annual weather patterns in Bangladesh influence various growth related parameters and which, in turn, affect productivity.

2.4. Monsoonal rainfall variations, impacts assessment, and response to minimize crop loss

Response farming, also known as short-term adjustment (as opposed to long-term adjustment or adaptation), can be satisfactorily applied to reduce crop loss due to abnormal rainfall during current crop growing season (*cf.*, Stewart, 1991). Stewart conducted a field study in Niamey, Niger and proposed a series of response scenarios to minimize crop loss. It is important to note that two types of adjustments exists — incidental and purposeful (Kates, 1985). When adjustments are made to cope with one or a series of problem(s) and they reduce vulnerability beyond their target, they are known as 'incidental adjustments'. For example, application of fertilizer for a particular crop may become beneficial to another crop, to be cultivated in the same land. On the other hand, purposeful adjustments accept losses and distribute the impacts to other sectors. For example, when crop failure becomes evident to a farmer in the middle of a growing-season, he/she may decide not to invest further for field management for this particular crop. Rather he/she decides to invest more on the next crop.

Jodha and Mascarenhas (1985) conducted a study on farmers' adjustment strategies under variable rainfall condition in India and Tanzania. They noted that farmers' adjustment strategies are connected to their perception of climate variability. Under rainfed subsistence farming conditions, rainfall and its amount, timing, and duration are the pre-dominant climate/weather variables that influence farmers' response strategies for adjustment. It is important to note that farmers start thinking about adjustment strategies after they experience unusual weather conditions (Jodha and Mascarenhas, 1985).

Under abnormal growing-season weather conditions farmers adopt largely two types of measures: risk/loss minimizing measures and risk/loss management measures. Risk/loss minimizing measures include salvage operation, mid-season corrections, and adjustments in operation, and cutback on resource use. On the other hand, risk/loss management measures include reduction in current commitments, resource augmentation, supplementary earning, and asset/inventory depletion. In addition to the farmers' mid-season adjustment, institutions also can generate various adjusting options to cope under abnormal weather condition. Jodha and Mascarenhas (1985) suggested that these options should not be substitute for existing strategies rather they should be additional alternatives.

Climate impact assessment studies provide an opportunity for both farm level and institutional decision makers to understand the true nature of the vulnerability of agriculture to extreme climate and weather conditions (*cf.* Stewart, 1991; Easterling *et al.*, 1993; and Kunkel *et al.*, 1995). This type of exercise may also enable institutional level decision-makers to devise appropriate adjustment strategies (in addition to farmers' own experience-based responses). Kates (1985) proposed an impact model for climate impact assessment that consists of four sets of study elements including climate events, exposure units, impacts and consequences, and adjustment responses. In the present study monsoonal rainfall variations are recognized as climate events, rainfed rice farming is the exposure unit, variations in rice productivity under abnormal conditions are impacts and consequences, and proposed management practices are adjustment responses (Figure 1.3a and b). Kates (1985) also noted that a significant absence of literature exists vis-a-vis scientific studies addressing climate impacts in developing nations. This observation is still largely correct even now. In addition, developing nations are significantly more vulnerable to abnormal climate conditions. Successful mitigation of the climate related damages require climate impacts assessment and resulting response strategies. By studying the impacts of abnormal monsoons on rainfed rice and devising suitable management practices, especially planting dates, for minimizing crop loss, this research project fulfills some of the void in scientific literature.

Scenario analysis using crop models can be very useful for assessment of climate impacts on agriculture and subsequent response strategies. Model applications to various scenarios provide a longer lead time for impact analysts and decision makers to identify the impacts of variable weather conditions and develop response strategies (Lave and Epple, 1985). Impacts of various weather/climate scenarios on agricultural productivity can be performed in a number of ways. For example, we can use weather data from past extreme conditions as scenarios. In the present study I use data from 1975-1987 to examine the impacts of intra- and inter-seasonal variations of monsoonal rainfall and monsoon arrival and departure dates on rice plant growth and production. Furthermore, planting dates are selected as a response to these extreme conditions to minimize additional crop loss.

2.5. Crop-climate models for impacts studies

International concern about weather anomalies and resultant crop loss and hunger greatly galvanized the efforts to improve existing agro-climatic models and to develop new models for impact analysis, long-term planning, and operational use (Baier, 1983). These models can help to improve our understanding of climate variations and their interactions with local crop growth and crop productivity, and help farmers to adopt more suitable adjustment strategies. Furthermore, Baier (1983) noted that crop yield models are able (1) to assess potential crop productivity related to climate, (2) to monitor crop condition based on available current data, and (3) to determine impacts of climate variations.

Since the soil-crop-atmosphere system is complex and composed of many biological, physical and chemical processes, various types of models with different resolution, scope, and diagnostic and predictive abilities have been introduced (Terjung *et al.*, 1985). Most of these models can be grouped into two categories which represent the two ends of a modeling type continuum. One group represents empirical regression models which assume linear relationships between crop yields and environmental variables. Some examples of this type of model to predict rice yield can be found in the works of da Mota and da Silva (1980), Huda *et al.* (1975), Thompson (1975), Yao and Le Duc (1980). The empirical regression models are only applicable to the specific time and locations for which they were derived (Katz, 1977; Bakema and Jansen, 1987). The success of these models depends on the 'representativeness of the input data, the selection of variables and the design of the model' (Baier, 1983). Also, statistical models do not explain cause-and-effect relationships. However, when data availability is restricted and the need of interpretation of climate in terms of crop management is immediate, the empirical regression model can be very useful.

The other end of the continuum represents deterministic plant growth simulation models. Examples of this type of models include the Rice Clock Model of Gao *et al.*, (1992), the CORNGRO model of Childs *et al.* (1977) and revised by Kundu *et al.* (1982), the RICEMOD model of McMennamy (1980), the GRORYZ model of van Keulen (1978), the CERES-Rice model (Ritchie *et al.*, 1987), the MACROS model of Penning de Vries *et al.* (1989), RICESYS model by Graf *et al.* (1990a and 1990b and 1991) and the works of Angus and Zandastra (1980) and Angus *et al.* (1990). The deterministic models are based upon the transfer of energy and mass within a multi-layered crop canopy and include the major plant physiological processes of photosynthesis, respiration, transpiration, and partitioning of photosynthates within plant storage sites (Hayes, 1982a). These models are sensitive to weather and management practice and are able to simulate daily growth and development of crop plants as they respond to daily weather conditions. In addition, this allows impact analysts to identify relationships among certain environmental conditions and crop growth. Moreover, deterministic crop models help to organize current information and to test hypotheses related to soil-plant-atmosphere interactions (Baier, 1983). Also, they can guide in explaining various field problems and limiting factors for crop growth and productivity. The input requirements of these models are usually very demanding. As a result, they are not easily applicable to regional studies despite many of the environmental and physiological processes involved in the growth of crops that can be satisfactorily summarized by these models.

Rosenberg (1982) recognized the need for the development of hybrid or parametric models which would combine both empirical and deterministic methodologies and enable scientists to study large-area crop productivity and water use with a reasonable degree of explanatory power. The YIELD model of Hayes *et al.* (1982a, 1982b), the PADIWATER model of Bolton and Zandastra (1981), and the wetland rice model of Angus and Zandastra (1980) represent such hybrid models. It should be noted that although most of the deterministic models had not been applied to estimate large area crop productivity, some attempts had been made to develop models that would be applicable to regional studies of photosynthesis and/or yield, for example, Baier *et al.* (1976) and Band *et al.* (1981).

2.6. Crop-climate model-based studies in geography

Research in this particular area in geography was pioneered by Werner H. Terjung of the University of California, Los Angeles and his collaborating graduate students. They have developed a hybrid crop model for regional studies which is able to simulate growth and end-of-the season productivity of 11 crops (*cf.*, Hayes *et al*, 1982a and 1982b). Furthermore, Terjung and his collaborators understood and emphasized the need for regional-scale application of crop models to estimate impacts of climate. As a result, Terjung and his associates applied their model in

China, Korea, Australia, the North American Great Plains, and California to estimate impacts of climate change and climate variations on grain yield, crop water requirements, crop's water use efficiency, and growth indicators (*cf.*, Burt *et al.*, 1980 and 1981; Liverman *et al.*, 1986; Terjung *et al.*, 1982, 1983, 1984a, b, c, d, e, f, and g, 1985, 1989; and Todhunter *et al.*, 1989). It is important to note that Terjung *et al.* initiated crop model-based studies on the impacts of climate change in the mid-70s when it was not the trend.

In the 1980s and 1990s crop-climate model-based studies have been continued by some of Terjung's students and other geographers. Easterling *et al.* (1993) conducted a major study estimating the impacts of climate change on the crop productivity in the Great Plains of the United States. They have applied the EPIC (Williams *et al.*, 1984) model to estimate regional productivity and used 1930s climate data as analogue to climate change conditions. This study is popularly known as the MINK (Missouri, Iowa, Nebraska, and Kansas) study. Some of the significant contributions of this study include yield estimates after farm-level adjustments under enhanced CO_2 condition, inter-industry linkages, and economic analysis of the impacts.

The most notable contribution of Mearns and her collaborators is the investigation of daily and inter-annual variability of climate and their impacts on the crop-productivity. She and her associates used modeled weather data with various degrees of variability to conduct their tests for major crop growing regions of the United States for current and changed climate conditions (*cf.*, Mearns, 1992; Mearns *et al.*, 1992 and 1996). Furthermore, Mearns and her associates are currently completing a series of studies on the crop-climate relationship under changing climate conditions (Mearns, 1997). These include, for example, development of scenarios from regional/global climate model outputs for various research groups, further studies on the high frequency variability under enhanced CO_2 conditions and their impacts on the crop productivity, and up and down-scaling of observed and GCMs generated climate data and yield estimates (Mearns, 1997).

It is clear that a number of significant studies focusing on crop-climate relationships have been conducted in geography. However, most of these studies were performed for technologically advanced and climatically less vulnerable mid-latitude agricultural systems. On the other hand, there is a significant need for scientific studies on the crop-climate relationships in technologically less advanced and climatically more vulnerable tropical regions. Hence, this study not only addresses this need but also helps to improve our knowledge in crop-climate relationships under monsoonal conditions.

CHAPTER 3

THE CERES-Rice MODEL

The CERES-Rice model is representative of the current array of advanced physiologically-based rice crop growth simulation models. CERES-Rice has been widely applied to understand the relationship between rice and its environment (Bachelet and Gay, 1993; Rosenzweig and Parry, 1994). Bachelet and Gay (1993) applied this model to determine impacts of climate change in Asia. Rosenzweig and Parry (1994) investigated impacts of climate change on world- wide crop productivity by using the CERES-Rice and several other crop climate models. In addition, this model has also been successfully applied to a number of country/regional studies to estimate the impacts of climate change on rice productivity (*cf.*, Baer et al., 1994; Escano and Buendia, 1994; Tongyai, 1994; Barry and Geng, 1995; Jin *et al.*, 1995; Seino, 1995; and Singh and Padilla, 1995). It is important to note that the CERES-Rice model is variety specific (e. g., BR11) and thus, is able to predict rice yield and rice plants response to various environmental conditions more accurately.

The model assumes that cultivar, soil water conditions, and crop management are primary influences on rice productivity (Bachelet and Gay, 1993). Climatic data requirements include daily precipitation, daily maximum and minimum air temperature, and daily solar radiation. CERES-Rice also requires information on soil characteristics to calculate evapotranspiration and other components of water balance, and detailed information on management practices which include cultivar, planting date, plant density, sowing depth, and nitrogen fertilization (Ritchie *et al.*, 1987; Tsuji *et al.*, 1994; Hoogenboom *et al.*, 1995; and Hunte and Boote, 1998).

Table 3.1. Selected input data requirements for the CERES-Rice model (modified from Ritchie *et al.*, 1987; and Tsuji *et al.*, 1994).

Weather data:
Daily maximum and minimum air temperature
Daily Precipitation
Daily solar radiation
Pedological-hydrological data:
Soil classification
Texture
Number of layers in soil profile
Slope
Permeability
Drainage
Soil layer depth
Soil horizon
Clay, silt, and sand content
Bulk density
Saturated hydraulic conductivity for each soil layer
Total nitrogen for each layer
pH of the soil in water for each layer
Root quantity for each layer
Agronomic:
Transplanting date
Row spacing
Number of plants per hill
Number of plants per square meter
Age of seedling
Base temperature to estimate phenological stages
Floodwater depth
Fertilizer application dates, amounts
Planting depth

The CERES-Rice model assumptions and key aspects of the model components have discussed in detail in a number of studies (*cf.*, Ritchie *et al.*, 1987, 1998b; Singh, 1992; Singh and Padilla, 1995; Godwin and Singh, 1998; and Ritchie, 1998a). As a result, the following discussion presents a summarized outline of the relevant sections (to this research project) of the model and it (discussion) is primarily based on the above studies. Moreover, since this study assumes an optimum supply of fertilizer, as recommended by the Bangladesh Rice Research Institute (BRRI), and focuses on the impacts of water availability, a description of the nitrogen sub-model will not be included in the following discussion. Therefore, the model description focuses primarily on the plant growth and water balance components.

3.1. Plant growth sub-model

In the CERES-Rice model, rice plant development consists of two different features. These include phasic and morphological development. Phasic development represents changes in growth stages and is related to significant changes in the biomass partitioning pattern. The model assumes the major growth stages are juvenile, floral induction, heading, flowering, grain filling, maturing, and harvesting. Completion of these growth stages is determined by accumulation of heat or growing degree-days. Growing degree-day (GDD) is calculated from equations 1, 2, and 3 by using a base temperature of 9°C. When daily mean temperature, T, reaches 34°C a high mean temperature cutoff function become activated and GDD values decrease linearly to zero at 44°C. These relationships can be described as follows:

$$GDD = 0.0 \qquad \text{for } T \leq 9 \text{ and } T \geq 44 \qquad (1)$$

$$GDD = T - 9 \qquad \text{for } 9 < T < 34 \qquad (2)$$

$$GDD = (44 - T)/10\ (34 - T) \qquad \text{for } 34 \leq T < 44 \qquad (3)$$

Morphological development includes the beginning and ending of various plant organ growth within a plant's life cycle, and temperature plays a key role in this morphogenesis. It is important to note that water and nutrient stress also affect plant morphological development. The CERES-Rice simulates development of roots, leaves, tillers, and grains. Phasic and morphological development have been separated to identify differences in impacts of water or nutrient stresses on these processes.

Beer's Law has been used to measure the solar radiation absorption. This can be expressed as follows:

$$I/I_o = \exp(-k \times LAI) \qquad (4)$$

where I/I_o is light transmission ratio, k is extinction coefficient for rice plant (0.625), and LAI is leaf area index. In this model potential dry matter production is a function of photosynthetically active radiation (PAR) which can be presented as follows:

$$DM_{pot} = RUE \times PAR \times (1\text{-}\exp(k \times LAI)) \quad (5)$$

where DM_{pot} is potential dry mattter production (g m^{-2}) and RUE is radiation use efficiency (g MJ^{-1}). The model assumes PAR (MJ m^{-2}) equals 50% of incoming solar radiation. The CERES-Rice adjusts potential dry matter production for thermal stress, water and nitrogen deficiency to estimate actual dry matter production.

It is important to note that LAI is not an input to the model. It is simulated as a function of leaf tip appearance rate and leaf expansion growth (thus it is temperature driven). CERES-Rice assumes that leaf and stem growth are proportional and the proportionality changes as the crop grows. Assimilates stored in the stem are used by the plants partly or totally for grain filling depending on the degree of environmental stress and resultant inadequate biomass production. In the beginning of a rice plant growth, a small fraction of assimilates gets partitioned to stems and it becomes large when leaf growth stops. Allocation of biomass into the root influences the density of roots and their efficiency in supplying nutrients to shoots. The amount of allocation of biomass to roots also depends on the growth stage. It has been assumed that the allocation of biomass to root decreases as the growing season progresses and the rice plant becomes mature. It is also presumed that partitioning to roots will increase under water or nitrogen stress during all of the growth stages except during grainfilling stage. It is important to note that the model maintains a constant proportionality between root mass and length through the whole growing season. Finally, end-of-the season rice yield estimation is the product of rice grain numbers (estimated from the panicle weight at maturity), individual kernel grain weight and the number of plants per unit area.

3.2. Soil water balance sub-model

The soil water balance sub-model of the CERES-Rice calculates infiltration, runoff, drainage and evapotranspiration. The CERES-Rice estimates runoff using a modified Soil Conservation Service Curve Number Technique. The difference between daily precipitation and runoff provides estimates of infiltration. Water content at the drained upper limit determines the drainage. To estimate potential ET, the model offers the option of using the Priestly-Taylor method (Priestly and Taylor, 1972),

$$ET_p = \alpha\, [\Delta/(\Delta+\gamma)]\, (R_n + S) \qquad (7)$$

Where ET_p is potential evapotranspiration, α is an empirically derived constant, Δ is slope of saturation vapor pressure curve, γ is psychrometric constant, R_n is net radiation, and S is soil heat flux. To estimate actual ET, Ritchie's method (Ritchie,

1972) has been incorporated in the model. Ritchie's method can be described as follows:

$$E = E_p + E_s\,(E_{so}) \qquad (8)$$

given

$$E_p = E_o(-0.21 + 0.70 * (LAI * 0.50) \qquad (8a)$$
$$E_s = \beta t^{1/2} - \beta(t-1)^{1/2} \qquad (8b)$$
$$E_{so} = [\Delta/(\Delta + \gamma)]R_{no} \exp -0.398*LAI \qquad (8c)$$

where E is total evapotranspiration from the soil and plant surface, E_p is transpiration from plant surfaces, E_s is evaporation from below canopy soil surface (when soil is drying), E_{so} is potential evaporation from below canopy soil surface, E_o = potential evaporation calculated from Penman method, t is number of days, β is a calculated coeffcient, dependent on hydraulic properties of soil. CERES-Rice estimates potential water uptake by roots and uses this parameter in conjunction with potential transpiration to calculate a water stress deficit factor. This water deficit factor is the ratio of potential root water uptake to potential transpiration. This factor ranges from 0 to 1 and represents absence and the highest water stress, respectively. The following chapters show the relationship between various degrees of water stress and end-of-season yield.

3.3. Additional aspects of the model and yield estimate

The model integrates conditions measured with a daily temporal resolution over the duration of the growing season to estimate yield. In addition, the model is able to simulate rice plant physiological processes and the phasic growth of the rice plant and soil-water balance at a daily temporal resolution. This allows identification of plant responses to various soil and atmospheric conditions and crop management practices.

After calibration of the CERES-Rice model (Chapter 5), it is run for the rice growing regions of Bangladesh to confirm that it represents actual rice ecological conditions. Subsequently, it is applied to average monsoonal conditions to establish baseline estimates (Chapter 6) and to variable monsoonal conditions (Chapter 7) to determine their impacts and selection of optimum transplanting dates.

CHAPTER 4

MONSOONAL RAINFALL CLIMATOLOGY AND SOILS OF BANGLADESH

Webster (1987: 269) noted: "Of all the major weather phenomena on earth, the monsoon systems of Africa, Asia and Indonesia-Australia are the most vigorous, persistent, and energetic, with circulation features that are readily identifiable over the entire Eastern Hemisphere during all seasons...... Despite variations in the intensity of the circulations from year to year, or in the amount of rainfall at any one location the annual monsoon cycle is most remarkable for its geographic and temporal consistency".

Considering this 'geographic and temporal consistency', the climate of Bangladesh can be divided into three seasons -- (1) the spring (March-May), (2) the rainy monsoon (June-October), and (3) the dry winter (November-February) (Choudhuri, 1988; Manalo,1976). As previously noted, the *aman* rice growing season extends from July to November. Thus, the *aman* rice growing season starts during the early part of the rainy summer monsoon season and persists through the early part of the dry winter season. The spring season and the dry winter season is the prelude and the epilogue, respectively, to the arrival and the withdrawal of the monsoon. As a result, this discussion on climate of Bangladesh starts with the spring season and continues with the summer monsoon and finishes with the winter season.

4.1. The Climate of Bangladesh

4.1.1. The spring season. The spring season is marked by violent thunderstorms, locally known as Nor'westers, that occur usually late in the afternoon or in the early evening(Islam, 1987; Choudhuri, 1988; Manalo, 1976). These thunderstorms are short in duration but intense in severity, with wind speeds of up to 96 km hr^{-1}. Most of the rainfall during this season is associated with these thunderstorms. The Nor'westers can cause temperature drops of 9°C to 11°C, and in extreme cases up to 17°C (Rashid, 1977). Most of the time these storms are accompanied by hailstorms; hail of up to 50 mm in diameter and in extreme cases up to 80 mm in diameter is not unusual. April is the hottest month with average monthly temperature ranges between 31°C to 37°C. May is usually wetter than March or April. A distinct feature of May is the development of violent cyclones in the Bay of Bengal, many of which hit Bangladesh and ravage coastal areas with high storm surges and heavy rainfall.

4.1.2. The onset of the monsoon and variable rain. The onset of the monsoon in Bangladesh during the month of June is marked by heavy showers which continues until the end of the season in October. A study by Talukder *et al.* (1988) reports that July records the highest number of days with precipitation (362 days). Two stations, Sylhet and Dhaka, receive the most rainfall during June (954 and 420 mm, respectively) while the rest of the representative stations receive maximum rainfall in July. It is important to note that Bangladesh receives 74% to 84% of its annual rainfall during the monsoon months (Islam, 1987). For example, Sylhet records an average rainfall of 2933 mm during monsoon months which is approximately 80% of the average annual total rainfall (3839 mm).

The early and late arrival of the monsoon may lead to the failure of *boro*, *aus* and *aman* rice crops (Islam, 1987). The early arrival of the monsoon and associated rainfall causes flooding of the *boro* and the *aus* rice fields which results in crop loss. B*oro* rice requires dry soils during the harvesting period and transplanted *aus* seedlings are still too young to cope with the heavy onrush of flood water. On the other hand, the late arrival of the monsoon causes a shortage of water needed for growing *aus* rice crop and for puddling of the *aman* rice crop. *Aman* rice crop is cultivated during the monsoon months. A late departure of the monsoon also adversely affects *aman* rice yields because it results in clouded skies, above normal rainfall during the end of the season, and excessively wet crop fields which are particularly detrimental during late season maturing and harvesting (Islam, 1987).

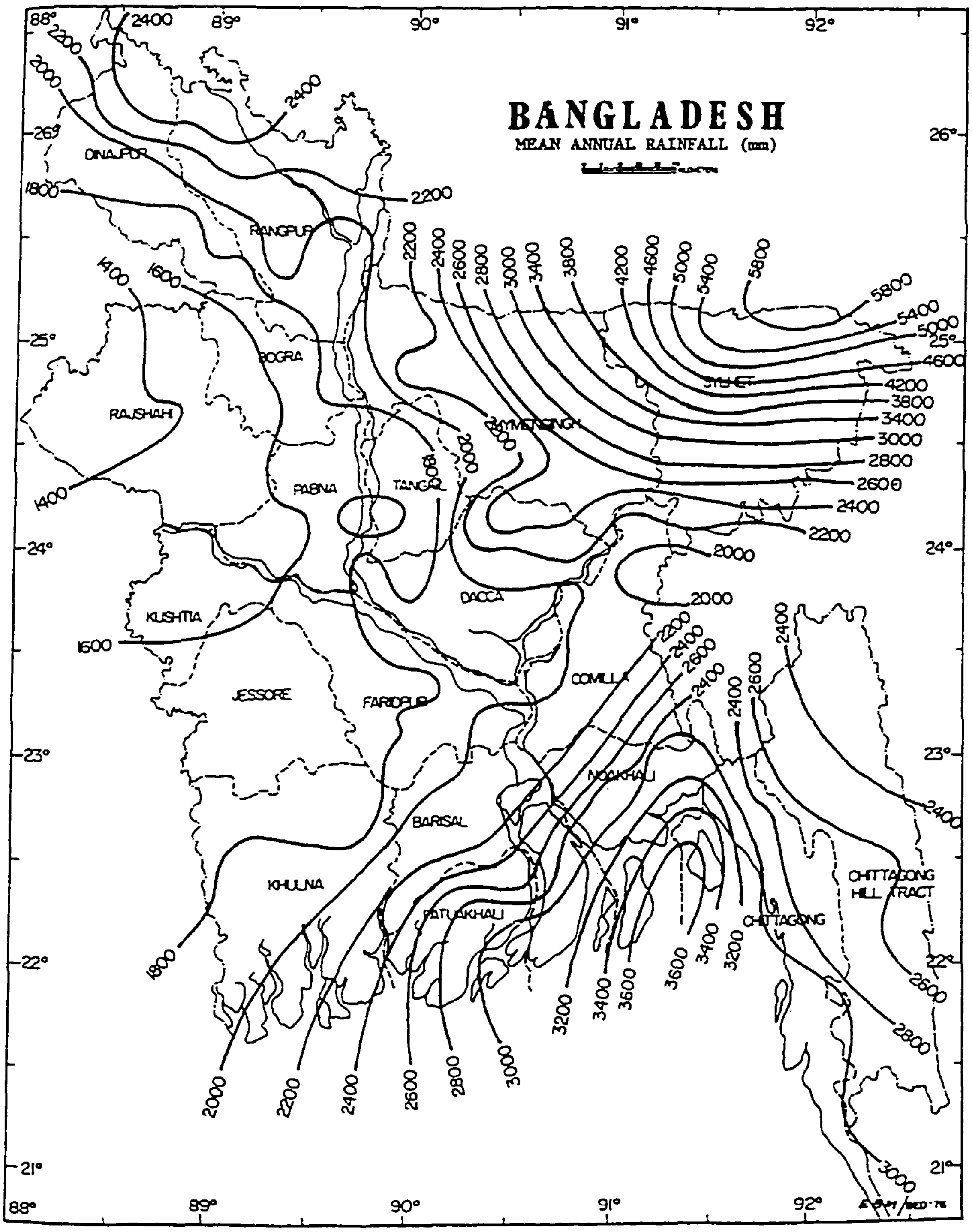
The onset of monsoonal rains over Bangladesh exhibits a regional pattern. It is characterized by an earlier arrival in the eastern region than in the western region (Das *et al.*, 1987; Ahmed and Karmakar, 1993). In the eastern part of the country the rains usually arrive during the very end of May or in the very beginning of June; in the western part of the country the monsoon sets in during any part of the first week of June. So, overall, the monsoon typically arrives between 30 May and 7 June in Bangladesh. However, it is important to note that the arrival date varies from one year to another (Table 4.1).

Table 4.1. Arrival dates of the monsoon in Bangladesh.

Year	Arrival date	Source
1982	June 17	Ramasastry *et al.*, 1983
1983	June 18	Ramasastry *et al.*, 1984
1984	June 4	Ramasastry *et al.*, 1985
1985	June 6	Ramasastry *et al.*, 1986
1986	June 16	Das *et al.*, 1987
1987	June 3	Das *et al.*, 1988

Ahmed and Karmakar (1993) reported that the monsoon arrival dates in Bangladesh may deviate up to 2 weeks. They have used a data set starting from 1958 through 1987. Lack of published data on the onset of the monsoon in Bangladesh is an impediment to more extensive evaluation of the variability of the monsoon arrival. However, it is possible to examine at the extent of the fluctuations of the onset dates of the monsoon from the long term record of the southern Indian state of Kerala India (presented in Chapter 3), since its long term average monsoon onset date coincides with the onset date of the monsoon for Bangladesh (Webster, 1987). The average complete withdrawal date of the monsoon from Bangladesh is the 2nd week of October. Ahmed and Karmakar (1993) have noted that the withdrawal dates fluctuated up to nearly 2 weeks from their mean.

The regional distribution of rainfall in Bangladesh shows a distinct pattern (Figure 4.1). Some of the hilly extreme northeastern parts of Bangladesh receive as much as 5800 mm rainfall annually while, in contrast, some of the extreme western parts of Bangladesh receive only 1400 mm of rainfall annually. Mean monthly rainfall for four representative stations (Figure 4.2a-d) have been prepared based on the long-term estimates provided by the Food and Agricultural Organizations (FAO, 1987) of the United Nations. These figures show that, for all four stations, monthly total rainfall increases gradually during the spring season and reaches to its maximum during the monsoon season. It is also shown in these figures that rainfall decreases as monsoon season progress. Monthly total rainfall decreases significantly after the departure of the monsoon. Sylhet and Jessore records the highest and the lowest seasonal total rainfall during the monsoon, respectively. Local orography results in such higher rainfall in Sylhet. In addition, June or July is the wettest month of the monsoon season for all stations. Manalo (1976) shows that Sylhet and Jessore also receive the highest and the lowest



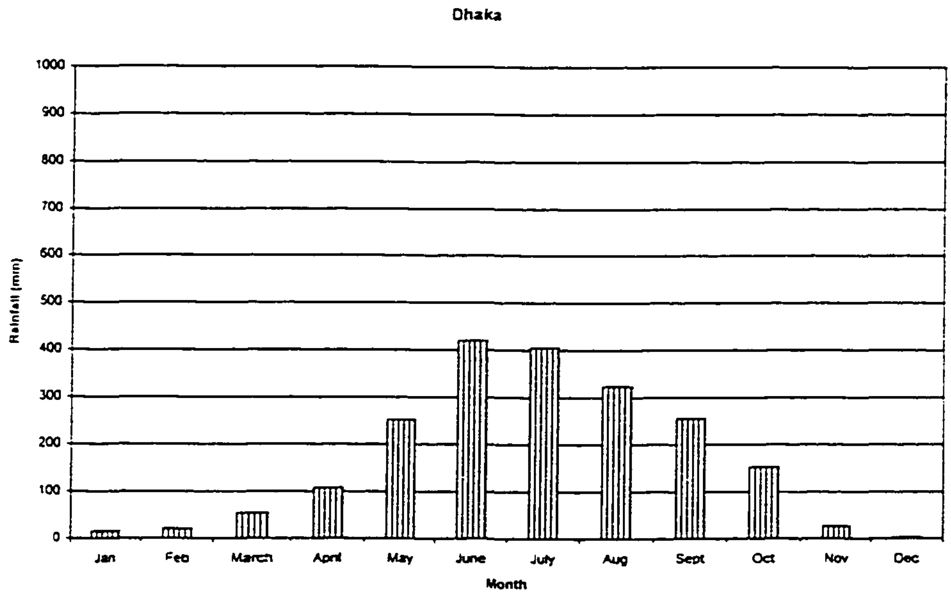
Adopted from: Manalo (1976)

Figure 4.1. Mean annual distribution of rainfall in Bangladesh.

seasonal total rainfall, respectively, during the spring. The northeastern parts of Sylhet experience as high as 1400 mm of rainfall while the western parts of Jessore record only 200 mm of rainfall during this season (Figure 4.3). Mean summer monsoon (June-October) rainfall shows high incident rainfall (4600 mm) in the northeast and lower rainfall in the west (1200 mm) (Figure 4.4). The mean winter rainfall distribution pattern is mapped in Figure 4.5 and it is not substantially different from that of the hot summer and the monsoon season. It is apparent that north- and south-eastern Bangladesh receive much higher rainfall than other parts of the country. Overall, the eastern part of the country is much wetter than the western part.

To further illustrate the intra-seasonal distribution of rainfall during a monsoon season, Talukder *et al.* (1988) presented examples from Dhaka using a rainfall time series starting from 1965 through 1980 that July experienced 13 events of above 300 mm rainfall while June August, September, and October recorded 9, 10, 5, and 1 such events, respectively (Table 4.2). This table also shows that June recorded 7 events of 200-300 mm of rainfall while July, August, September, and October recorded 2, 4, 5, and 4 such events, respectively. In addition, Talukder *et al.* (1988) showed that July records the highest number of rainy days in Dhaka (362) during the period 1965 through 1980 (Table 4.3). July also records the highest number of rainy day per month and the highest rainfall per rainy day.

a)



b)

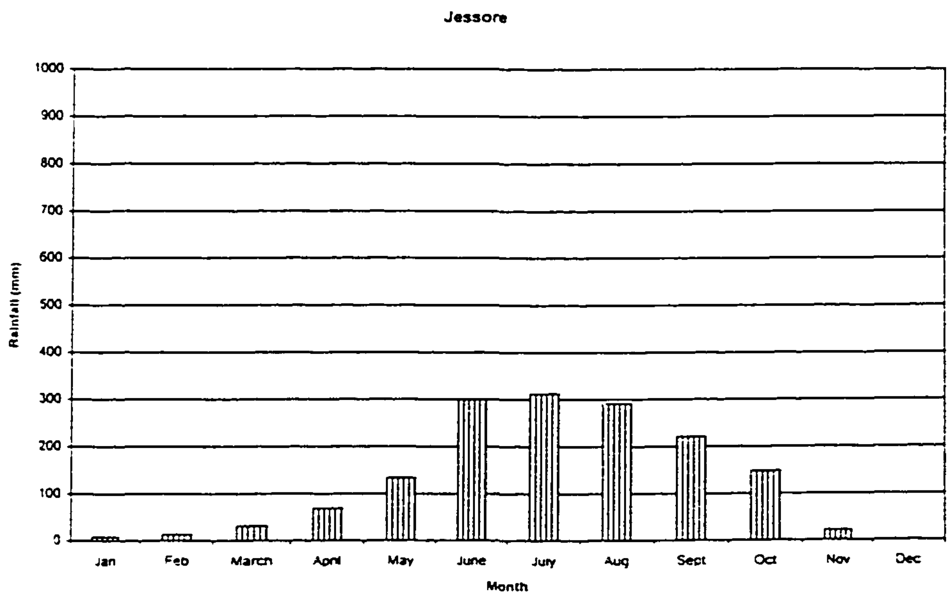
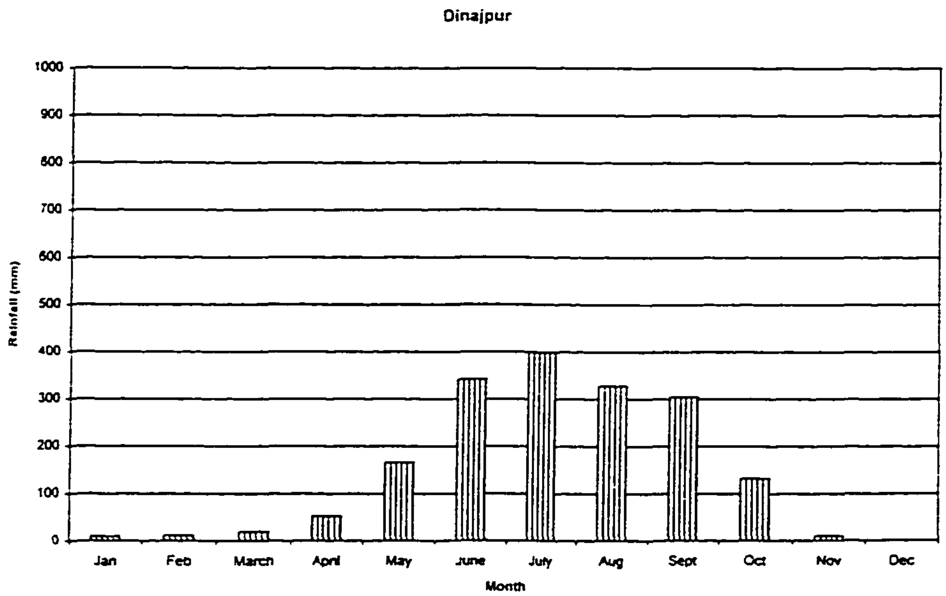
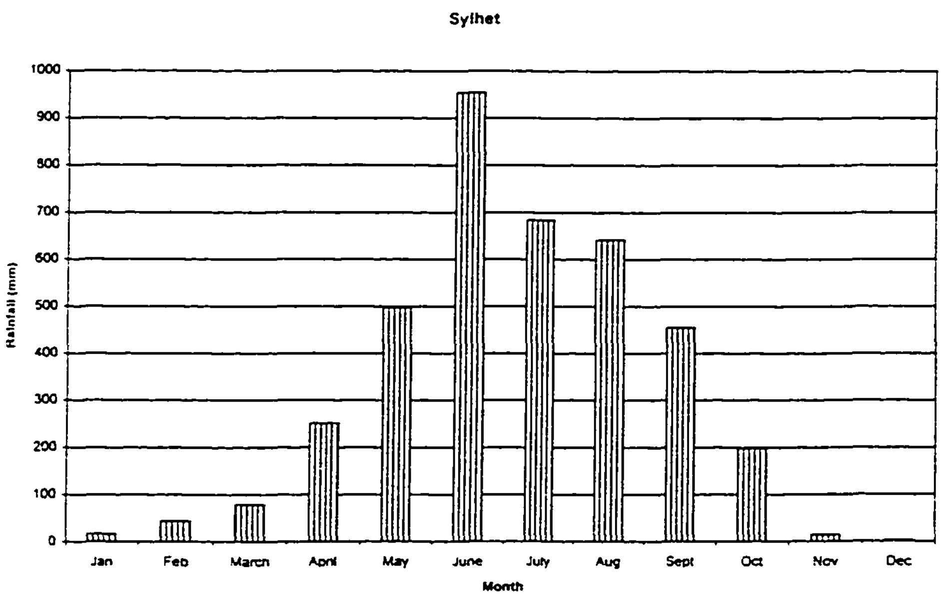


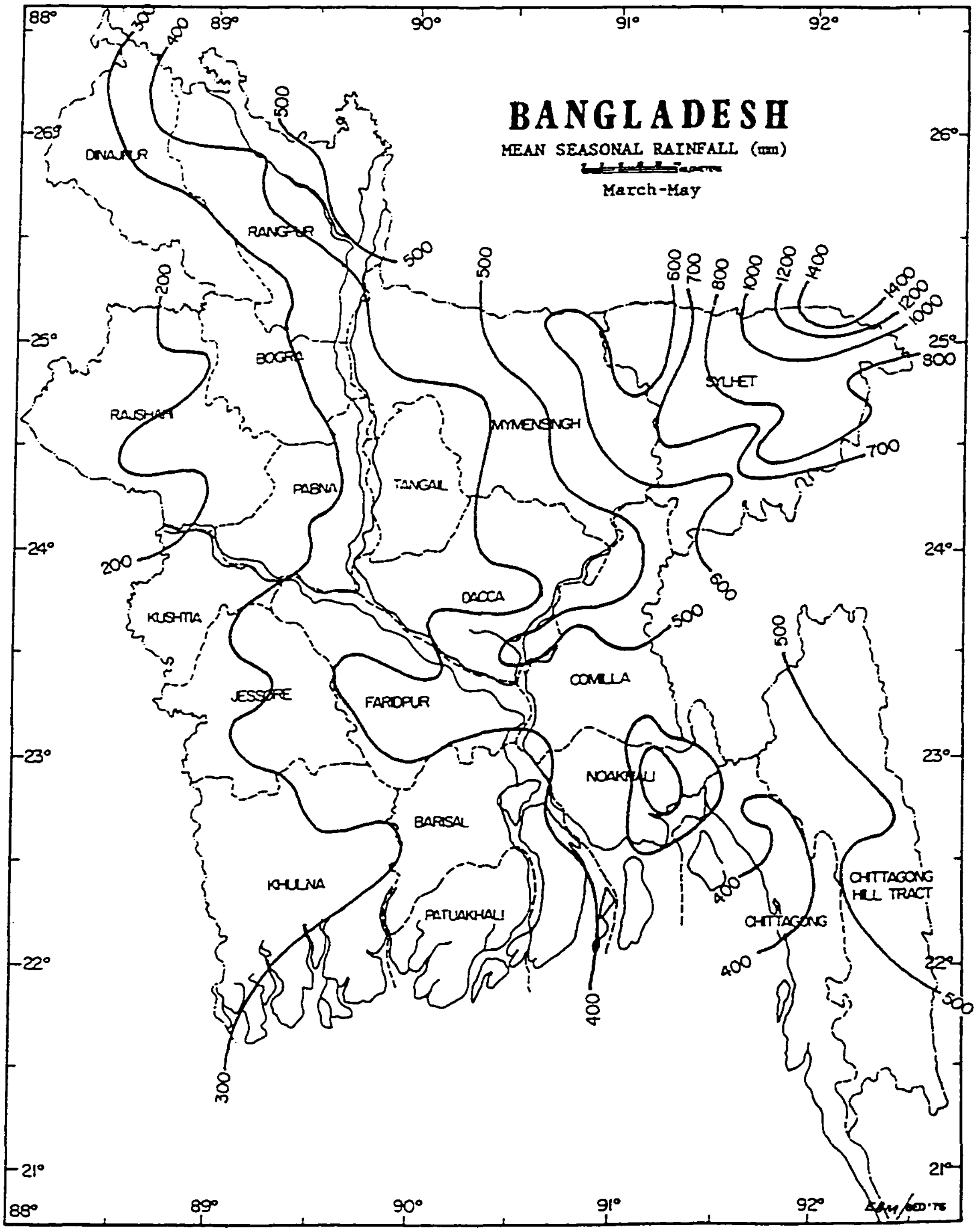
Figure 4.2a-d. Mean monthly rainfall for the four selected stations in Bangladesh.

c)


Dinajpur
Rainfall (mm)
0
100
200
300
400
500
600
700
800
900
1000
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec
Month

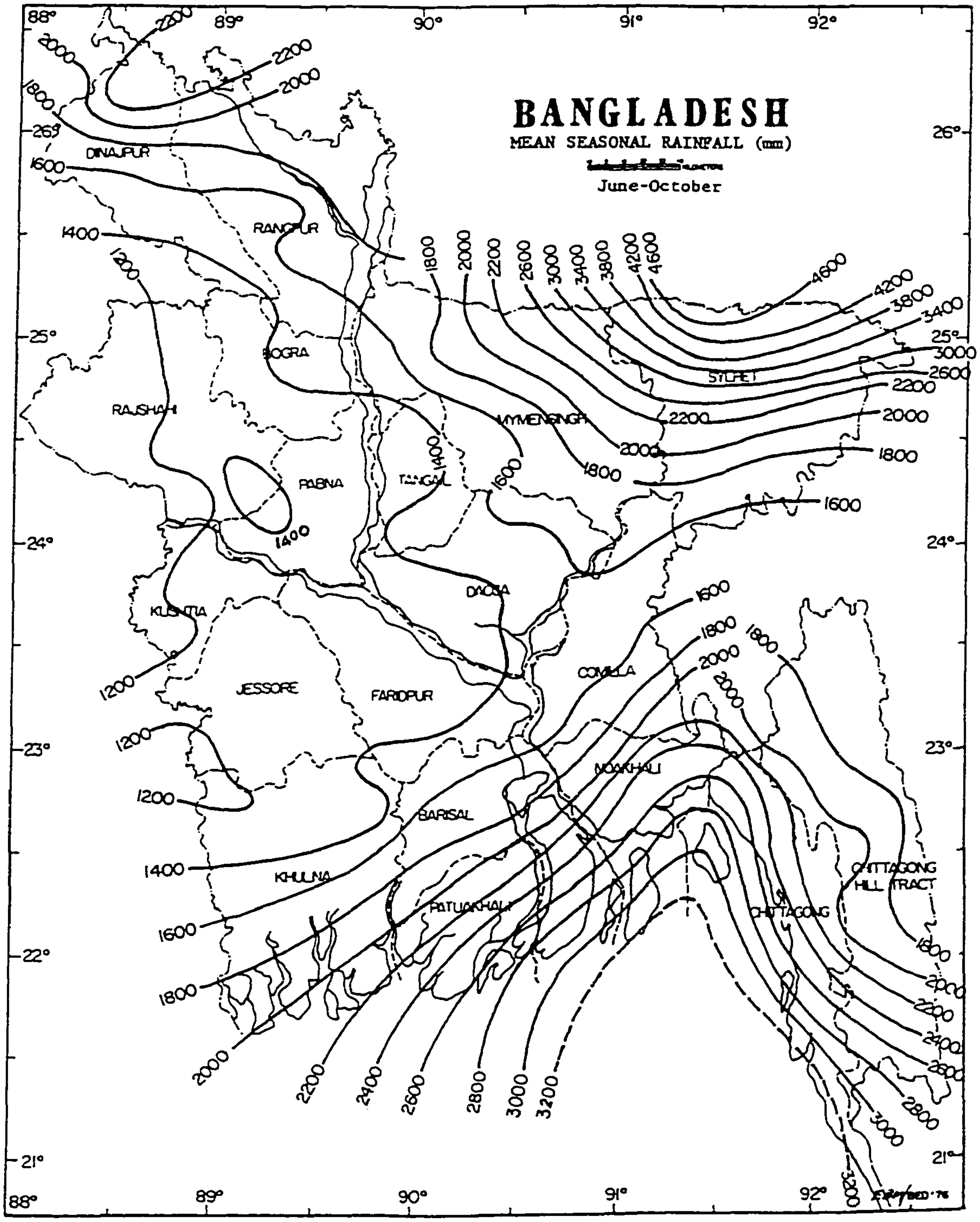
d)


Sylhet
Rainfall (mm)
0
100
200
300
400
500
600
700
800
900
1000
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec
Month



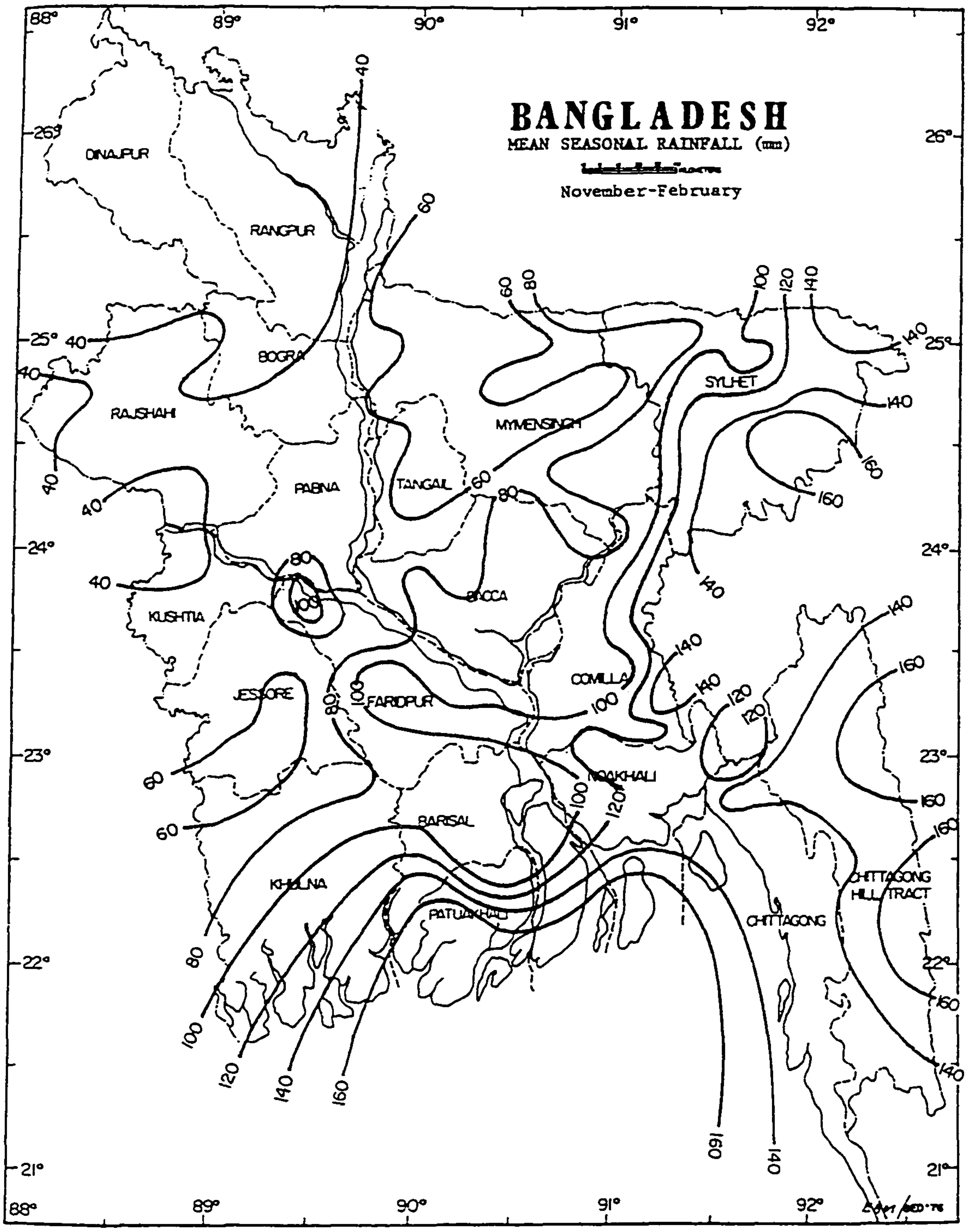
Adopted from: Manalo (1976)

Figure 4.3. Mean spring season rainfall distribution in Bangladesh.



Adopted from: Manalo (1976)

Figure 4.4. Mean monsoon season rainfall distribution in Bangladesh.



Adopted from: Manalo (1976)

Figure 4.5. Mean winter season rainfall distribution in Bangladesh.

Table 4.2. Frequency distribution of rainfall categories during monsoon months (1965-1980) for Dhaka (modified from Talukder *et al.*, 1988).

Months	> 300 mm	200-300 mm	100-200 mm	50-100 mm	50 < mm
June	9	7	--	--	--
July	13	2	1	--	--
August	10	4	1	1	--
September	5	5	6	--	--
October	1	4	7	4	--

Table 4.3. Total number of rainy days, average rainy day per month, and rainfall per rainy day for Dhaka (1965-80) (modified from Talukder *et al.* 1988).

Month	Total number of rainy days	Mean rainy day per month	Rainfall per rainy day (mm)
June	291	18	19.4
July	362	23	19.9
August	346	22	15.7
September	258	16	16.1
October	140	9	19.7

Table 4.4 presents some statistical characteristics of mean daily monsoonal rainfall for 1975 through 1987 for 16 stations. A detailed discussion on the source of this data set is presented later. It has been found that Rangpur's and Comilla's daily rainfall contains the highest and lowest variability, respectively. The highest and the lowest standard deviation of daily rainfall have been estimated for Maijdi Court and Comilla, respectively. These estimates are related to the second highest and the lowest seasonal rainfall totals, respectively. The table also shows that Sylhet and Comilla record the highest and the lowest daily mean precipitation for

Table 4.4. Some statistical characteristics of the monsoonal rainfall in Bangladesh for the period of 1975-87.

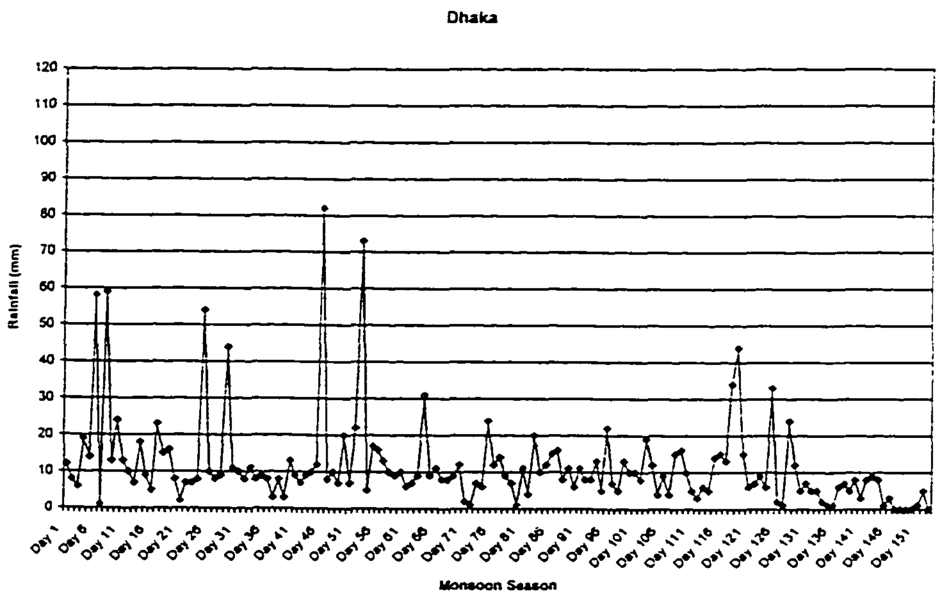
Station	Seasonal total rainfall (mm)	Daily mean rainfall (mm)	Standard deviation (mm)	Coefficient of variation (%)
Dhaka	1794	11.72	12.43	106.0
Rangpur	2344	15.32	19.60	128.0
Jessore	1448	9.46	10.12	107.0
Khulna	1566	10.23	11.00	107.5
Chandpur	1978	12.92	13.57	105.0
Comilla	1417	9.26	6.46	69.8
Faridpur	1617	10.56	10.98	104.0
Mymensingh	1757	11.48	11.16	97.2
Maijdi Court	3542	23.15	26.51	114.5
Feni	2806	18.33	20.88	114.0
Sylhet	3699	24.17	22.24	92.0
Satkhira	1529	9.99	10.53	105.4
Barisal	1863	12.17	11.64	95.6
Bogra	1754	11.46	13.60	118.7
Dinajpur	1549	10.12	10.03	99.1
Ishwardi	1535	10.13	11.30	112.7

the whole monsoon season. As expected, Sylhet recorded the highest monsoon season total rainfall. As shown earlier, the eastern sector of Bangladesh receives higher seasonal total rainfall compared to the western sector. Figures 4.6a-e present the temporal distribution of average daily rainfall recorded at five representative stations from 1975 through 1987. Day 1 represents June 1 which is the beginning of the monsoon season. The most common feature of figures 4.6a-e is heavy precipitation during the end of the first and the beginning of the second week of June. This is the indication of arrival of the monsoon. Since these figures represent the daily mean, most of the days of the monsoon record rainfall.

Only a few days at the end of the monsoon season (which is end of the month of October) record no rainfall. It is also evident from the figures 4.6a-e that intra-seasonal monsoonal rainfall distribution contains a number of events of heavy rainfall and days of relatively low rainfall. Sylhet (Figure 4.6c) shows more frequent occurrence of heavy rainfall events than any other stations. These heavy rainfall events are reflected in the seasonal total rainfall of Sylhet. The intra-seasonal fluctuations in rainfall are connected to synoptic and planetary scale behavior of the monsoonal circulation (*cf.*, Madden and Julian, 1972; Sikka and Gadgil, 1980; Webster, 1987; Webster *et al.*, 1998).

From a rice farmer's view point in Bangladesh, a little below normal rainfall is far better than excessive rainfall because during a normal summer monsoon season, Bangladesh receives much more rainfall than it needs. Another important aspect of the monsoonal rainfall is that all excessively rainy summer monsoons do not always cause severe flooding, and in some cases slightly above normal rainfall or average seasonal rainfall could cause flooding. This occurs due to short period burst and related high intensity of rainfall and its distribution over the Ganges-Brahmaputra-Meghna catchment. It is important to note that the size of the whole catchment is 1,758,000 km^2 while only 8% of the catchment is within the political boundary of Bangladesh. However, approximately all of the total annual surface runoff of the whole catchment passes through Bangladesh (Rogers *et al.*, 1989). Thus, excessive rainfall over the catchment outside of the political boundary could

a)



b)

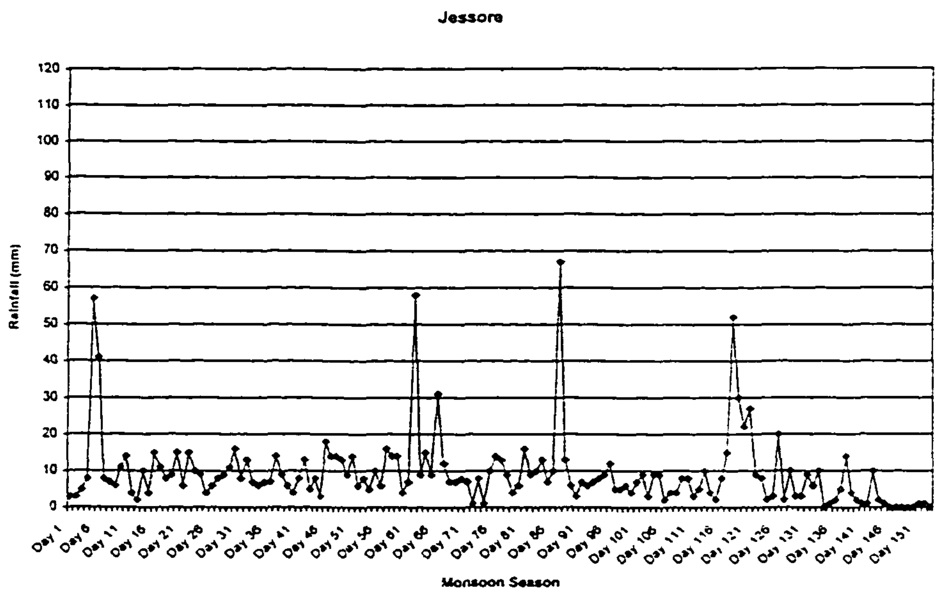
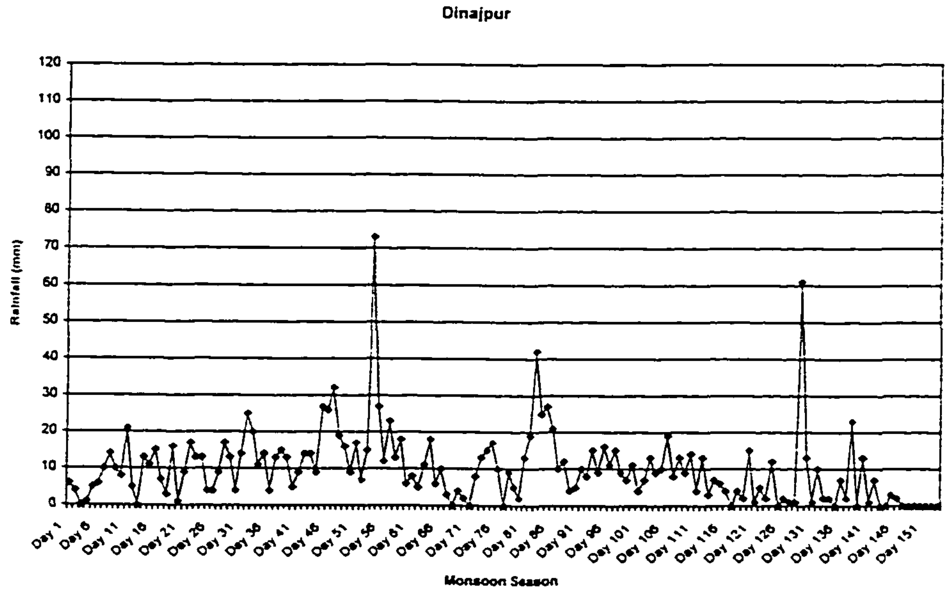


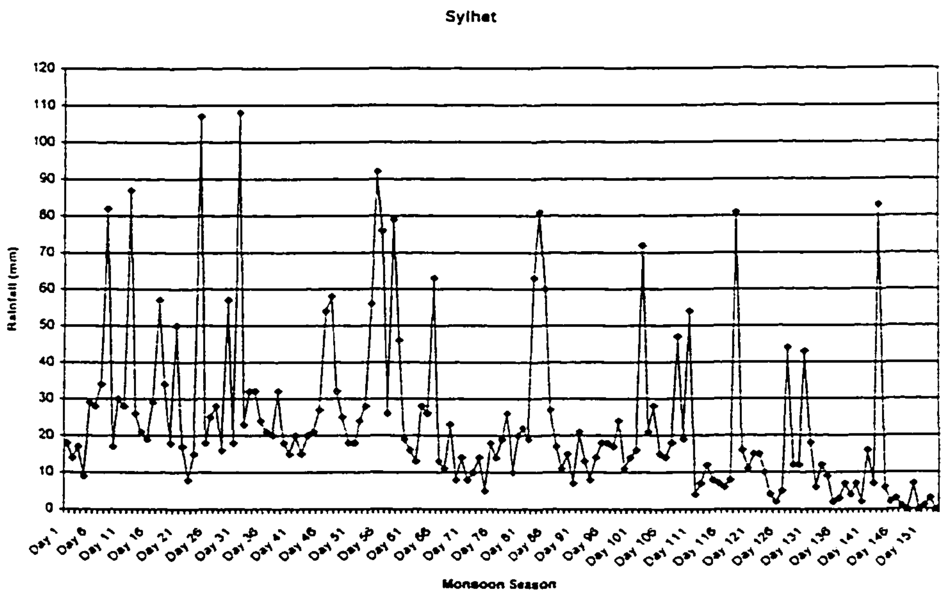
Figure 4.6a-e. Daily mean (1975-1987) monsoon season rainfall for the five selected stations in Bangladesh.

c)



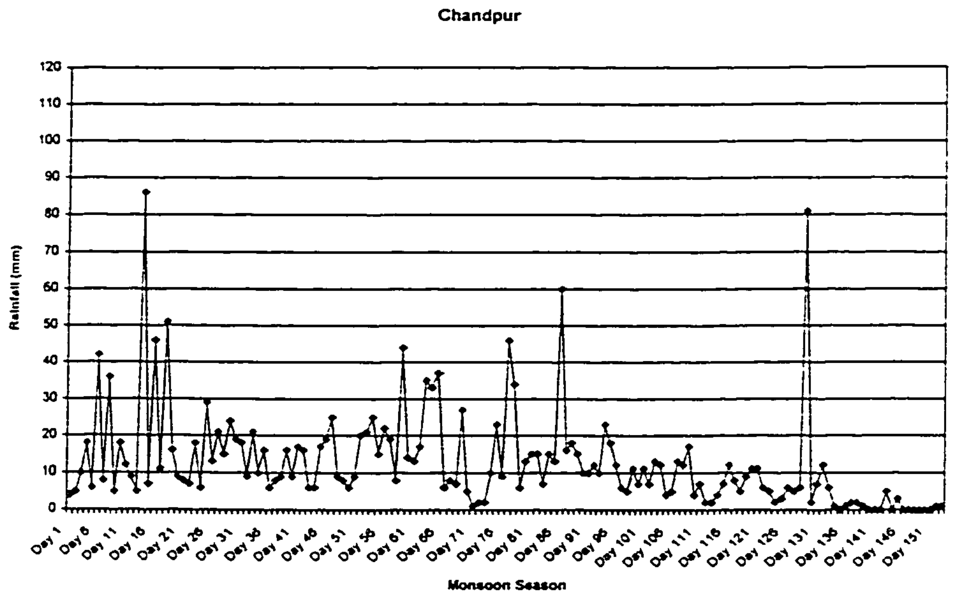
Dinajpur
Rainfall (mm)
Monsoon Season

d)



Sylhet
Rainfall (mm)
Monsoon Season

e)



cause severe flooding in Bangladesh. In 1987, the summer monsoon rainfall departure in Bangladesh was +40% and in 1988, it was +13% but the severity of the flood of 1988 was much greater than that of 1987 and the resultant loss of crop was immense too. This occurred due to the short-period burst of monsoon rainfall and heavy rainfall in the upper-catchment and resultant huge runoff through Bangladesh (Brammer, 1990).

The withdrawal of the monsoon in Bangladesh is marked by a sharp decrease of rainfall in October (Figures 4.2a-e). The monsoon trough starts to shift progressively to a southerly direction with the march of the thermal equator to the south. An important feature of the withdrawal of the monsoon in Bangladesh is the development of depressions and severe cyclonic storms and associated storm surges and downpours during the month of October. This is more like the onset of the summer monsoon. These storms very often result in a loss of the *aman* rice crop, which is ready to be harvested, due to high winds. The severe weather conditions cause lodging of the mature crop due to high wind, and flooding of the crop field due to intense rainfall during cyclonic storms. Storm surges flood coastal rice fields with saline water, which is detrimental to rice crop growth and yield. The salt that accumulates in the soil during the storm surges is not only harmful to standing crops but also reduces the fertility of soil for the longer period, which, in turn, reduces rice crop yield in those particular storm surge affected areas. The late withdrawal of the monsoon forces Bangladeshi farmers to practice late sowing and resultant late transplanting of the boro rice because of higher depth of water in the rice fields. The late sowing and transplanting results in a shorter growing season and lower yield.

4.1.3. The winter season. Winter in Bangladesh is less eventful compared to the hot summer and the monsoon seasons, except for the cyclonic storms in November. These storms are usually the most severe in Bangladesh. The November storm of 1970 is a classic example of the devastating power of such cyclones. A storm surge of 15 m was associated with this cyclone which drowned more than 500,000 people in coastal areas and destroyed over 400,000 hectares of harvestable rice crop which was inundated with salt water (Bryant, 1991).

During the winter season Bangladesh receives maximum sunshine because of clear skies. Rainfall is very scant and is not more than 4% of the annual rainfall. In the low-lying areas, the harvest of the *aman* rice crop continues into November because it takes more time for the paddy fields to dry. The *Boro* rice crop season starts in December in general, but in relatively higher lands it starts in November because of the early drying of farm lands. The *Boro* rice crop in Bangladesh is mostly irrigated. Thus, the effects of climatic variability on *boro* rice crop is less than the *aus* and *aman* rice crops.

4.2. Soils

In Bangladesh rice cultivation does not always follow soil type. Population pressure has forced Bangladeshi farmers to practice rice farming almost all over the country (Islam, 1965). Exceptions are the eastern hills and the southwestern mangrove forests which are also known as the Khulna Sundarbans or the Sundarbans. Although rice cultivation is widespread all over Bangladesh, the important role of soil type for rice yields is undeniable. The United Nations Development Program (UNDP) and Food and Agricultural Organization (FAO) proposed a soil classification for Bangladesh in 1971 (Rashid, 1977). They classified the soils of Bangladesh in 20 categories.

Four soil types have been used in this study as inputs to the CERES-Rice model. These soil types include grey flood plain soil, non-calcareous dark-grey flood plain soil, non-calcareous alluvium, and grey terrace soil. Soils of Dhaka, Dinajpur, Khulna, Rangpur, Satkhira, Chandpur, and Feni have been identified as grey flood plain soils in this study. Rashid (1977) noted that this type of soil is agriculturally very productive. Two weeks of submergence makes the topsoil near- neutral and becomes medium to strongly acid during drying (Rashid, 1977). On the other hand, soils of Comilla, Jessore, Faridpur, and Mymensingh have been identified as non-calcareous dark-grey flood plain soils. This type of soil is also becomes near-neutral when it is submerged for two weeks and becomes acid during dry conditions (Rashid, 1977). He also suggested that it is sticky when wet and crack widely under dry conditions. In addition, soils of Barisal, Maijdi Court, and Ishwardi are classified as non-calcareous alluvium and of Sylhet and Bogra are classified as grey terrace soils. Rashid (1977) noted that non-calcareous alluvium is silty or sandy and neutral to alkaline. Moreover, it suffers from poor permeability. Grey terrace soil is also slightly to strongly acid (Rashid, 1977). However, topsoil becomes near-neutral after near two weeks of continuous submergence. Since this study primarily focuses on precipitation variability, water availability, and yield, a detailed discussion on these soil types and their detailed physio-chemical characteristics is not provided in this dissertation.

CHAPTER 5

THE CERES-Rice MODEL PREPARATION FOR BANGLADESH APPLICATION

5.1. Scenario building, selection of the study period, and weather data

Scenarios can be constructed in various ways. This study uses an analogue approach to determine the impacts of the monsoonal rainfall variations on rainfed rice productivity. This approach has been successfully applied by several authors (*cf.*, Easterling *et al.*, 1993). It is important to note that climate scenarios are not predictions of future climate. However, these scenarios are internally consistent and depict a potentially plausible future climate which would allow us to estimate potential impacts of climate change on the human society (Wigley *et al.*, 1986). This assessment is also applicable to the scenarios of the current study. The present study uses daily weather data from 1975 through 1987. Thus, the actual monsoonal conditions for the specified period will be used as scenarios. This period is marked by significant inter- and intra-annual variations in the monsoonal rainfall (*cf.*, Krishnamurti *et al.*, 1989, Matsumoto, 1992; and Shukla, 1989).

Matsumoto's (1992) analysis shows that Bangladesh recorded up to +40% and -20% above and below normal rainfall, respectively, during the monsoon seasons of 1975 through 1987. Ahmad and Karmakar (1993) reported remarkable inter-annual variations in arrival and departure dates of the monsoon in Bangladesh. In addition, they found that monsoon arrival and departure dates fluctuated nearly 2 weeks for various regions of Bangladesh during 1975-1987. Therefore, selection of this period will not only serve the purpose of this study but also presents a 'sample' segment of time-series representing long-term monsoonal variations.

First, the model is calibrated and then applied the CERES-Rice model for 16 stations representing major rice growing regions to determine baseline estimates. Subsequently, the model was run for the period 1975 through 1987 to identify impacts of intra-annual variations of precipitation on the rice plant growth and the final yield. The CERES-Rice model allows for an examination of the impacts of unusual monsoonal weather conditions on the following processes which include, among others, plant growth, phasic and morphological development of plants, and soil water balance. Outputs of the model include yield, above-ground biomass, dates of phasic development changes, soil water balance components, and an index of water stress. Subsequently, values of the precipitation and water stress parameters were correlated to corresponding yield estimates to determine the strength of the relationship between rice productivity and precipitation.

To apply the model, daily surface weather data for Bangladesh including daily maximum and minimum temperature and daily precipitation for the period of 1975 through 1987 for 16 stations were obtained from the Bangladesh Meteorological Department (BMD). A survey of the temperature and precipitation data set shows that it contains missing data. It is important to note that, in most cases, missing data points are located in the non-monsoon months and the number of missing data points for each station is very small. However, the model requires a complete data set for the whole year even if there are no missing data for the growing season. As a result, this study adopted separate methods to estimate missing daily maximum and minimum temperature and precipitation data (Legates, 1998).

5.1.1. Estimation of missing precipitation data. To estimate missing precipitation data, daily average precipitation was first calculated for each of the 16 stations based on the available data. Subsequently, the correlation between each station and the 15 other stations were calculated. At this stage, to estimate missing values for a particular station, the station with which this particular station's (where precipitation data is missing) precipitation is highest correlated was identified. A ratio of average daily precipitation for these two stations then was multiplied by the recorded precipitation of the highest correlated station to estimate the missing value. This estimation method is similar to a double mass analysis (Linsley *et al.*, 1975).

$$P(B_{est}) = (P(B_{mean}) / P(A_{mean})) * P(A) \qquad (9)$$

where $P(B_{est})$ is estimated daily precipitation for missing data of station B, $P(A_{mean})$ is mean daily precipitation for station A, $P(B_{mean})$ is mean daily precipitation for station B, and P(A) is observed precipitation for station A.

5.1.2. Estimation of missing daily maximum and minimum temperatures. Estimates of temperature is slightly different compared to the method used to obtain daily precipitation estimates for missing data. Daily average maximum temperature for each of the 16 stations was computed from available data and the correlations between each station and 15 other stations were calculated. To estimate missing values for a particular station, the station with which this particular station's (where daily maximum temperature data is missing) maximum temperature is most highly correlated was identified. Finally, the estimate was obtained from

$$T(B_{est}) = T(A) + (T(B_{mean}) - T(A_{mean})) \qquad (10)$$

where $T(B_{est})$ is estimated daily maximum temperature for a missing data point, and $T(A_{mean})$ and $T(B_{mean})$ is average daily maximum temperature for station A and B, respectively. This method was also applied to estimate missing daily minimum temperature.

5.1.3. Estimation of daily solar radiation data. The BMD supplied daily solar radiation for seven stations from 1984 through 1990. A survey of this data shows that the data quality is extremely poor and missing data points are widespread. However, many of the solar radiation estimation methods are temperature-based and region specific (*cf.*, Hook and McClendon, 1992; Bindi and Miglietta, 1991; Hodges *et al.*, 1985). To fulfill the model input data requirement, Black's (1956) method was modified (Legates, 1998) to estimate solar radiation from the daily cloud cover data of 16 stations. This modified method

$$R_s = R_{so} * .66667 * (.803 - .00340C - .0000458C^2) + .33333 * R_{so} \quad (11)$$

where, R_s is actual radiation at the earth's surface, R_{so} is radiation at the top of the earth's atmosphere, and C is cloud cover (percent). The .66667 and .33333 are direct and diffused beam radiation during summer monsoon months, respectively. These two terms have been added from Stanhill (1966) and resulted from earth-sun relationship during the summer months. It is important to note that cloud cover data were obtained from the BMD and that those data contained no missing observation.

5.1.4. Model validation of data estimations procedures. A formal model validation procedure was not applied to determine the accuracy of these methods for a number of reasons. The volume of the missing data for growing season for each station for the time series is small. On the average 3.7% data is missing for each station except for Dinajpur (46% missing). This station reports unavailability of data from 1975 through 1980. However, its data record is complete from 1981 through 1987. In addition, some of the missing data are located in the non-growing season months, and the model does not use non-monsoonal and non-growing season meteorological data for crop growth simulation. As a result, the impacts of these estimated data are minimal on the model simulated yield predictions. Furthermore, it was not possible to determine directly the accuracy of estimated solar radiation data due to the absence of reliably measured data. However, in a following section model's yield estimates are evaluated satisfactory by comparing modeled and reported yield. The modeled yield also demonstrates that the accuracy of estimated meteorological variables is acceptable.

5.2. Soils, agronomic, and management data

Soils data have been collected from the Bangladesh Agricultural Research Council (BARC) (Hussain, 1997) and Hussain (1995). Agronomic and management data also have been collected from the BARC (Hussain, 1997). Table 5.1 presents the agronomic and management data that were used as inputs during this study.

Planting dates relative to the temporal distribution of monsoonal rainfall can significantly influence the final rice yield. This distribution not only affects the availability of moisture from the monsoon rain but also the solar radiation and dry weather required during maturing and harvesting stage for optimum yield. It is important to note that the BRRI suggests that farmers transplant BR11 rainfed

Table 5.1. Agronomic and management parameter input data for the study (after Hussain, 1997).

Agronomic and management parameter	Input data
Transplanting date	06/01, 06/15, 07/01, 07/15, 08/01, 08/07, 08/15, 08/23
Row spacing	20 cm
Number of plants per hill	6
Number of plants at emergence	44 m^{-2}
Transplanting age	30 days
Base temperature to estimate phenological phases	9°C
Floodwater depth	15 cm
Planting depth	6 cm
Planting method	transplanted
Fertilizer (N) application:	
15 days after transplanting	application depth: 15 cm application amount: 25 kg ha^{-1}
25 days after transplanting	application depth: 15 cm application amount: 30 kg ha^{-1}
50 days after transplanting	application depth: 15 cm application amount: 25 kg ha^{-1}

aman rice between July 15 and August 15 (BRRI, 1995) for attaining an optimum yield. Six additional transplanting dates to identify optimum planting dates were incorporated in this study (Table 5.1). Initial model runs showed that yield decreases rapidly if the transplanting date is after July 15. To further monitor this decrease temporal resolution was increased for transplanting dates during the month of August.

5.3. The CERES-Rice model application and evaluation of its performance

This model has been previously successfully validated by Li-Ling (1987) and Jintrawet (1991). Recently Timsina *et al.* (1998) also evaluated the performance of the model by applying it to a Rice-Wheat sequence. The performance of the model is satisfactory. They collected experimental data from the field for BR11 and BR14 *aman* rice grown under irrigated and rainfed conditions and under various levels of nitrogen application. These data were compared with the modeled yield for 1994 at Nashipur (25°48′N and 88°4′E) site in Bangladesh. Timsina *et al.* (1998) found that the root mean squared error (RMSE) between simulated and observed yield was 1279.8 kg ha^{-1} and the RMSE between simulated and observed number of days to flowering and to maturity were 4.3 and 2.3 days, respectively. They noted that some of the overestimation of simulated yield was due to the model's inability to incorporate insect damage and lodging as a result of high nitrogen (N) rates.

To evaluate the CERES-Rice model calibration and performance for the present study, it was applied to Joydebpur (24° N and 90°26′E), Bangladesh for the period 1975 through 1987. This model was run for eight selected transplanting dates and under a specified set of management conditions (Table 5.1). For the evaluation, yields were compared from a July 15 transplanting date. However, whenever available, recorded yield estimates from other comparable dates were also presented against simulated yield.

A primary reason for selecting this site is the availability of observed yield data. It is also important to note that the reported results of the field experiments that have been used to evaluate model performance are not completely comparable to the experiments conducted here. For example, in some cases transplanting dates are not exactly the same for field and model experiments, nor were fertilizer treatments the same in most cases. However, reported yields from various experiments were collected carefully so that they can be satisfactorily comparable to experiments performed here. For example, transplanting dates and management practices for the observed yield were required to be comparable to this study. Due to the unavailability of totally comparable experiments for all applications, however, standard statistical methods for model evaluation were not used in this analysis. Rather a qualitative evaluation is presented (Table 5.2). It is important to note that applications of this type are common in the scientific literature (*cf.*, Easterling *et al.*, 1993; Mahmood and Hayes, 1995; Mahmood, 1997; and Mahmood, 1998).

The comparative analysis of simulated and observed yields show close agreements in most cases (Table 5.2). Discrepancies are caused by differences in model and field experimental set up and actual field conditions. It is also important to note that under favorable weather and management conditions farmers would

Table 5.2. Comparison of simulated and observed yield.

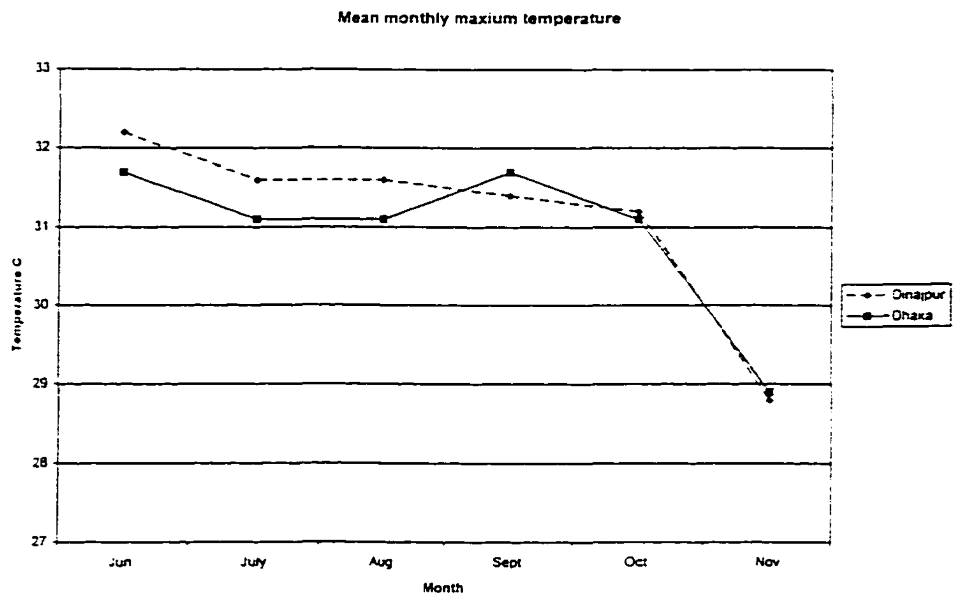
Simulated Yield (t ha^{-1})	Observed Yield (t ha^{-1})
07/15/1987: 3.7	3.8-4.2 (BRRI, 1990); nitrogen (N) applications experiment.
07/15/1986: 5.5	3.6-3.3 (BRRI, 1988); N application experiment.
06/15/1986: 7.3	6.7 (BRRI, 1988); transplanting date experiment.
08/01/1986: 2.6	2.94 (BRRI, 1988); transplanting date: 07/25/1986.
08/07/1986: 3.8	3.62 (BRRI, 1988); transplanting date: 08/10/1986.
07/15/1985: 3.4	3.4 (BRRI, 1987); N application experiment.
	3.8 (BRRI, 1987); N application experiment.
08/01/1985: 1.5	4.25 (BRRI, 1987); transplanting date experiment.
08/15/1985: 1.3	3.8 (BRRI, 1987); transplanting date experiment.
	4.8 (BRRI, 1987); transplanting date experiment.
07/15/83: 5.3	4.9–4.0 (BRRI, 1985c); fertilizer application experiment.
07/01/81: 4.7	3.8 (BRRI, 1985a); transplanting date: 06/30/81; seedling age 20.

attain yields up to 5.5-6.5 t ha^{-1} (BRRI, 1995). Thus, in some cases, lower modeled yields (for the July 15 transplanting date) are the result of unfavorable weather conditions. For example, June and the first part of July were unusually dry months in 1987 (Krishnamurti *et al.*, 1989). As result, the model simulated lower yields (3.7 t ha^{-1}). Overall, based on close agreements between observed and simulated yields, it is possible to conclude that the modeled yield estimates are satisfactory.

Crop growth and phenology partly determine the availability of soil water and exposure to stressful conditions. Thus, evaluation of the model-estimated number of days to reach various growth stages is essential. Unfortunately, field experiments exactly matching these experiments conducted by running the CERES-Rice model are unavailable. However, performance of the CERES-Rice model is shown by presenting and analyzing data from comparable field experiments and modeled estimates (Table 5.3). To achieve this goal the results were compared from experiments at Nashipur (25°48'N and 88°4'E) conducted by Timsina *et al.* (1998) and model runs for Joydebpur (24° N and 90°26'E). It is important to note that the thermal environment largely determines phenological changes (*cf.*, De Datta, 1981; Yoshida, 1981) and that these two stations experience quite similar seasonal temperature regimes. This similarity is shown (Figures 5.1a-c) using temperature data from Dhaka (23°46'N and 90°23'E) and Dinajpur (25°39'N and 88°41'E). These two stations, Dhaka and Dinajpur, are only a few miles from Joydebpur and Nashipur, respectively. Table 5.3 presents the number of days to reach flowering/heading and physiological maturity stages as observed in the field and by the model. During both the field and model experiments, BR11 was transplanted on July 15. Applications of N for field and model experiments are 90 and 80 kg ha^{-1}. Field data are for 1994 while modeled estimates are for 1975 through 1987. The purpose of presenting modeled estimates for 1975 through 1987 is to show that the model estimates are consistently reliable, as the seasonal thermal environment during the monsoon season does not fluctuate noticeably in Bangladesh at these stations.

It is clear that the model estimates are satisfactorily in agreement with the observed days to reach two phenological stages. The small disagreements are related to the fact that the observed and modeled values are not from the exactly similar thermal weather conditions, and the measurement and model runs were conducted over different years. In addition, the Nashipur experiment reports that the higher N applications result in a higher number of days to reach flowering and maturity stage (Timsina *et al.*, 1998). I have already noted that seasonal total fertilizer application in Nashipur is higher compared to the modeled experiments. Thus, the discrepancies between observed and modeled days to reach to flowering/heading and maturity also may have resulted from the different amount of N application during the growing season.

a)



b)

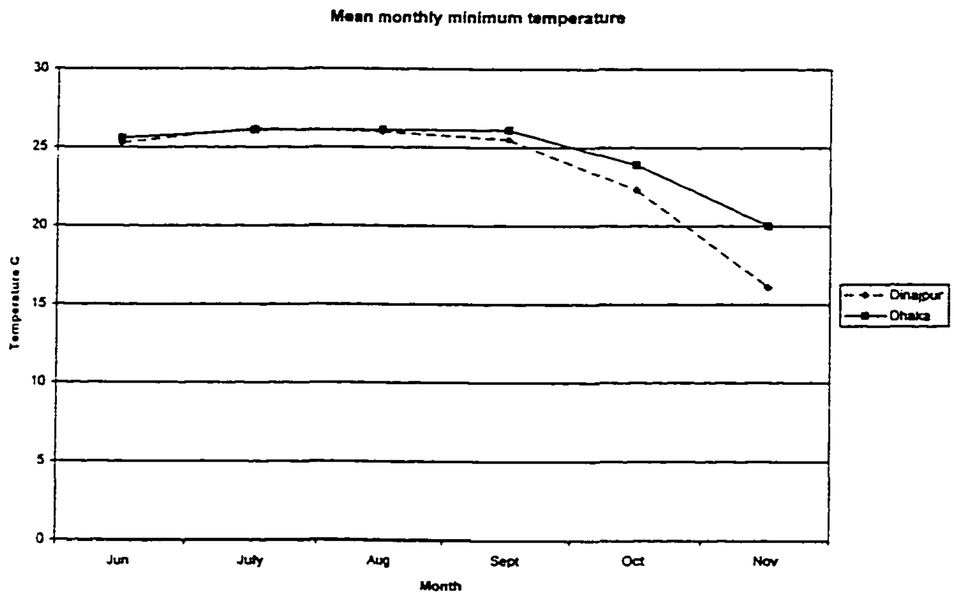


Figure 5.1. Monthly mean maximum temperature (a), monthly mean minimum temperature (b), and monthly mean temperature in Dhaka and Dinajpur (c).

c)

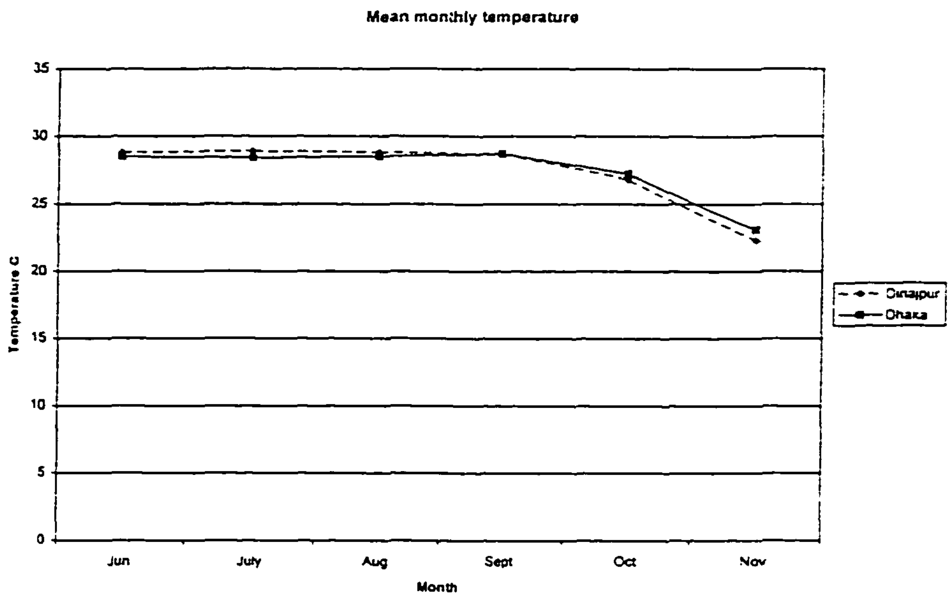

Mean monthly temperature
Temperature C
Month
Jun
July
Aug
Sept
Oct
Nov
0
5
10
15
20
25
30
35
Dinajpur
Dhaka

Table 5.3. Observed (Nashipur) and modeled (Joydebpur) lengths of days to reach flowering/heading and physiological maturity stages after transplanting.

Observed days to reach flowering	Modeled days to reach flowering	Observed days to reach maturity	Modeled days to reach maturity
Year 1994: 97	Year 1975: 93	Year 1994: 128	Year 1975: 126
	1976: 92		1976: 124
	1977: 91		1977: 125
	1978: 90		1978: 121
	1979: 90		1979: 122
	1980: 90		1980: 124
	1981: 89		1981: 121
	1982: 90		1982: 122
	1983: 89		1983: 121
	1984: 90		1984: 121
	1985: 89		1985: 121
	1986: 90		1986: 121
	1987: 88		1987: 119

A comparison of modeled and observed harvest index was also conducted for comparable yields from Nashipur and Joydebpur, respectively. The harvest index can be defined as ratio of grain to straw (*cf.*, Murata and Matsushima, 1975; De Datta, 1981; Yoshida, 1981). High ratio indicates a more balanced growth. The harvest index is approximately 0.5 for short improved varieties and 0.3 for tall traditional varieties (Yoshida, 1981). The Nashipur field experiment in 1994 and Joydebpur model run for 1987 records 4.1 and 3.7 t ha^{-1} yields (July 15 is the transplanting date in both cases), respectively. Harvest Indices for Nashipur and Joydebpur experiments are 0.35 and 0.31, respectively. Thus, it appears, again, that the model performance is satisfactory.

Water stress can significantly affect rice plant growth and yield. As shown in Chapter 3, the CERES-Rice model contains a detailed scheme for soil water balance calculation. In this scheme, daily, phenological, and seasonal evapotranspiration estimates play an important role in determining water stress and its impacts on the plant growth and yield. Thus, it is important that the model is calculating evapotranspiration correctly. Evapotranspiration data from the rice fields in Bangladesh are unavailable. However, monthly total evaporation data for Joydebpur for the period of 1978 through 1987, except 1986, has been reported by the BRRI. After conducting an international level survey, Tomar and O'Tool (1979) determined a coefficient of 1.2 which can be used to convert evaporation to evapotranspiration (ET = 1.2 x E) for lowland rice. Monthly pan evaporation reported by BRRI was converted by using this method and present them in the form of growing season total (Table 5.4). Recorded evaporation data were summed for the months of July, August, September, and October for the time series and converted the grand total to seasonal evapotranspiration. It is important to note that evaporation data for 7 out of 9 years have been extracted from published figures. Model estimated growing season total evapotranspiration for a July 1 rice transplanting date to match the time period of recorded evaporation were subtracted. The model estimated length of growing season for July 1 transplanting date ranges from 117 days to 123 days. In other words, the rice crop matures between October 25th to October 31st. Estimates for average daily evapotranspiration for the growing period for observed and modeled seasonal data also were computed (Table 5.4).

Table 5.4. Model estimated and observed evapotranspiration and pan evaporation (Observed ET estimate = pan evaporation x 1.2).

Year	Model estimated seasonal total ET (daily average) in mm	Observed seasonal total ET (daily average) in mm	Seasonal total pan evporation (daily average) In mm
1978	726 (5.95)	811 (6.59)	676 (5.54) (BRRI, 1981)
1979	803 (6.63)	732 (5.95)	610[f] (4.95) (BRRI, 1982)
1980	885 (7.19)	798 (6.48)	665[f] (5.40) (BRRI, 1984)
1981	744 (6.20)	635 (5.16)	529 (4.30) (BRRI, 1985a)
1982	789 (6.52)	768 (6.24)	640[f] (5.20) (BRRI, 1985b)
1983	789 (6.52)	732 (5.95)	610[f] (4.95) (BRRI, 1985c)
1984	707 (5.84)	690 (5.60)	575[f] (4.63) (BRRI, 1985d)
1985	786 (6.49)	660 (5.36)	550[f] (4.47) (BRRI, 1987)
1987	832 (7.11)	684 (5.56)	570[f] (4.63) (BRRI, 1990)

f = evaporation data collected from a figure

Table 5.5. Statistics for modeled and observed evapotranspiration.

Statistic	Observed		Simulated
Daily mean, mm	5.87		6.48
Standard deviation (daily ET) , mm	0.41		0.49
Mean seasonal total, mm	723		784
Standard deviation (seasonal ET), mm	61.11		54.55
RMSE (daily ET), mm		0.85	
RMSE (seasonal total), mm		90	

Mean, standard deviation, and RMSE for observed and modeled ET are presented in Table 5.5. These statistics show that agreement between modeled and observed data are quite satisfactory. Legates and McCabe (1999) have evaluated ET estimates by a number of methods. A survey of ET estimates by this study and Legates and McCabe's (1999) study also show that the ET estimates of this study are satisfactory.

5.4. Summary

In short, weather and soils and agronomic input data for the model has been obtained from the Bangladesh Meteorological Department (BMD) and the Bangladesh Agricultural Research Council (BARC). Missing precipitation and maximum and minimum temperature data were estimated to complete these data sets. Solar radiation data has been estimated from the observed cloud cover data, which were also obtained from the BMD. After preparation of input data set, the CERES-Rice model was run for Joydebpur, Dhaka from 1975 through 1987.

Subsequently, the modeled yields, ET, phenology, and harvest index estimates were compared and evaluated with observed data. It appears that the model estimates are satisfactory. In the context of satisfactory model estimation of yield and yield related growth parameters, baseline yields were estimated for 16 stations. These estimates and accompanying analysis are presented in the following chapter.

CHAPTER 6

THE CERES-Rice MODEL APPLICATION TO BANGLADESH FOR BASELINE YIELD ESTIMATES

6.1. Transplanting date and yield

For baseline estimates, daily average precipitation, daily average maximum and minimum temperature, and daily average solar radiation were calculated for all 16 station from 1975 through 1987 which are distributed over the major rice growing regions in Bangladesh. Subsequently the model was run for each of these stations to determine baseline yields. These runs were conducted for 8 different transplanting dates (see Table 6.1) to identify suitable date(s) to attain optimum yield.

From Table 6.1 it is clear that Dinajpur and Sylhet report the highest (8413 kg ha^{-1}) and the lowest yield (5374 kg ha^{-1}), respectively, if farmers transplant rice on the prepared field on June 1. Jessore, Khulna, Faridpur, Maijdi court, Satkhira, Barisal,and Dinajpur report yields over 8000 kg ha^{-1}, while the rest of the stations except Sylhet, report above 7000 kg ha^{-1}. These estimates are quite high and related to the transplanting date. This is further illustrated later in the present chapter. Khulna and Sylhet report the highest (8131 kg ha^{-1}) and the lowest yield (5497 kg ha^{-1}), respectively, for the June 15 transplanting date. Under the June 15 transplanting date Khulna, Comilla, Satkhira, and Dinajpur estimates yields over 8000 kg ha^{-1} while ten other stations estimate yields over 7000 kg ha^{-1}. Barisal and

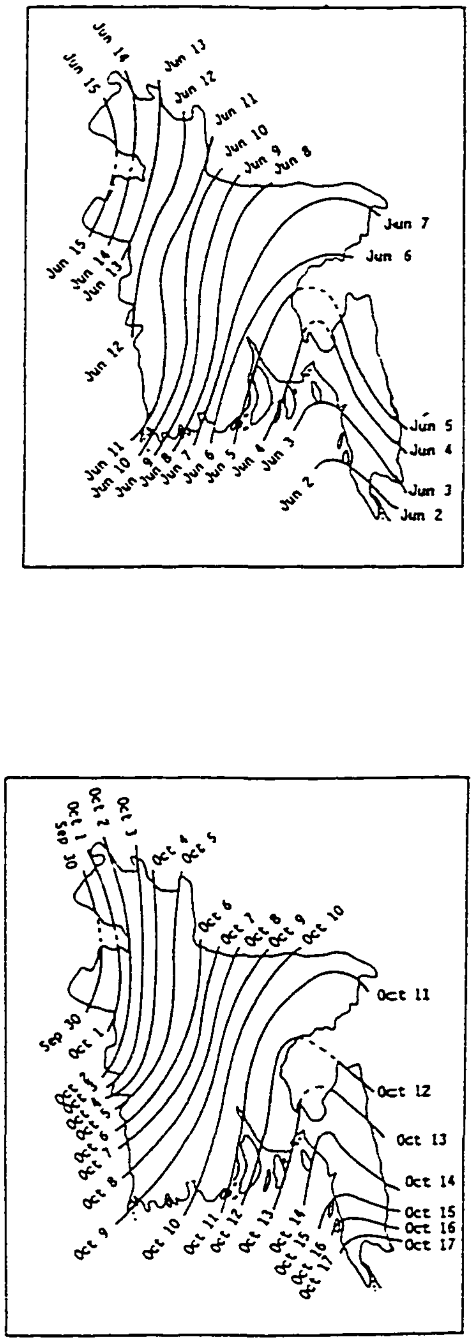
Table 6.1. Baseline yield estimates (kg ha^{-1}) for eight transplanting dates for 16 stations.

Station	06/01	06/15	07/01	07/15	08/01	08/07	08/15	08/23
Dhaka	7168	6932	6741	6335	3818	2752	1876	1312
Rangpur	7695	7556	6960	6700	3708	2319	1586	1465
Jessore	8045	7854	7688	6221	1988	1940	1553	1318
Khulna	8271	8131	7479	6640	3825	2462	1835	1451
Chand-pur	7910	7595	7068	5776	2086	1993	1491	1377
Comilla	7904	8113	7605	5600	1969	2099	1434	1329
Faridpur	8144	7885	7391	6312	2600	2316	1900	1431
Mymen-singh	7415	7381	7007	5020	2000	1686	1380	1299
Maijdi Court	8168	7262	6579	6168	3150	2075	1403	1256
Feni	7336	7192	6679	6364	3586	2319	1664	1340
Sylhet	5374	5497	5357	5737	3831	2755	1553	1339
Satkhira	8209	8107	7454	6839	3741	2421	1982	1452
Barisal	8396	7841	7350	7075	4409	2932	1698	1453
Bogra	7600	7319	7164	5725	2148	1552	1352	1262
Dinajpur	8413	8067	7506	5993	2759	1851	1556	1531
Ishwardi	7917	7760	7227	4797	1581	1594	1324	1269

Ishwardi record the highest (7075 kg ha^{-1}) and the lowest yield (4797 kg ha^{-1}) for the July 15 transplanting date, which marks the beginning of the BRRI recommended transplanting period. It is important to note that only Barisal reports over 7000 kg ha^{-1} yield for this date. On the other hand, 7 stations estimated an yield below 6000 kg ha-1. Satkhira and Ishwardi report the highest (1982 kg ha^{-1}) and the lowest yields (1324 kg ka^{-1}) for the August 15 transplanting date, which marks the end of the BRRI recommended transplanting period for BR11 *aman* rice. These estimates also show that the range of yield (the highest and the lowest) for early transplanting is greater compared to the late transplanting dates. Stations located west of 90°E benefit most if farmers transplant rice in June and the early part of July (Table 6.1). On the other hand, stations east of 90°E benefit most if farmers transplant rice during the early part of August. Relatively early departure of monsoon over the north-western and west-central part of Bangladesh results in early occurrence of moisture stress (Figures 6.1a, b). This causes the relatively higher yield losses in the northwestern and west-central Bangladesh. The monsoon departs a few days later over the eastern section of Bangladesh (Figure 6.1.b). Rice growing regions benefit from this extra moisture which helps to reduce water stress and results in relatively higher yields when farmers transplant rice during the first two weeks of August. In addition, early transplanting in June allows rice plants to grow under no or relatively very low moisture stress conditions in the northwestern and west-central Bangladesh during flowering/heading and maturing stage. These conditions allows to attain generally higher yields in these regions.

Yields also decline under average climatic condition as transplanting dates progress well in to the monsoon (Table 6.1). The BRRI also reports such a reduction from their field experiments (BRRI, 1988). This reduction in yield is significant if farmers transplant rice on July 15 instead of June 1. Furthermore, yield reduction is highly noticeable if farmers transplant rice on August 15 instead of July 15 (Figures 6.2a-e) as transplanting progresses from early June to late August for Dhaka, Jessore, Dinajpur, Sylhet, and Chandpur. As shown previously,

a)

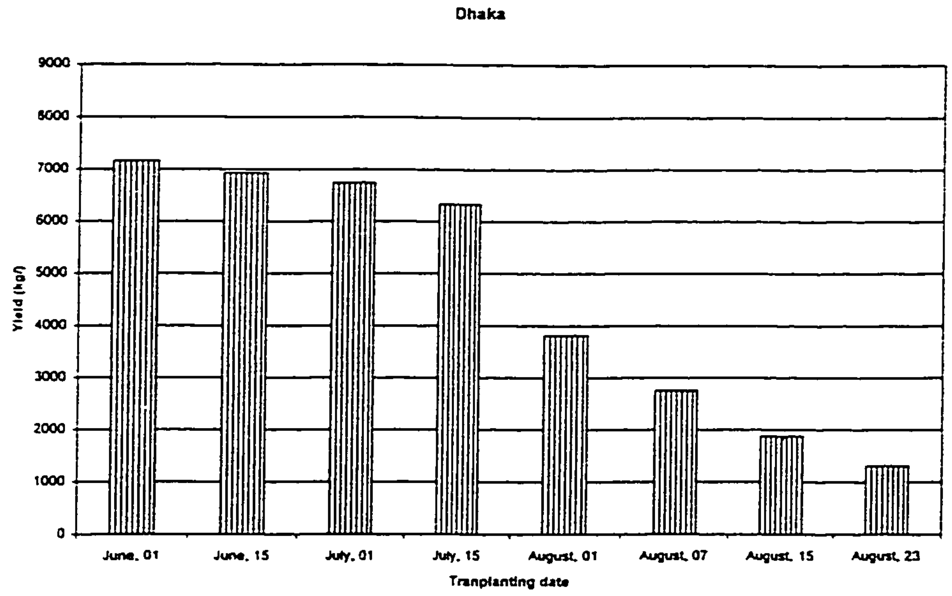


b)

Adopted from: Ahmed and Karmakar (1993)

Figure 6.1. Mean monsoon arrival dates (a), and mean monsoon departure dates in Bangladesh (b).

a)



b)

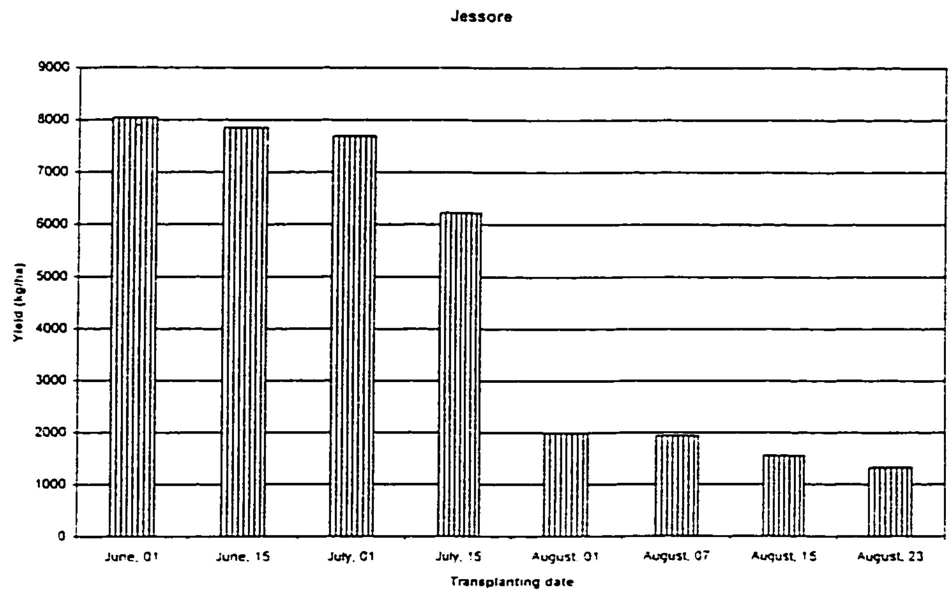
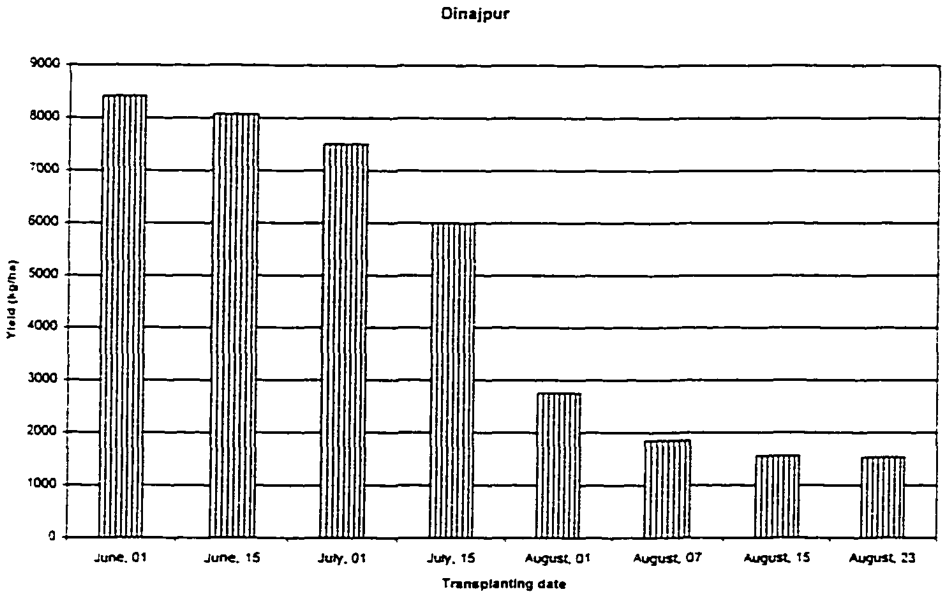
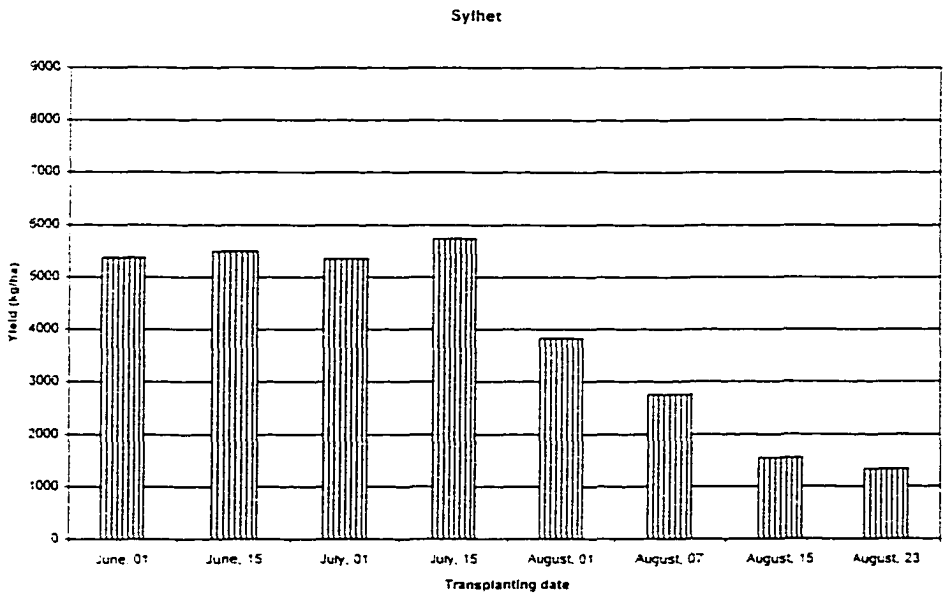


Figure 6.2a-e. Baseline yield losses for the five selected stations as transplanting dates progress from June to August.

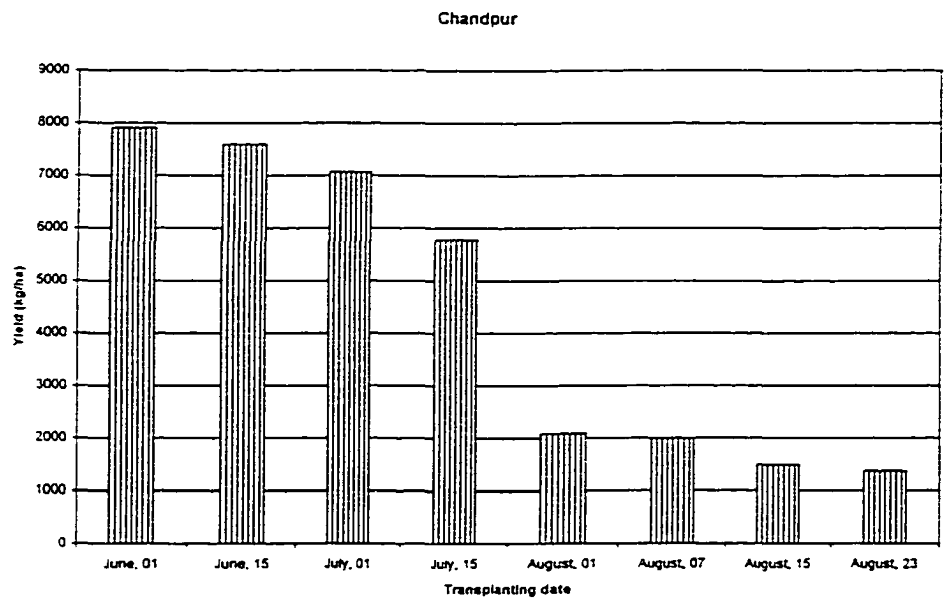
c)


Dinajpur
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
June, 01
June, 15
July, 01
July, 15
August, 01
August, 07
August, 15
August, 23
Transplanting date

d)


Sylhet
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
June, 01
June, 15
July, 01
July, 15
August, 01
August, 07
August, 15
August, 23
Transplanting date

e)


Chandpur
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
June, 01
June, 15
July, 01
July, 15
August, 01
August, 07
August, 15
August, 23
Transplanting date

each of these stations are located in different precipitation regimes (Figure 4.4).

Table 6.2 presents yield losses due to late transplanting under mean climatic conditions. Rice yield losses due to July 15 transplanting ranges from 11.6% to 39.40% for the 16 regions while average yield loss is 21%. These estimates are derived by comparing June 1 and July 15 transplanting date yields. It is also found that rice yield loss values range from 69% to 77% if farmers transplant rice on August 15 (base yield for July 15 transplanting date). These estimates of crop loss also agree with the previous observation which stated that the range of yield estimates is greater for early transplanting dates compared to the late (BRRI, 1988).

6.2. Intra-seasonal rainfall variability and its role in baseline yield estimates

To determine the causes of yield loss due to transplanting date selection and to identify role of intra-seasonal precipitation variability, a set of analyses were conducted. These include (1) the identification of the relationship between yields for various transplanting dates and seasonal daily rainfall variability, (2) height of the largest rainfall sequence, (3) height of the second largest rainfall sequence, (4) timing of the largest rainfall sequence, (5) timing of the second largest rainfall sequence, and (6) time distance between these two peaks. In this study, standard deviation has been used as a measure of rainfall variability, which plays important role in seasonal distribution of soil water and thus plant growth.

Table 6.2. Crop losses resulted from transplanting date selection.

Station	Yield loss (%) due to 07/15 transplanting (base yield for transplanting date: 06/01)	Yield loss (%) due to 08/15 transplanting (base yield for transplanting date: 07/15)
Dhaka	11.63	70.38
Rangpur	12.94	76.32
Jessore	22.67	75.03
Khulna	19.71	72.36
Chandpur	26.97	74.18
Comilla	29.14	74.39
Faridpur	22.49	69.89
Mymensingh	32.30	72.50
Maijdi Court	24.48	77.25
Feni	13.24	73.85
Sylhet	6.75 (gain)	72.93
Satkhira	16.68	71.01
Barisal	15.73	76.00
Bogra	24.67	76.38
Dinajpur	28.76	74.03
Ishwardi	39.40	72.39

First and second largest rainfall sequence is the highest and the second highest peak rainfall, respectively, during a monsoon season. Each peak is defined by days with no rainfall at the both ends. For example, if one assumes a sequence of rainy and dry days as follows: 3, 2, 0, 13, 40, 80, 35, 25, 0, 1 mm, then the peak is defined by the two zeroes at the two ends of this sequence of rainfall, which also contain the seasonal highest one day rainfall. Thus, the height of the peak would be: 13 + 40 + 80 + 35 + 25 = 193 mm. If records show that there is no dry day, then the two lowest rainfall days at the both ends will be the start and end dates of a peak rainfall. For example, if one assume a sequence of rainy days as follows: 3, 2, 1, 13, 40, 80, 35, 25, 1, 4 mm, then the peak is defined by the 1 mm rain at the two ends of the sequence. Again, the height of the peak would be: 13 + 40 + 80 + 35 + 25 = 193 mm. The timing of the 1st and 2nd peak is expressed in Julian days. The time delay between these two peaks is simply the number of days between the occurrences of peak rainfall. These seasonal rainfall characteristics also influence soil water distribution and thus yield (Legates, 1999).

Correlation analyses were performed for (1) yield versus standard deviation of rainfall, (2) yield versus height of the 1st peak, (3) yield versus height of the 2nd peak, (4) yield versus timing of the 1st peak, (5) yield versus timing of the 2nd peak, and (6) yield versus time delay between two peaks. Estimates from all 16 stations and for eight transplanting dates were used for this purpose. It was found that the correlation between yields and these parameters are generally very weak (Table 6.3).

Table 6.3 also shows that for the July 1 transplanting date, r^2 values for yield versus precipitation standard deviation and yield versus timing of the 2nd peak are 0.59 and 0.47, respectively. Further investigation indicated that these relationships are weak. It also needs to be noted that we cannot suggest that farmers change their farming practices based on only two near 0.5 r^2 values.

Table 6.3. Correlation between yields for eight transplanting date and baseline seasonal precipitation parameters for all stations (n = 16).

Precipitation parameters vs. yield	06/01	06/15	07/01	07/15	08/01	08/07	08/15	08/23
Standard deviation (mm)	-.448	-.651 r^2 = .42	-.769 r^2 = .59	.120	.382	.193	-.174	-.258
Height of the 1st peak (mm)	.024	-.245	-.306	.299	.266	.187	.022	-.081
Height of the 2nd peak (mm)	-.024	-.157	-.320	.360	.424	.178	.016	.007
Timing of the 1st peak (Julian day)	.130	.190	.269	-.083	-.088	-.184	-.292	.065
Timing of the 2nd peak (Julian day)	.506 r^2 = .26	.626 r^2 = .39	.686 r^2 = .47	-.024	-.259	.345	.110	.275
Time delay between two peaks (day)	.442	.502 r^2 = .25	.493	-.064	-.359	-.311	.161	.309

6.3. Soil water availability and yield

Soil is a medium from which plants extract most of its water for growth. The CERES-Rice model uses a soil water deficit factor, SW_{DEF} (0-1), to determine the relationship between water availability and yield. Earlier, it has been shown that SW_{DEF} is calculated from a ratio of potential root water uptake to potential transpiration. It is clear that a direct relationship between monsoon season precipitation and BR11 rice yield does not exist in Bangladesh. On the other hand, it is well-known that water availability plays a major role in rainfed lowland rice plant growth and yield (*cf.*, De Datta, 1981; Yoshida, 1981). Therefore, further investigation was conducted to identify the role of rain water in the form of soil water. To perform this analysis, the relationship between SW_{DEF} at the heading/flowering and grain-filling and maturing stage of rice plant growth and end-of-the season yield in Bangladesh was statistically quantified. It is important to note that rice plant and yield is most sensitive to water stress during the period a few days prior to heading/flowering to heading/flowering and during grain-filling and maturing stage (De Datta, 1981; Yoshida, 1981). Two sets of correlation estimates were computed to determine the relationship between water stress and yield. One set consists of the correlation between baseline yields for the 16 stations and SW_{DEF} for flowering/heading (F/H) stages for the eight transplanting dates as well as the correlation between baseline yields for all stations and SW_{DEF} for the grain-filling and maturing (GF&M) stage for the eight transplanting dates (Table 6.4). The other set consists of the correlation between baseline yield estimates for the eight transplanting dates for each station and SW_{DEF} for the flowering/heading stage in addition to the correlation between baseline yield estimates for the eight transplanting dates for each station and SW_{DEF} for the grain-filling and maturing stage (Table 6.5).

It is important to note that the analysis of variance (ANOVA) could be used to identify the interaction between water stress in both stages and yield.

However, ANOVA requires that its independent variables be nominal variables. The water stress factor does not fulfill this requirement. As result, contingency tables were developed to compare means so that impacts of the combined effect of water stress could be determined (see Table 6.6a-d).

Table 6.4. Correlation between baseline yield estimates for the eight transplanting dates for 16 stations and SW_{DEF} estimates for flowering/heading and grain-filling and maturing stage.

Growth stage vs. yield	06/01	06/15	07/01	07/15	08/01	08/07	08/15	08/23
F/H	X	X	X	X	-.956	-.950	-.851	-.308
GF&M	X	X	.137	-.799	-.710	-.330	-.205	-.293

X = correlation could not be calculated because of no ('0') water stress

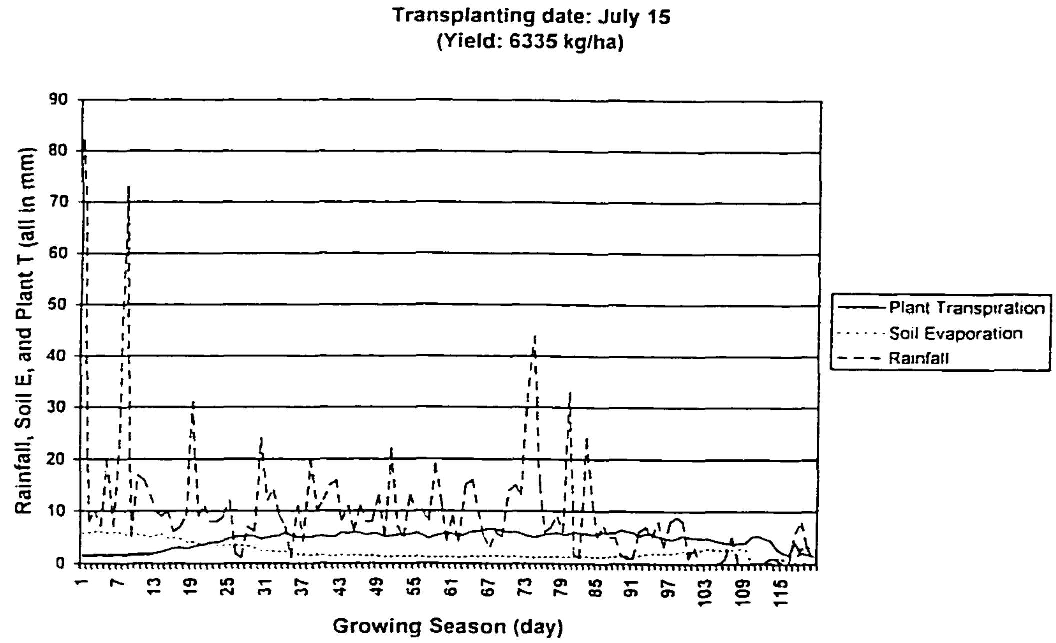
If farmers of Bangladesh transplant rice on June 1 and June 15, and climatic condition is 'normal', then the plants will not experience any water stress during the flowering/heading and the grain-filling and maturing stage Table (6.4). For the July 1 transplanting date, rice plants do not experience any water stress during their flowering/heading while the grain-filling and maturing stage experience low water stress. Water stress is also absent during the flowering/heading stage for July 15 transplanting. However, water stress begins to appear noticeably at the grain-filling and maturing stage (Appendix A.1.) and thus starts to affect yield estimates. The correlation between water stress (shown by SW_{DEF}) and yield is much higher for the August 1 transplanting date and high water stress (SW_{DEF} approaching 1) reduces yield more noticeably. All of the 16 stations experience high to severe water stress during the grain-filling and maturing stage (Appendix A.1.). Nevertheless, Table 6.4 shows a lower correlation between SW_{DEF} at the maturing stage and yield, compared to between SW_{DEF} at flowering/heading stage and yield for August 1 transplanting date. A number of relatively high and a number of relatively low water stress values exist during the flowering/heading stage and their associated low and high yields, respectively, resulted in a higher correlation. It is important to note that the crop loss for the August 1 transplanting date is the result of combined water stress during the last two growth stages of rice plant life cycle.

As above, the correlation between yield and SW_{DEF} for the flowering/heading stage was calculated for the August 7 and August 15 transplanting dates. These values show that yields and SW_{DEF} are negatively correlated. The cause is the same as discussed for the August 1 transplanting date. The correlation between yield and SW_{DEF} for maturing stage is very low for August 8 and 15. In this case, the correlation values hide the fact that yields are consistently low and water stress is consistently high for the August 7 and August 15 transplanting dates. Low correlation values for both growth stages for the August 23 transplanting can be explained similarly. It is interesting to note that water stress values for the flowering/heading stage are consistently lower compared to maturing stage for June, July, and up to mid-August transplanting dates with the exception of August 23. This exception possibly resulted from low atmospheric moisture demand and extremely restricted physiological growth.

Water stress due to late transplanting and resultant yield loss can also be understand from example of Dhaka (Figure 6.3a-b). Compared to the July 15 transplanting date (Figure 6.3a), the August 15 transplanting date (Figure 6.3b) resulted in sharp decline in daily transpiration before end of the vegetative phase and during the flowering/heading and maturing stage. This decline is caused by unavailability of soil water resulted from the low or no rainfall due to the departure of the monsoon. The sharp reduction in transpiration rate hampered rice plants' physiological processes and resulted in low yield.

Correlation values (Table 6.5) do not show any particular regional pattern. However, it is clear that a negative high correlation exists between yield loss and water stress. In addition, the r^2 values are also high. Thus, we can conclude that water stress plays a key role in determining BR11 rainfed transplanted *aman* rice. Figures 6.4a-j show this relationship between water stress during the flowering/heading and grain-filling and maturing stage and yield. During the monsoon season, it rains plentifully in Bangladesh and soil water availability is not limiting. As a result, intra-seasonal rainfall variability does not play a major role. However, by transplanting rice seedlings at the right time farmers can ensure an optimum yield. It is clear that water stress at the end of the rice growing season due to late transplanting can significantly reduce yield. This is further illustrated

a)



b)

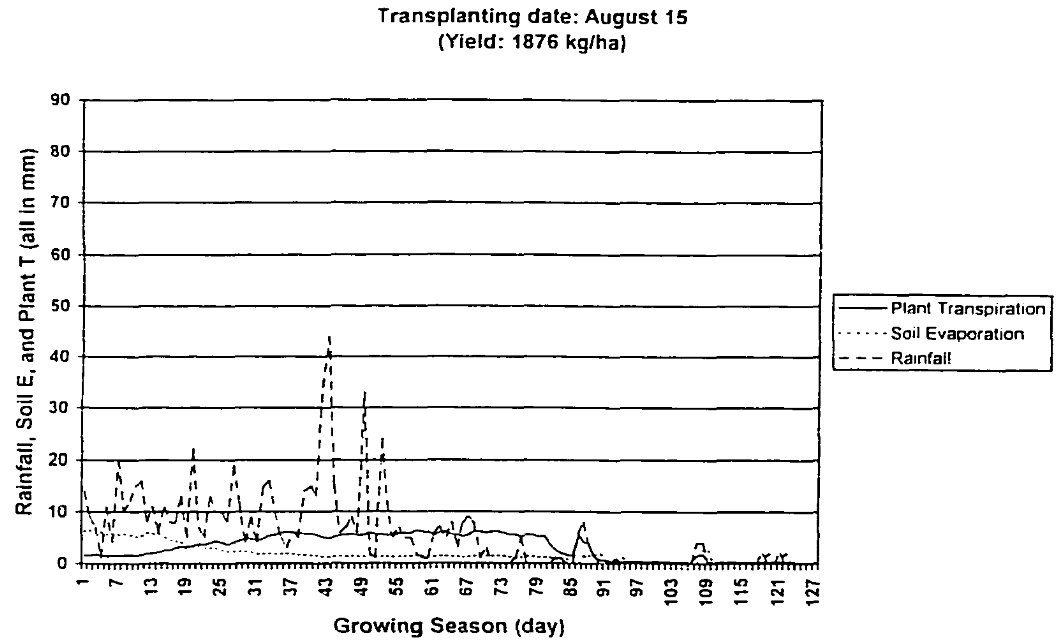


Figure 6.3a-b. Daily rainfall, soil evaporation, plant transpiration, and baseline yield estimates for Dhaka for two transplanting dates.

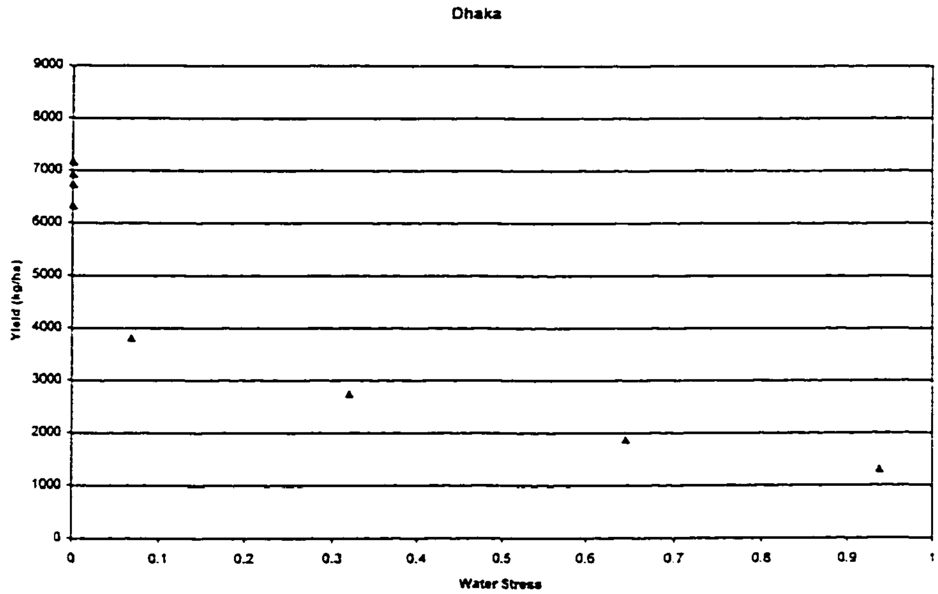
in the following chapter.

As discussed above, contingency tables (Table 6.6a-d) of yield estimates for 4 selected transplanting dates were created to demonstrate the combined impacts of various levels of water stress on the yield during the flowering/heading and maturing stage. In these tables, high and low water stress occurs when $SW_{DEF} \geq 0.6$ and $SW_{DEF} < 0.6$, respectively. These definitions were developed through survey of yield and water stress relationship. It has been found that yield sharply declines when water stress is above 0.6 (*cf.* Figures 6.4a-j). Tables 6.6a-d shows that when water stress is low in both the flowering/heading and maturing stages, yield is high. Yield decreased (Table 6.6c) when water stress is reported for the maturing stage. Crop loss was severe when the model estimated higher water stress during the maturing stage (Table 6.6d). This severity of yield loss increases when both flowering/heading and maturing stage reports high water stress (Table 6.6d).

Table 6.5. Correlation: yield vs. water stress for eight transplanting date and for 16 stations.

Station	Flowering/heading stage		Maturing stage	
	(r)	(r^2)	(r)	(r^2)
Dhaka	-0.890	(0.79)	-0.972	(0.94)
Rangpur	-0.893	(0.80)	-0.967	(0.93)
Jessore	-0.977	(0.95)	-0.986	(0.97)
Khulna	-0.910	(0.82)	-0.979	(0.96)
Chandpur	-0.967	(0.93)	-0.985	(0.97)
Comilla	-0.963	(0.93)	-0.984	(0.97)
Faridpur	-0.958	(0.92)	-0.989	(0.98)
Mymensingh	-0.953	(0.91)	-0.975	(0.95)
Maijdi Court	-0.883	(0.78)	-0.982	(0.96)
Feni	-0.858	(0.74)	-0.978	(0.96)
Sylhet	-0.908	(0.82)	-0.947	(0.90)
Satkhira	-0.907	(0.82)	-0.973	(0.95)
Barisal	-0.850	(0.72)	-0.978	(0.96)
Bogra	-0.960	(0.92)	-0.984	(0.97)
Dinajpur	-0.944	(0.89)	-0.977	(0.95)
Iswardi	-0.950	(0.90)	-0.974	(0.95)

a)



b)

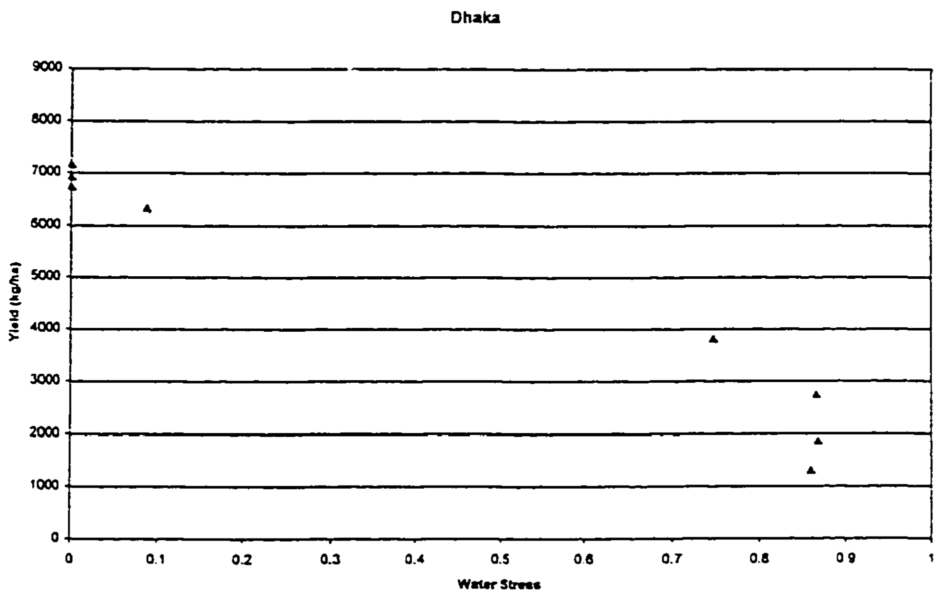
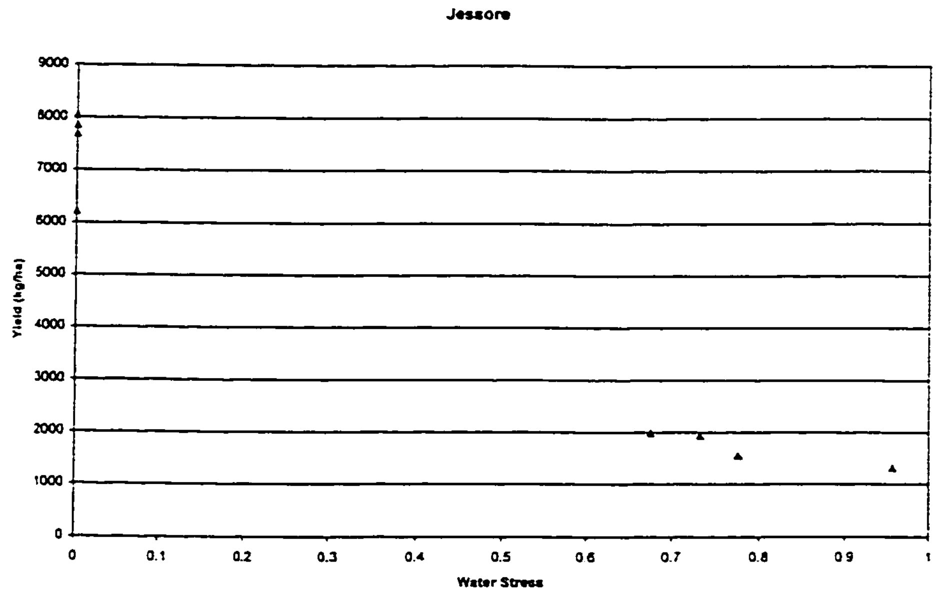


Figure 6.4. Dhaka: baseline yield and water stress during the flowering/heading (a), and the maturing stage (b).

c)



d)

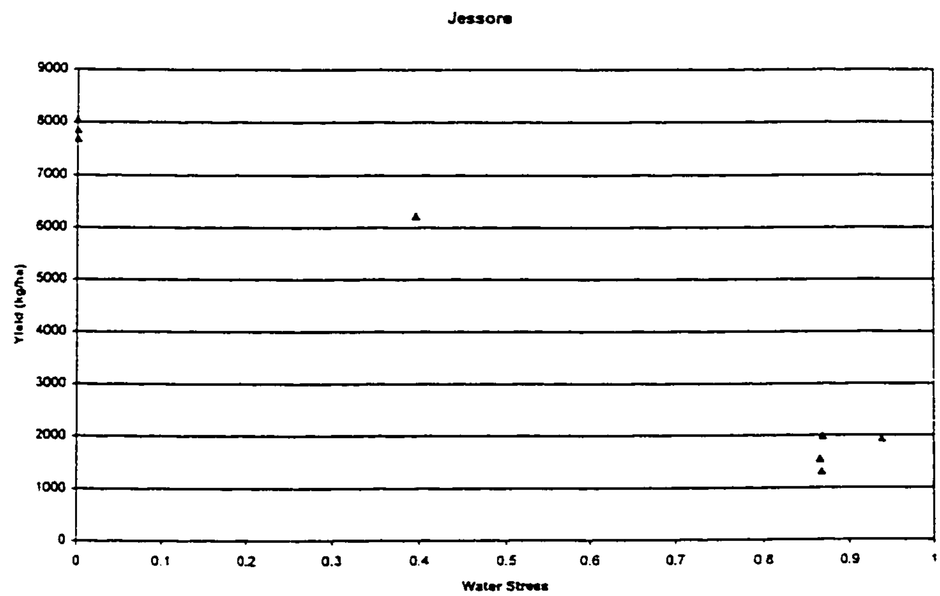
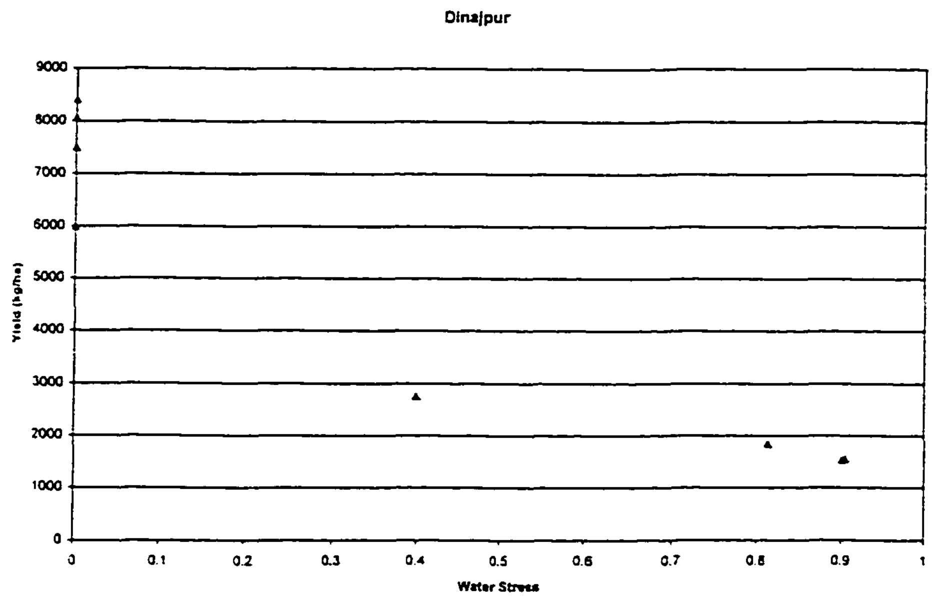


Figure 6.4. *continued.* Jessore: baseline yield and water stress during the flowering/heading (c), and the maturing stage (d).

e)



f)

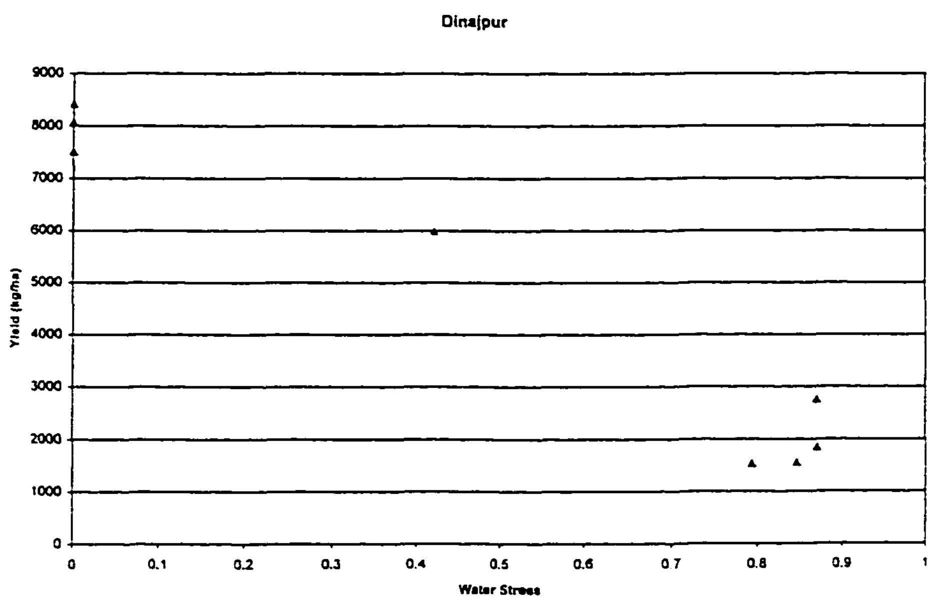
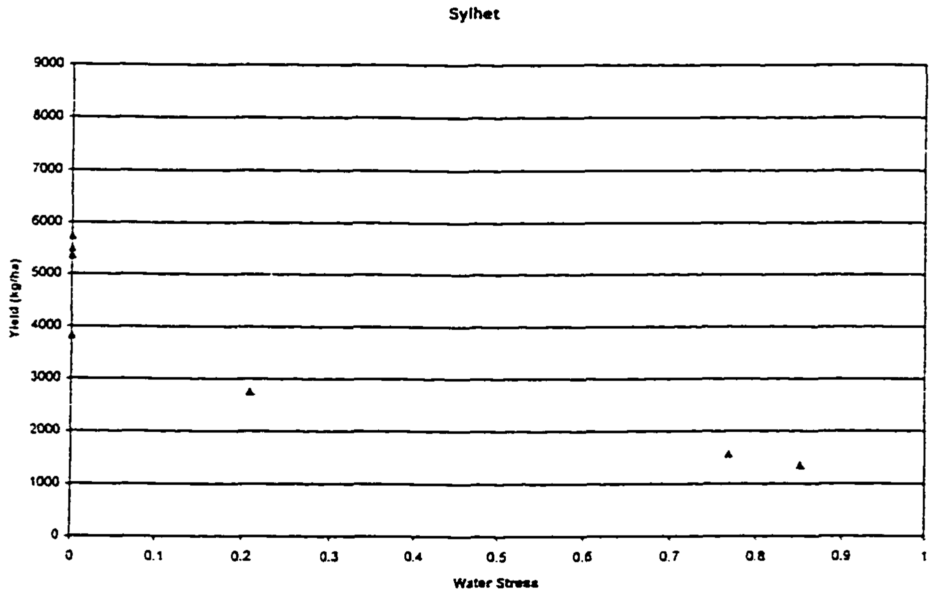


Figure 6.4. *continued.* Dinajpur: baseline yield and water stress during the flowering/heading (e), and the maturing stage (f).

g)



h)

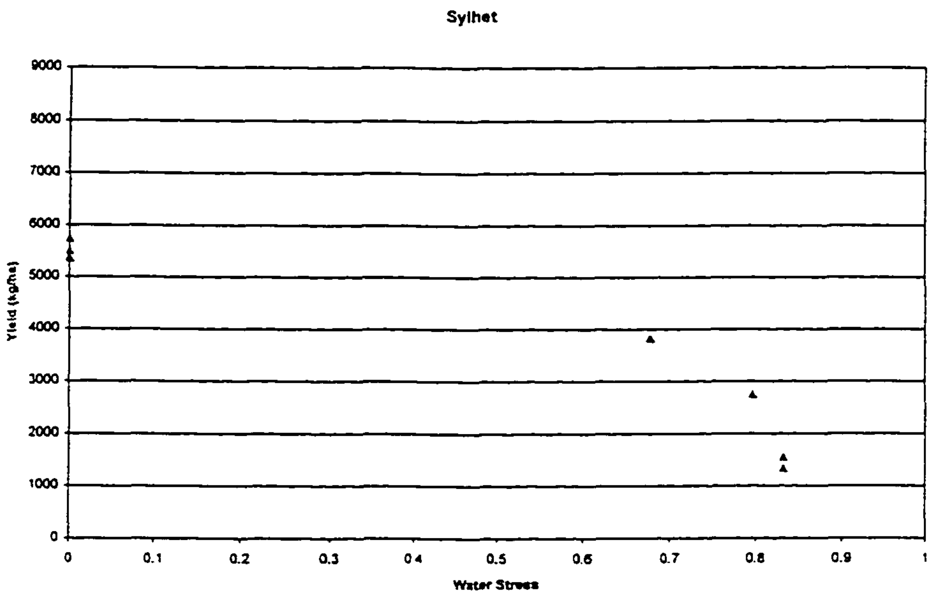
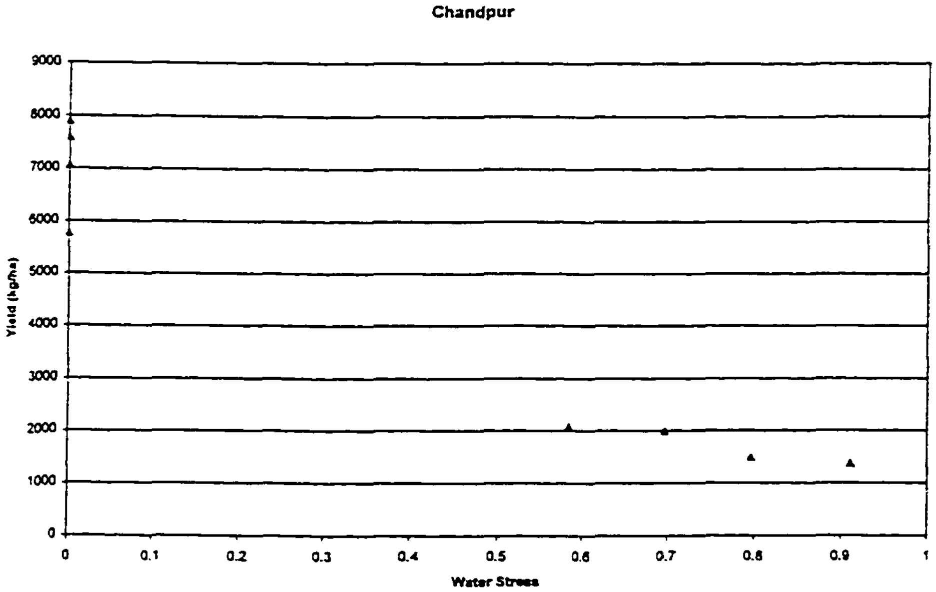


Figure 6.4. *continued.* Sylhet: baseline yield and water stress during the flowering/heading (g), and the maturing stage (h).

i)



j)

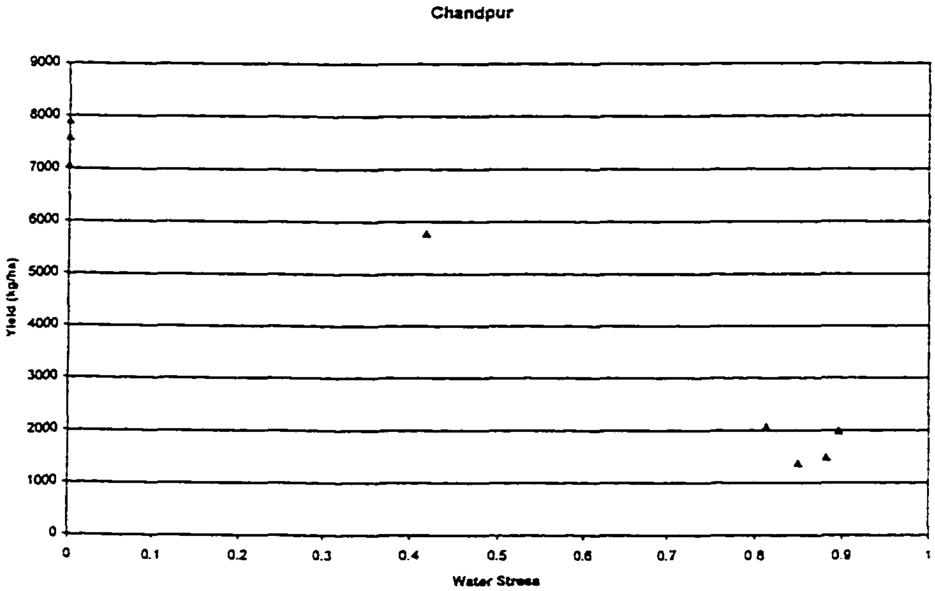


Figure 6.4. *continued.* Chandpur: baseline yield and water stress during the flowering/heading (i), and the maturing stage (j).

Table 6.6a. Baseline yield (kg ha^{-1}) estimates for 16 stations for high and low water stress, categorized for stage 4 and stage 5 water stress conditions. Stage 4: Flowering/heading; Stage 5: Maturing. Transplanting date: June 1.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	7168, 7695, 8045, 8271, 7910, 7904, 8144, 7415, 8168, 7336, 5374, 8209, 8396, 7600, 8413, 7917. Mean = 7748 kg ha^{-1}	None
Stage 5: High water stress	None	None

Table 6.6b. Baseline yield (kg ha^{-1}) estimates for 16 stations for high and low water stress, categorized for stage 4 and stage 5 water stress conditions. Stage 4: Flowering/heading; Stage 5: Maturing. Transplanting date: July 1.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	6741, 6960, 7688, 7479, 7068, 7605, 7391, 7007, 6579, 6679, 5357, 7454, 7350, 7164, 7506, 7227. Mean = 7078 kg ha^{-1}	None
Stage 5: High water stress	None	None

Table 6.6c. Baseline yield (kg ha^{-1}) estimates for 16 stations for high and low water stress, categorized for stage 4 and stage 5 water stress conditions. Stage 4: Flowering/heading; Stage 5: Maturing. Transplanting date: July 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	6335, 6700, 6221, 6640, 5776, 5600, 6312, 5020, 6168, 6364, 5737, 6839, 7075, 5725, 5993. Mean = 6167 kg ha^{-1}	None
Stage 5: High water stress	4797 Mean = 4797 kg ha^{-1}	None

Table 6.6d. Baseline yield (kg ha^{-1}) estimates for 16 stations for high and low water stress, categorized for stage 4 and stage 5 water stress conditions. Stage 4: Flowering/heading; Stage 5: Maturing. Transplanting date: August 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	None	None
Stage 5: High water stress	2752, 2319, 2462, 2075, 2319, 2755, 2421, 2932. Mean = 2504 kg ha^{-1}	1940, 1993, 2099, 2316, 1686, 1552, 1851, 1594. Mean = 1879 kg ha^{-1}

6.4. Summary

The results presented in this chapter corroborate the findings of many other studies (*cf.*, Jearakongman *et al.*, 1995; Lilly and Fukai, 1994; Thangaraj et al., 1990; Yambao and Ingram, 1988; and Gupta and Agarwal, 1989). Timsina *et al.* (1998) found in their field experiment that yield of BR11 declines up to 49% under rainfed conditions compared to irrigated conditions due to water stress. In addition, Islam and Mondal (1992) suggested that monsoon season rice yield declines significantly in Bangladesh due to moisture stress during the flowering and maturing stage. Wonprasaid *et al.* (1996) reported physiological stress due to water deficit during grain-filling. Boonjung and Fukai (1996a, b) found from their field experiment that soil water deficit adversely effects growth, phenology, and final yield. They have noted that there was a 40% decrease in filled grains, and that grain mass was decreased by 20% due to the water stress. Wopereis *et al.* (1996) also reported from their field experiment that drought during the flowering/heading stage severely reduces yield. They found that number of filled grains reduces significantly and this results in low yield.

CHAPTER 7

TRANSPLANTING DATE, WATER STRESS, AND VULNERABILITY OF RICE PRODUCTIVITY IN BANGLADESH

7.1. Transplanting date, water stress, and yield

The role of water stress in predicting the final yield has become very clear from the analysis of baseline rice productivity estimates. As a result, further analyses have been conducted for all the stations and for the complete study period (1975-1987). Table 7.1 presents the correlation estimates between yield and water stress during the flowering/heading stage. The yield estimates of Feni, Faridpur, Rangpur, Dinajpur, Rangpur, Mymensingh, Dhaka, and Dhaka, show the highest negative correlation with water stress during flowering/heading stage (4^{th} stage of growth in the model) for the transplanting dates of June 1, June 15, July 1, July 15, August 1, August 7, August 15, and of August 23, respectively. In other words, yields in these eight regions are going to be the most affected due to water stress at the 4^{th} stage if farmers transplant rice on these respective dates. It is important to note that rice plants in Khulna and Maijdi Court and in Rangpur did not experience any water stress during the flower/heading stage when transplanted on June 1 and June 15, respectively. It has also been found that the yields of Barisal, Sylhet, Sylhet, Barisal, Mymensingh, Ishwardi, Bogra, and Ishwardi show the lowest correlation with water stress during the 4^{th} stage of rice plant growth for

Table 7.1. Correlation between yield and water stress during flowering/heading stage under selected transplanting dates.

Station	June 01	June 15	July 01	July 15
Dhaka	-0.905	-0.900	-0.758	-0.872
Jessore	-0.780	-0.811	-0.855	-0.917
Dinajpur	-0.946	-0.781	-0.809	-0.942
Mymensingh	-0.692	-0.674	-0.754	-0.939
Comilla	-0.841	-0.911	-0.833	-0.895
Faridpur	-0.726	-0.934	-0.867	-0.890
Barisal	-0.109	-0.501	-0.919	-0.751
Maijdi Court	---	-0.832	-0.807	-0.793
Ishwardi	-0.866	-0.841	-0.681	-0.959
Bogra	-0.913	-0.797	-0.881	-0.894
Khulna	---	-0.920	-0.829	-0.854
Rangpur	0.334	---	-0.929	-0.848
Satkhira	-0.745	-0.912	-0.651	-0.931
Chandpur	-0.854	-0.863	-0.802	-0.918
Feni	-0.964	-0.901	-0.864	-0.870
Sylhet	-0.580	-0.629	-0.482	-0.860

Station	August 01	August 07	August 15	August 23
Dhaka	-0.932	-0.887	-0.992	-0.974
Jessore	-0.793	-0.958	-0.964	-0.890
Dinajpur	-0.962	-0.982	-0.987	-0.926
Mymensingh	-0.704	-0.984	-0.976	-0.580
Comilla	-0.874	-0.857	-0.927	-0.828
Faridpur	-0.860	-0.981	-0.927	-0.844
Barisal	-0.971	-0.961	-0.893	-0.639
Maijdi Court	-0.975	-0.969	-0.962	-0.952
Ishwardi	-0.955	-0.733	-0.295	0
Bogra	-0.948	-0.931	-0.031	-0.133
Khulna	-0.940	-0.870	-0.864	-0.814
Rangpur	-0.987	-0.952	-0.655	0.859
Satkhira	-0.941	-0.781	-0.981	-0.937
Chandpur	-0.963	-0.929	-0.911	-0.586
Feni	-0.897	-0.913	-0.892	-0.941
Sylhet	-0.949	-0.915	-0.874	-0.946

the transplanting dates of June 1, June 15, July 1, July 15, August 1, August 7, August 15, and of August 23, respectively. However, the highest and lowest correlations between water stress during the 4^{th} growth stage and yield alone did not explained the reduction of yield. Rather it can be explained by analyzing the combined impacts of water stress at the flowering/heading and maturing stages of rice plant growth. This is illustrated later in this chapter. Nevertheless, these correlation values can be used as important indicators of water stress and yield relationships by crop planners and policy makers. Furthermore, Table 7.2 presents the correlation estimates between water stress during the maturing stage and yield. This table shows productivity estimates for Khulna, Chandpur, Bogra, Faridpur, Jessore, Satkhira, Dinajpur, and Dinajpur maintain the highest negative correlation with water stress during the maturing stage for the transplanting dates of June 1, June 15, July 1, July 15, August 1, August 7, August 15, and of August 23, respectively. The lowest correlation values for these dates do not explain yield variations despite significant productivity reduction with progression of transplanting dates toward the end of the monsoon season. The reasons for such low values were discussed in Chapter 6.

To illustrate the impacts of the combined effect of water stress during flowering/heading and maturing stage, contingency tables for 4 transplanting dates including the June 1, July 1, July 15, and August 15, and 5 selected stations including Dhaka, Jessore, Dinajpur, Sylhet, and Chandpur were created that

Table 7.2. Correlation between yield and water stress during maturing stage under selected transplanting dates.

Station	June 01	June 15	July 01	July 15
Dhaka	-0.916	-0.390	-0.839	-0.855
Jessore	-0.833	-0.855	-0.948	-0.894
Dinajpur	-0.891	-0.901	-0.858	-0.875
Mymensingh	-0.602	-0.685	-0.877	-0.784
Comilla	-0.931	-0.739	-0.925	-0.667
Faridpur	-0.773	-0.951	-0.805	-0.932
Barisal	-0.074	-0.873	-0.862	-0.867
Maijdi Court	-0.764	-0.847	-0.866	-0.908
Ishwardi	-0.814	-0.369	-0.644	-0.644
Bogra	-0.611	-0.824	-0.953	-0.728
Khulna	-0.918	-0.902	-0.948	-0.881
Rangpur	-0.134	-0.879	-0.811	-0.817
Satkhira	-0.859	-0.793	-0.941	-0.815
Chandpur	-0.930	-0.970	-0.951	-0.899
Feni	-0.873	-0.861	-0.771	-0.843
Sylhet	-0.533	-0.546	-0.780	-0.792

Station	August 01	August 07	August 15	August 23
Dhaka	-0.704	-0.703	-0.068	0.218
Jessore	-0.856	-0.879	-0.199	0.080
Dinajpur	-0.100	-0.731	-0.799	-0.814
Mymensingh	-0.688	-0.465	-0.210	0.219
Comilla	-0.514	-0.514	-0.082	0.490
Faridpur	-0.502	-0.385	-0.081	-0.038
Barisal	-0.485	0.240	0.460	-0.479
Maijdi Court	-0.821	-0.475	-0.428	-0.177
Ishwardi	-0.070	-0.277	-0.138	-0.066
Bogra	-0.201	-0.353	-0.090	-0.268
Khulna	-0.501	-0.721	-0.755	0.119
Rangpur	-0.307	-0.039	-0.219	-0.088
Satkhira	-0.460	-0.916	-0.605	-0.142
Chandpur	-0.401	-0.517	0.131	0.401
Feni	-0.732	-0.713	-0.646	-0.400
Sylhet	-0.141	-0.057	-0.008	-0.055

represent various precipitation regimes (*cf.*, Manalo, 1976). Table 7.3a-d shows that, in Dhaka, water stress at growth stages 4 and 5 affects rainfed rice crop productivity, and that this effect becomes acute if we shift the transplanting date from the early part of the monsoon season to the late (see also Figures 7.1a-d and 7.2a-d). Table 7.3a shows low water stress when the farmers of Dhaka, Bangladesh transplant rice on June 1 and this results in the highest average yield (7565 ka ha^{-1}) compared to other transplanting dates. However, if farmers shift the transplanting date on July 1, at least in one case, they experience pronounced water stress (Figure 7.2b). It is also found that for the July 1 transplanting date, the average yield declines compared to the June 1 transplanting date during low water stress conditions for both the flowering/heading stage and the maturing stage. This trend continues for the July 15 transplanting date (Table 7.3c). Hence, an increase in the degree of water stress plays an important role in this yield reduction trend. Furthermore, cases of yield obtained under low water stress also decrease up to the July 15 transplanting date. By August 15, high water stress appears during at least one growth stage. It is important to note that number of cases of high water stress-affected yields increase as we shift transplanting dates well into the monsoon. For the July 15 transplanting date, there is only one case of high water stress-affected yield. This water stress occurs at both the flowering/heading and the maturing stage. On the other hand, for the August 15 transplanting date, there are 9 yield estimates which are affected by high water stress at both stages. In addition, yield reduction is very noticeable when water stress is high at both stages compared to one growth stage (Table 7.3a-d). The effect of water stress at stage 4 and stage 5 has on the yield is also illustrated in Appendix B for Jessore, Dinajpur, Sylhet, and Chandpur.

Figures 7.3 to 7.10 show that effect of water stress during the flowering/ heading and maturing stage on yield for these four regions. These figures also show that yield decreases as water stress increases during the stage 4 and 5 with progress of transplanting dates into the monsoon. Rainfall-wise relatively dry Jessore (Figure 7.3b), Dinajpur (Figure 7.5b), and Chandpur (7.9b) experience a few events of high water stress during stage 4 even for the July 1 transplanting date. High water stress is most pronounced for the July 15 and August 15 transplanting dates during both stage 4 and 5 growth phases for these four regions (Figures 7.2c-d to 7.10c-d).

Table 7.3a. Yield (kg ha^{-1}) estimates for Dhaka (1975-87) for high and low water stress. Transplanting date: June1.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	8160, 7177, 4434, 7271, 8389, 8287, 8152, 8221, 7744, 6900, 8010, 7764, 7384. Mean = 7565	None
Stage 5: High water stress	None	None

Table 7.3b. Yield (kg ha^{-1}) estimates for Dhaka (1975-87) for high and low water stress. Transplanting date: July 1.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	7722, 5616, 6498, 6292, 7713, 8271, 6622, 7461, 3555, 7154, 7747, 7259. Mean = 6826	None
Stage 5: High water stress	5661. Mean = 5661	None

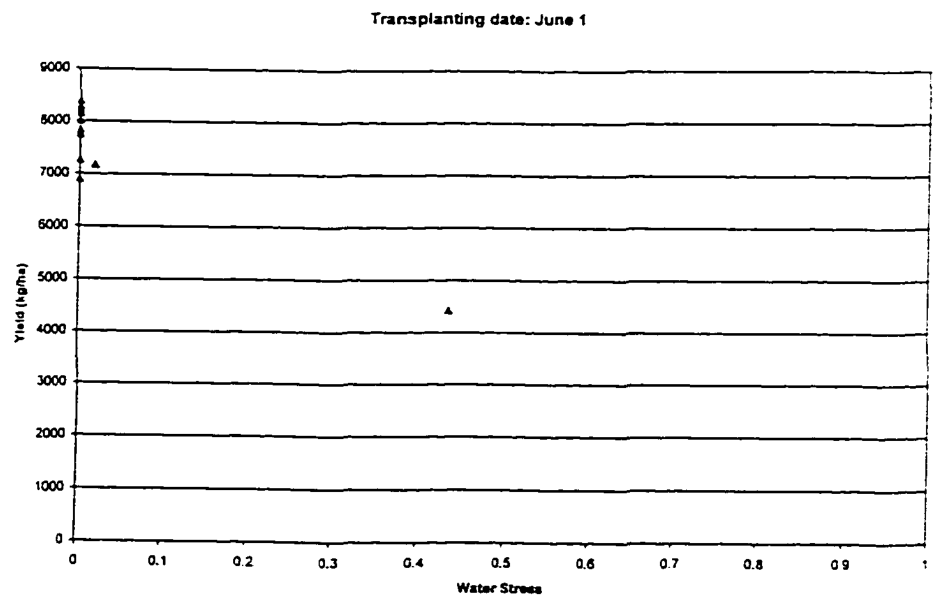
Table 7.3c. Yield (kg ha^{-1}) estimates for Dhaka (1975-87) for high and low water stress. Transplanting date: July 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	7508, 6828, 5219, 8109, 4446, 7014, 6959, 6092. Mean = 6522.	None
Stage 5: High water stress	3439, 4976, 2483, 4123. Mean= 3755	2237 Mean = 2237

Table 7.3d. Yield (kg ha^{-1}) estimates for Dhaka (1975-87) for high and low water stress. Transplanting date: August 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	None	1406, 1419 Mean = 1412
Stage 5: High water stress	3576, 4854 Mean = 4215	2014, 1446, 1969, 1441, 1977, 1525, 1364, 1420, 1758 Mean = 1657

a)



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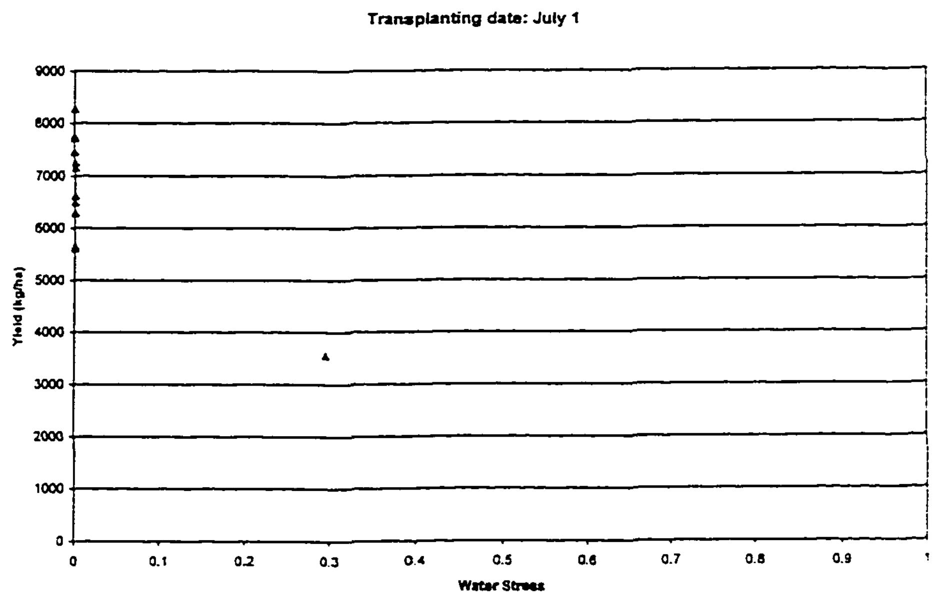
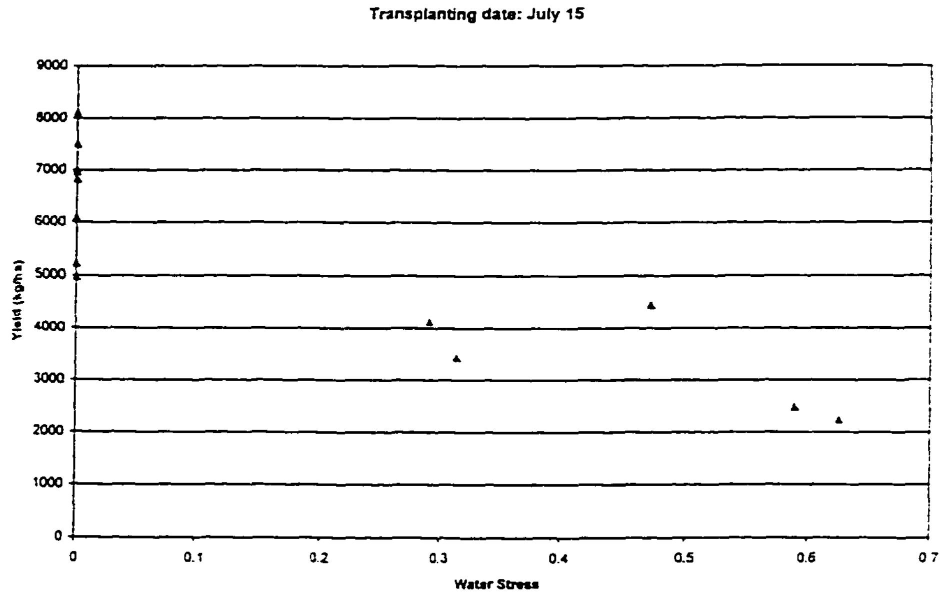


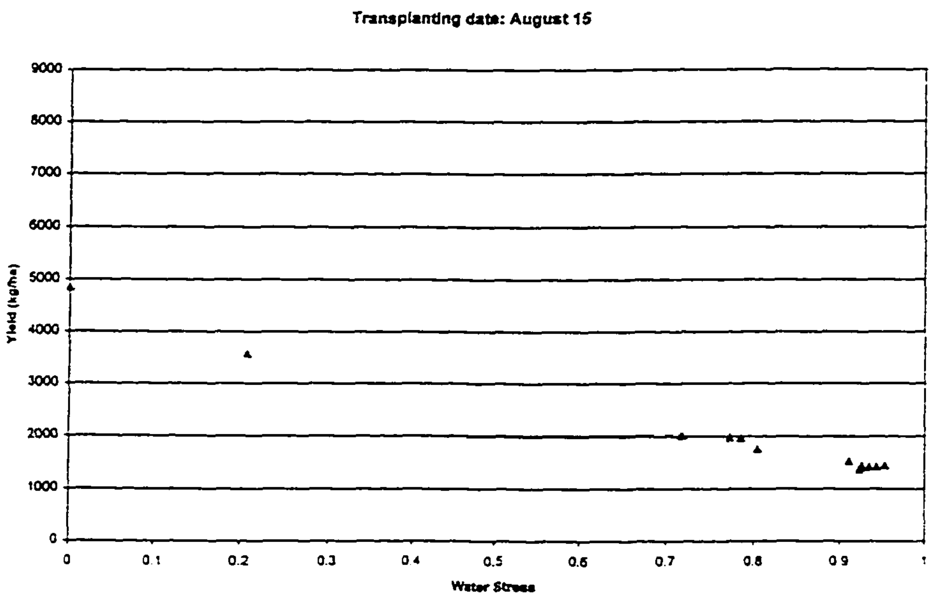
Figure 7.1a-d. Dhaka: Water stress during the flowering/heading stage and yield.

c)



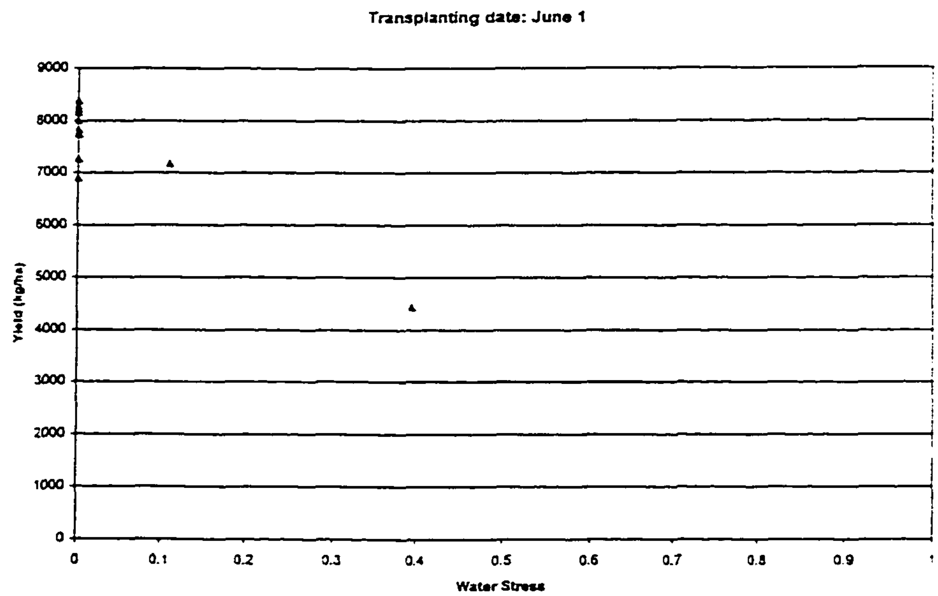
Transplanting date: July 15
Yield (kg/ha)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Water Stress

d)



Transplanting date: August 15
Yield (kg/ha)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

a)



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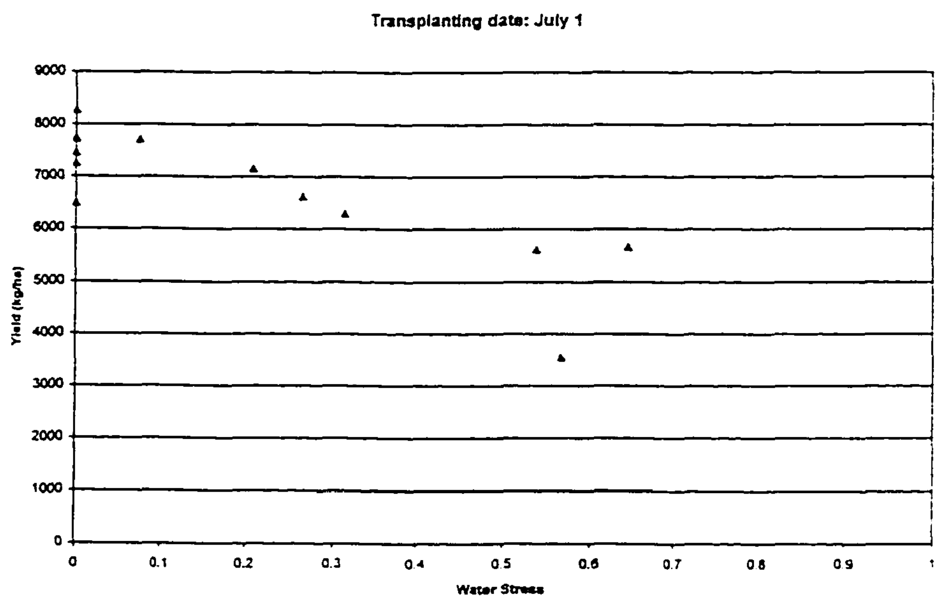
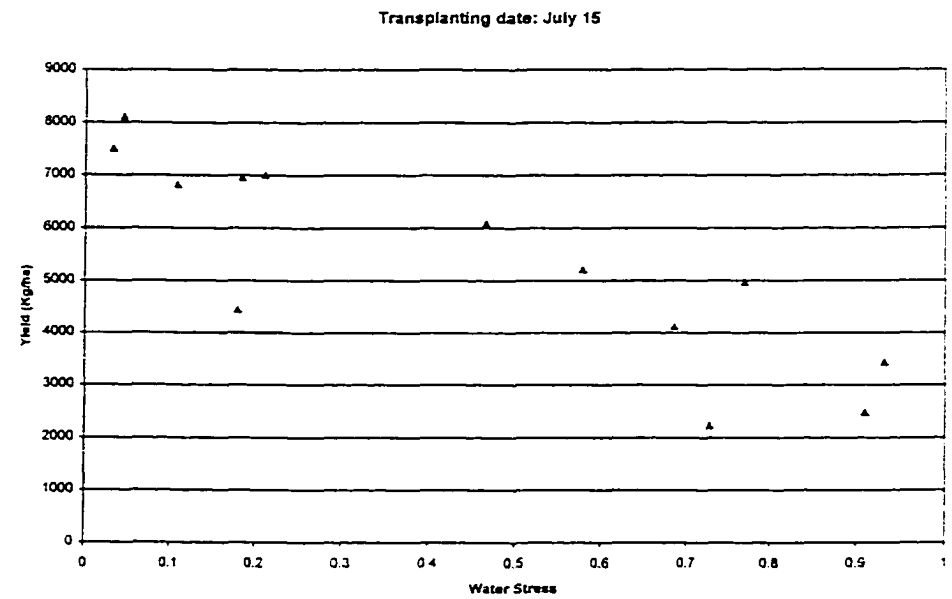
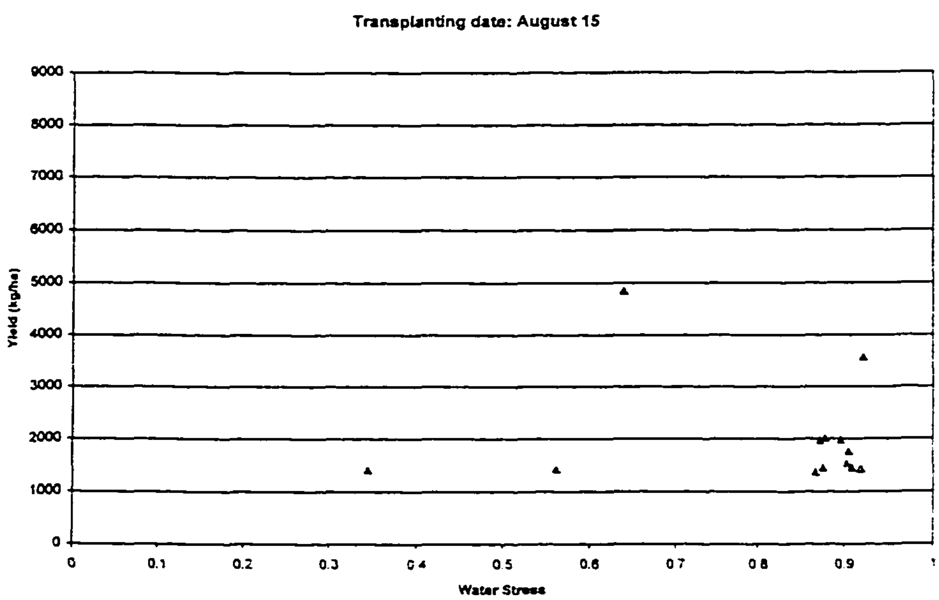


Figure 7.2a-d. Dhaka: Water stress during the maturing stage and yield.

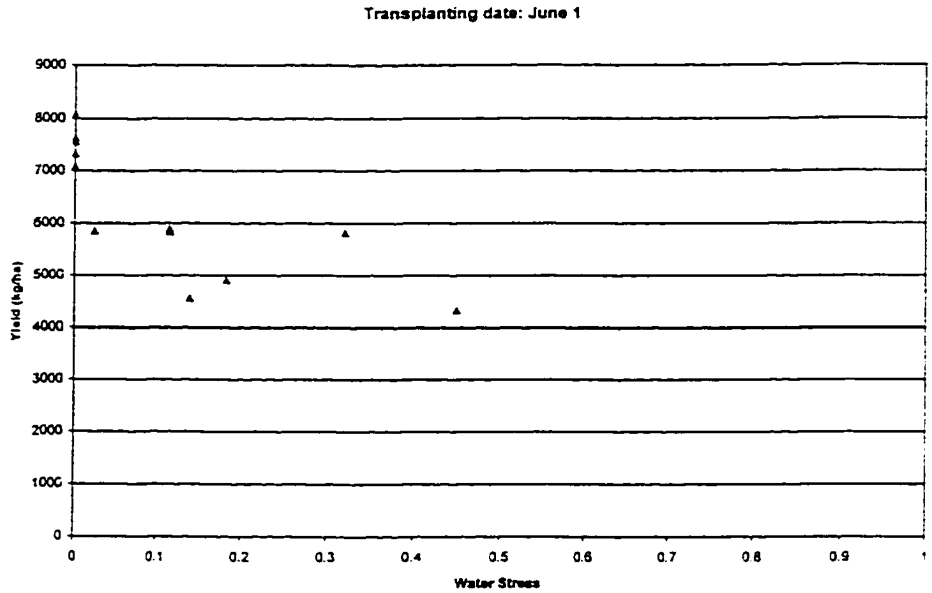
c)


Transplanting date: July 15
Yield (Kg/ha)
Water Stress
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

d)


Transplanting date: August 15
Yield (kg/ha)
Water Stress
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

a)



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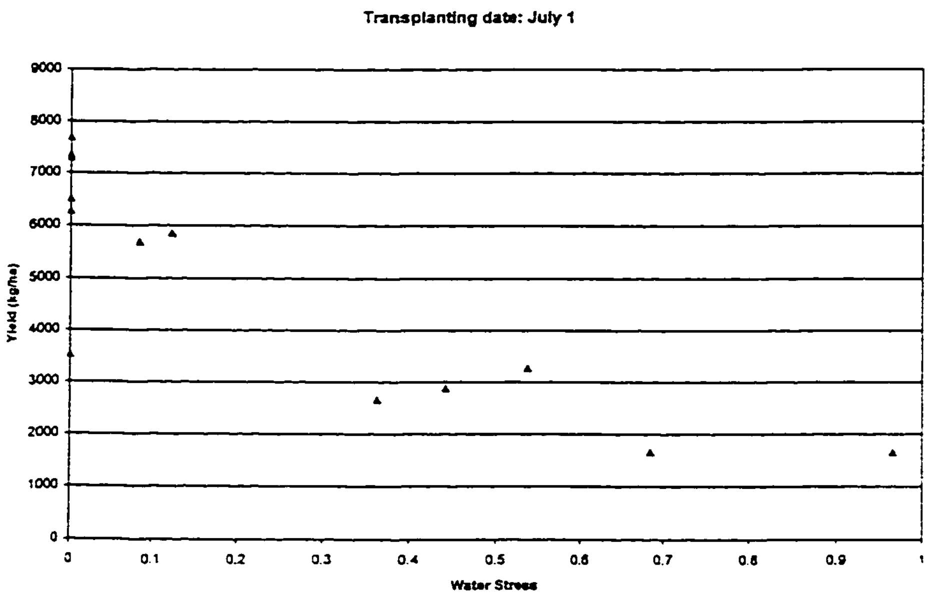
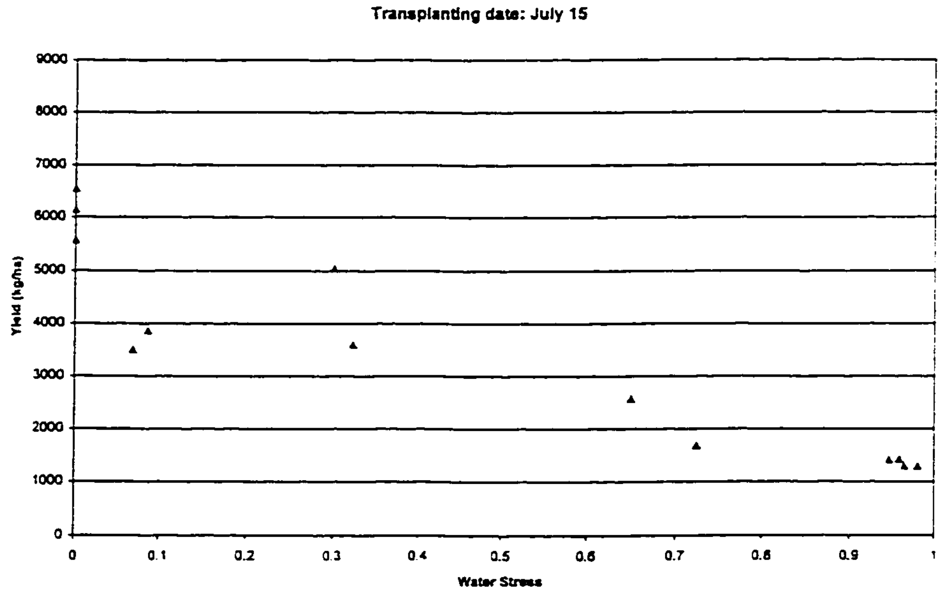


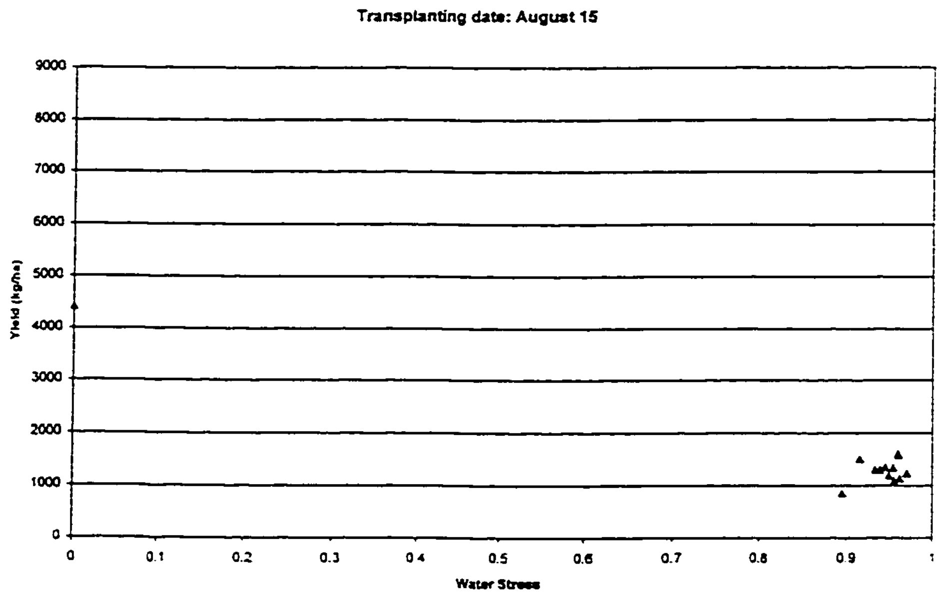
Figure 7.3a-d. Jessore: Water stress during the flowering/heading stage and yield.

c)



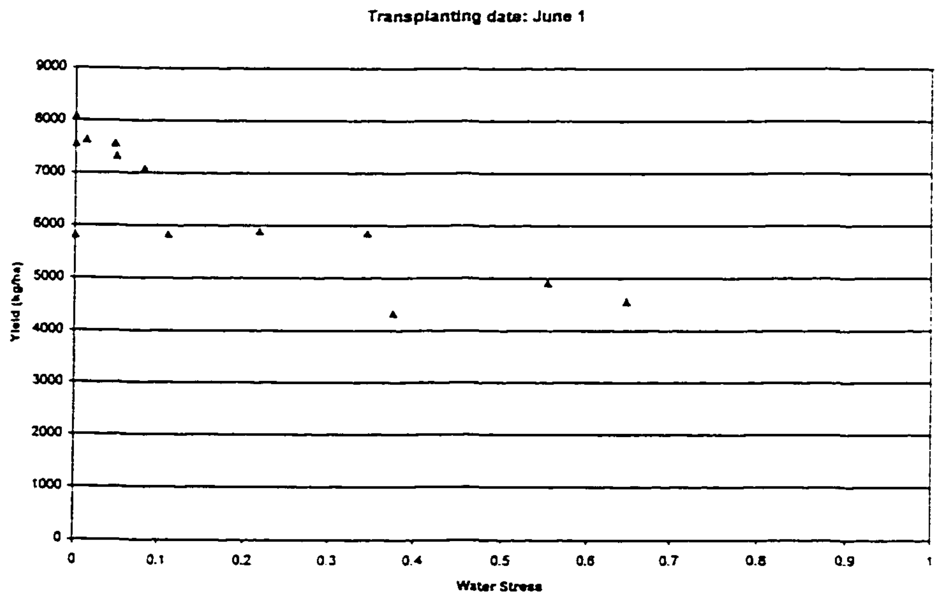
Transplanting date: July 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

d)



Transplanting date: August 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

a)



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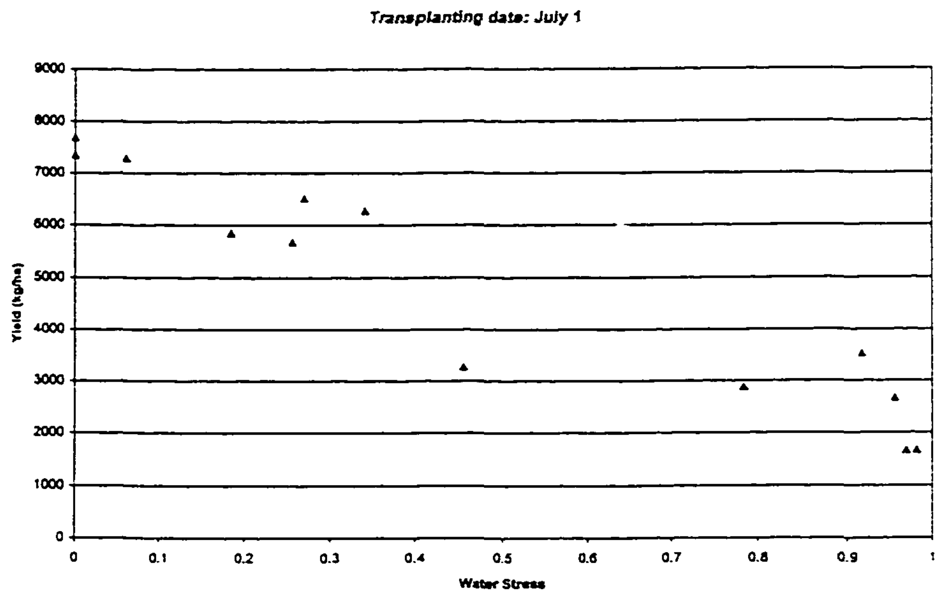
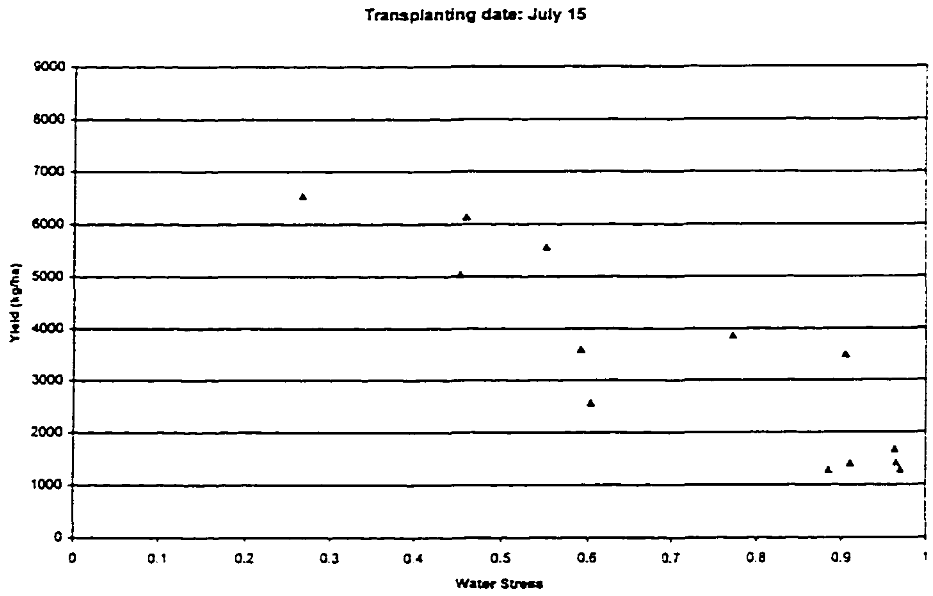
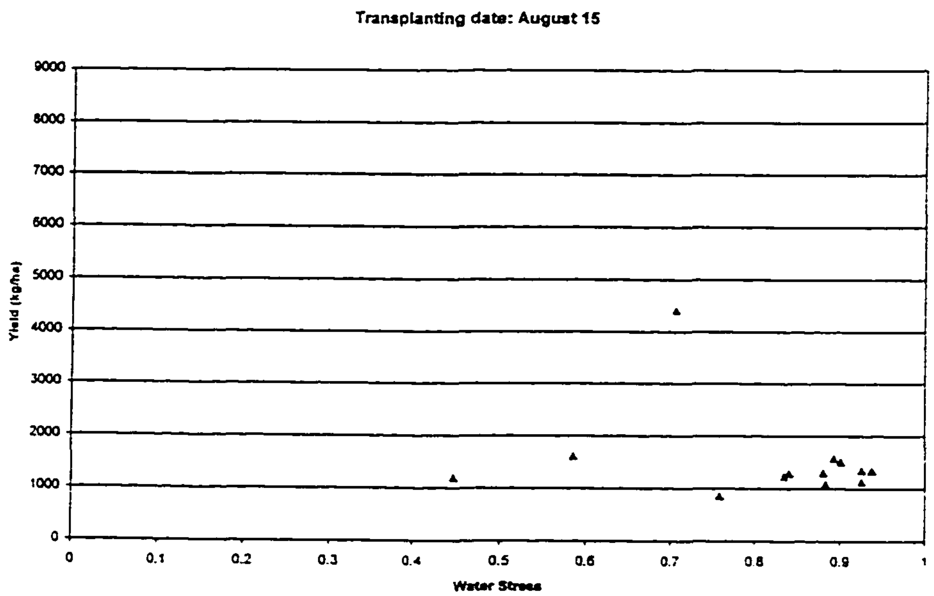


Figure 7.4a-d. Jessore: Water stress during the maturing stage and yield.

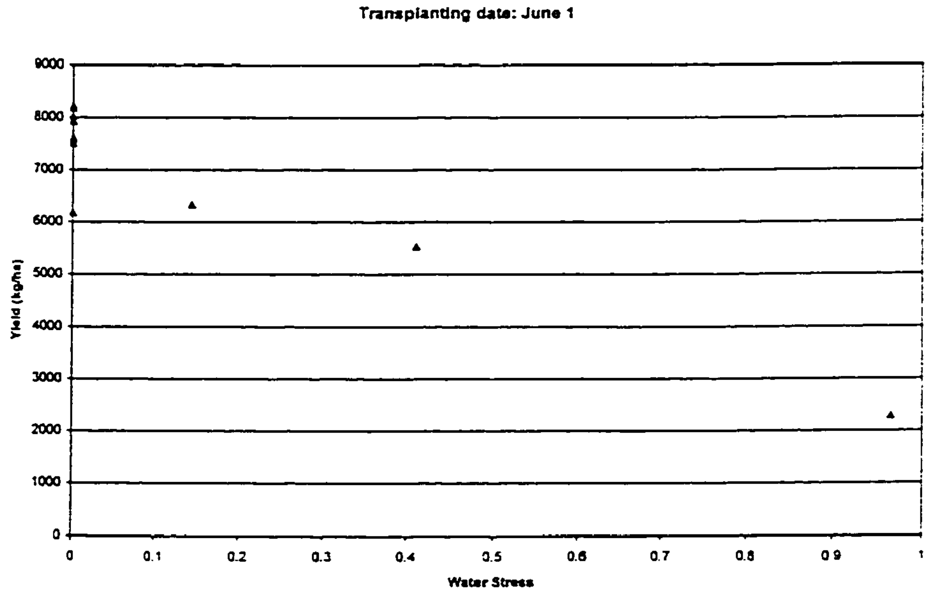
c)


Transplanting date: July 15
Yield (kg/ha)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

d)


Transplanting date: August 15
Yield (kg/ha)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

a)



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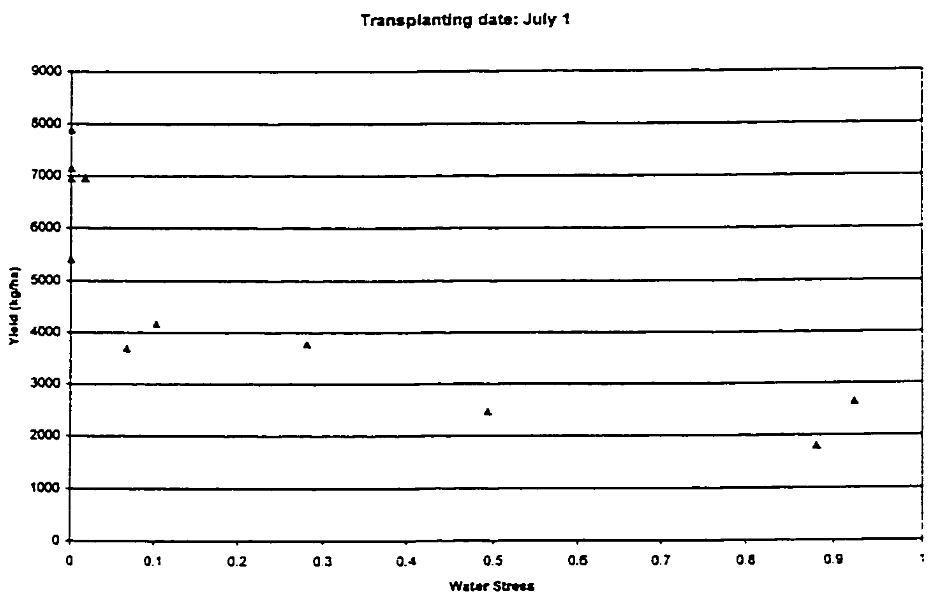
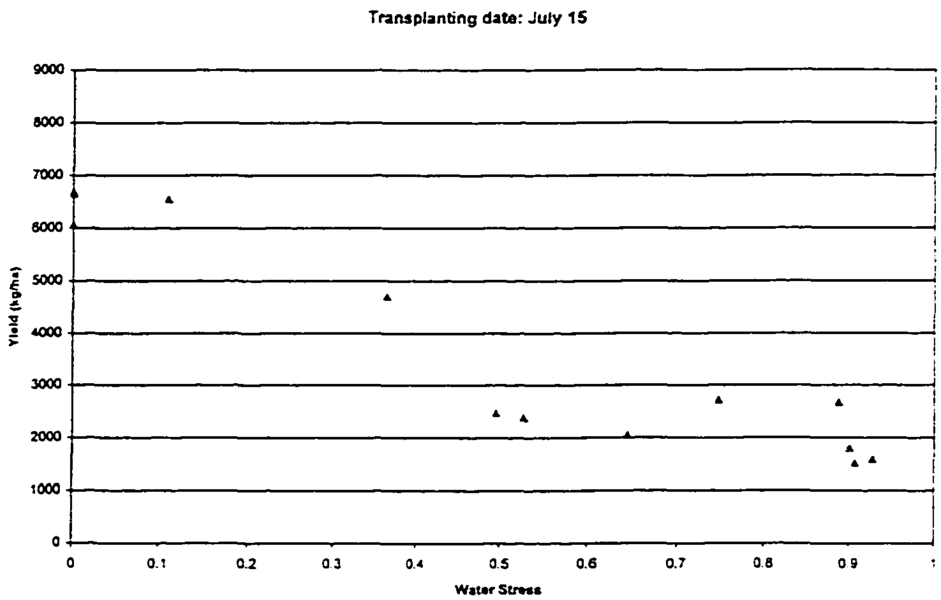
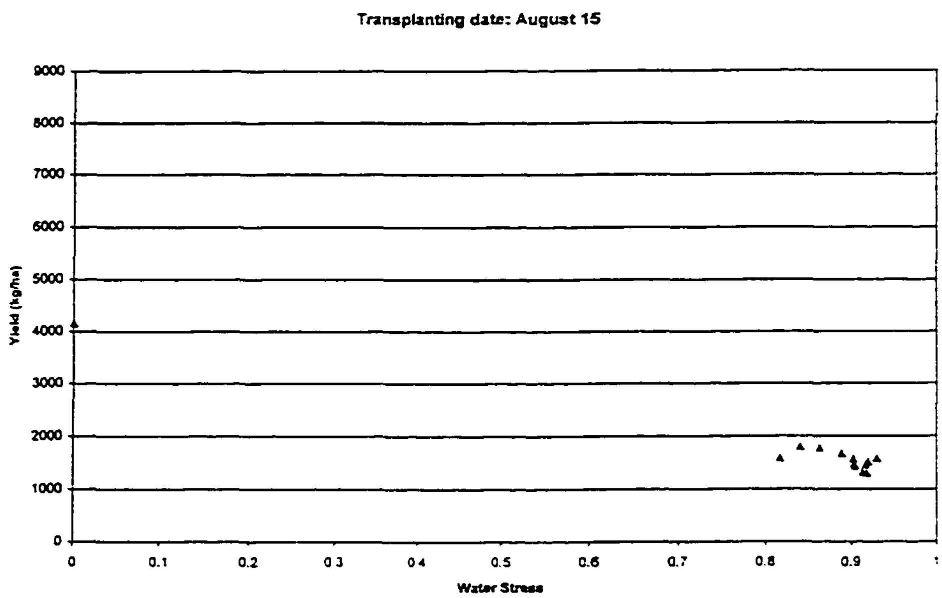


Figure 7.5a-d. Dinajpur: Water stress during the flowering/heading stage and yield.

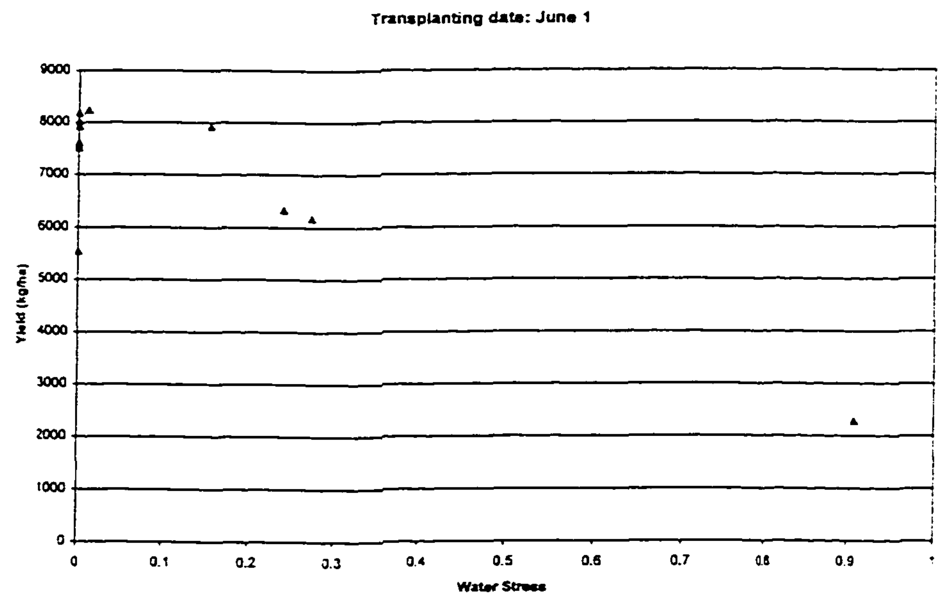
c)


Transplanting date: July 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

d)


Transplanting date: August 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

a)



b)

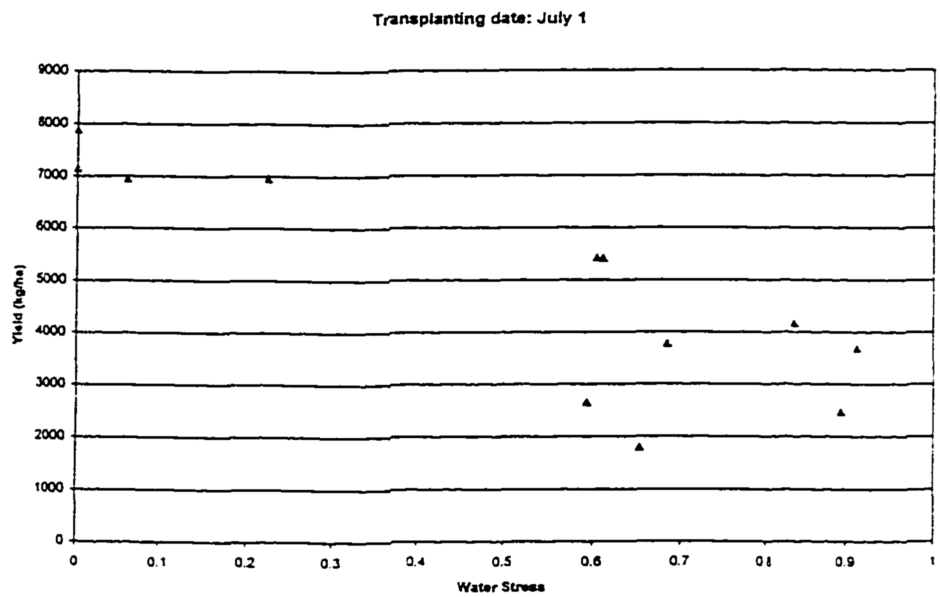
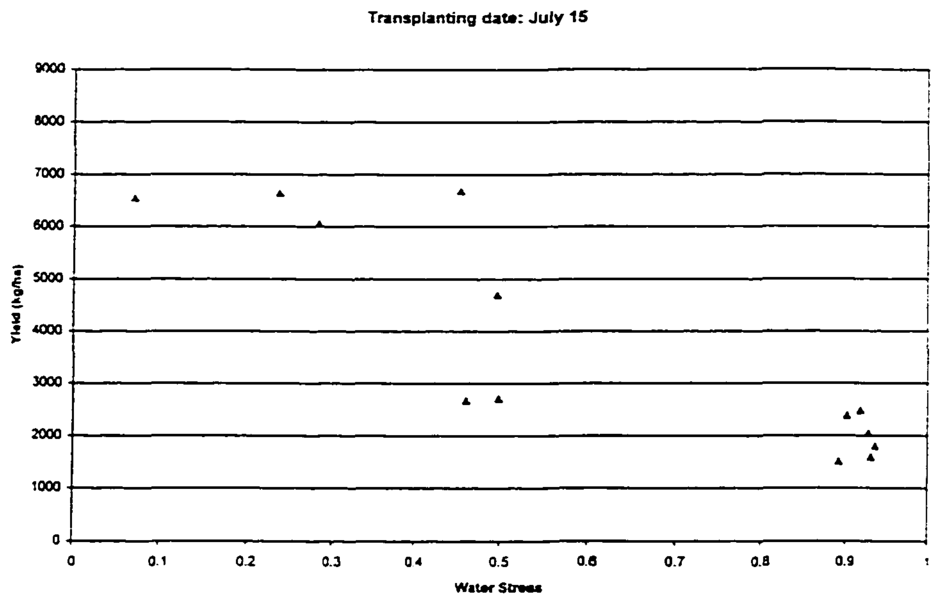
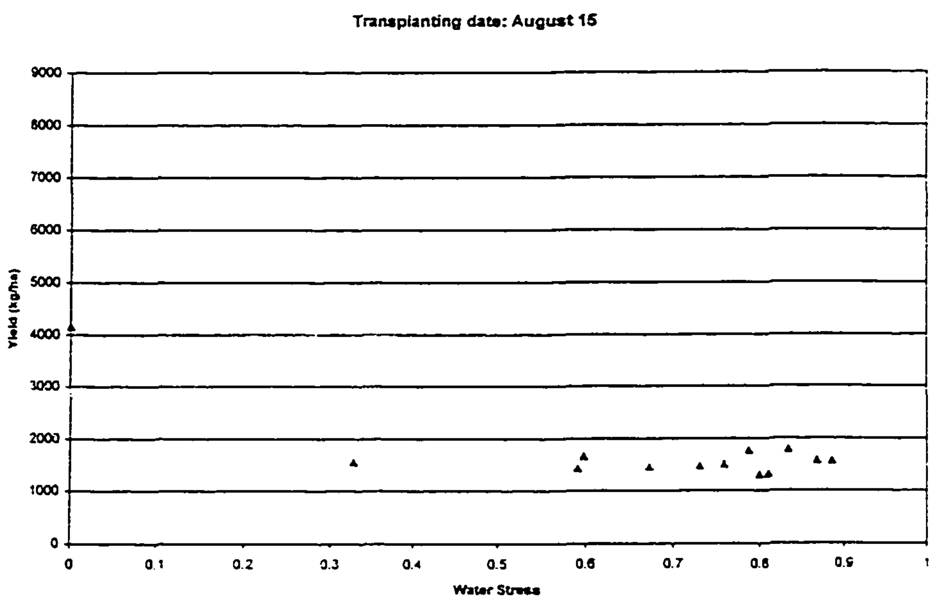


Figure 7.6a-d. Dinajpur: Water stress during the maturing stage and yield.

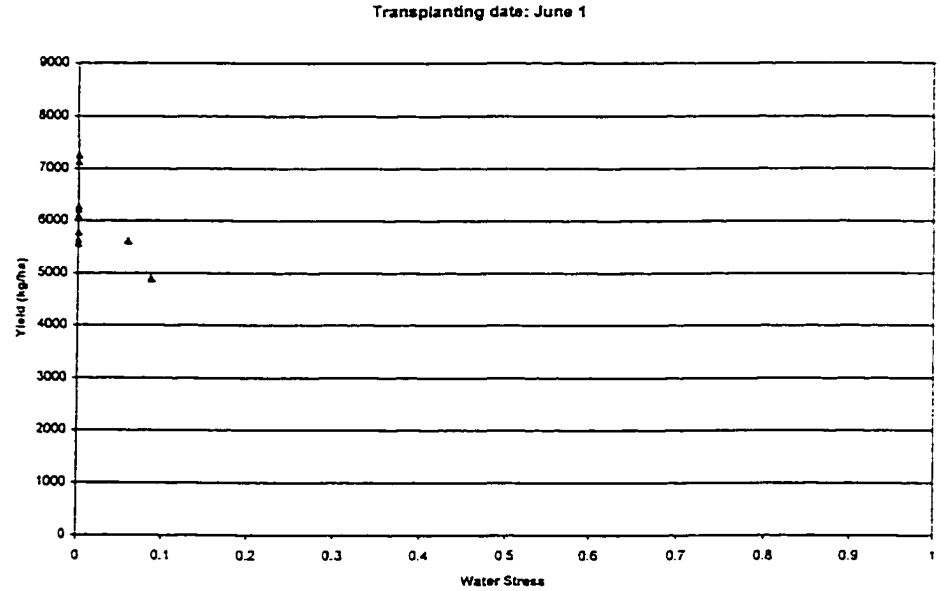
c)


Transplanting date: July 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

d)


Transplanting date: August 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

a)



b)

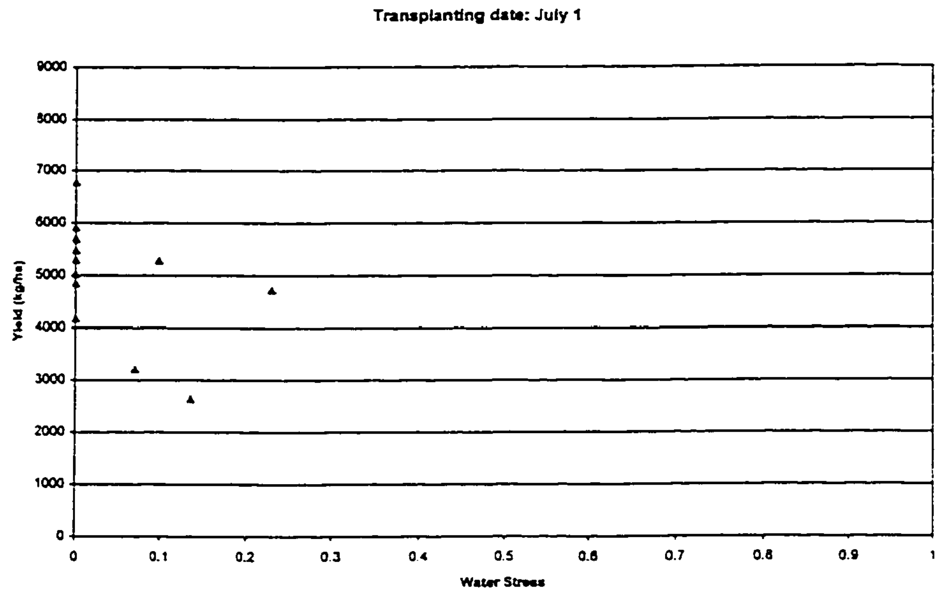
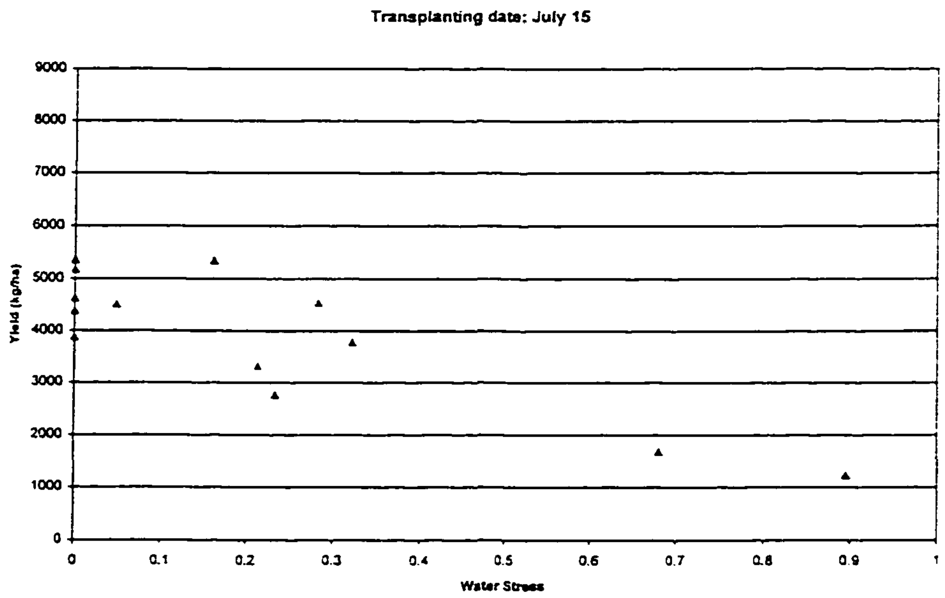
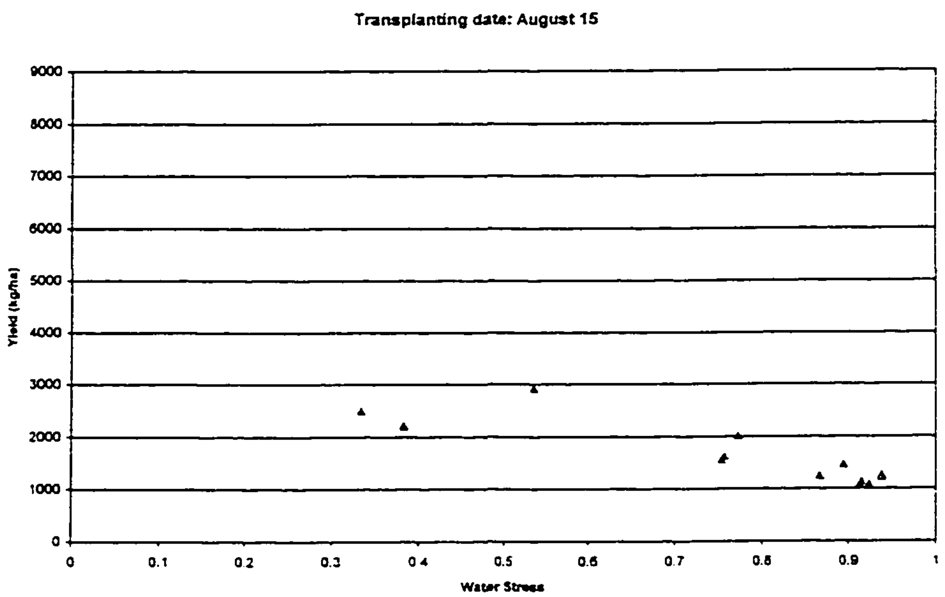


Figure 7.7a-d. Sylhet: Water stress during the flowering/heading stage and yield.

c)


Transplanting date: July 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

d)


Transplanting date: August 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
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0.4
0.5
0.6
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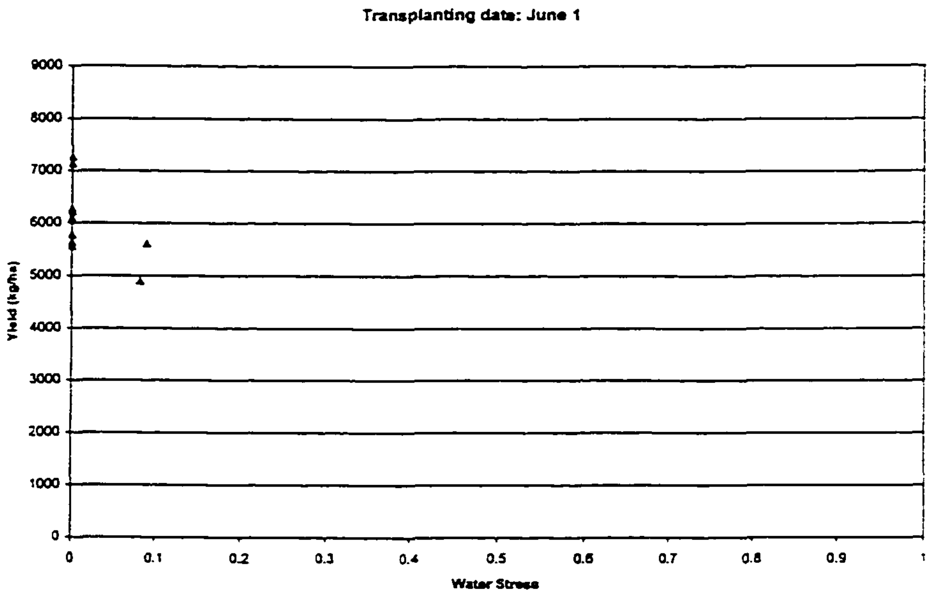
0.8
0.9
1
Water Stress

a)



b)

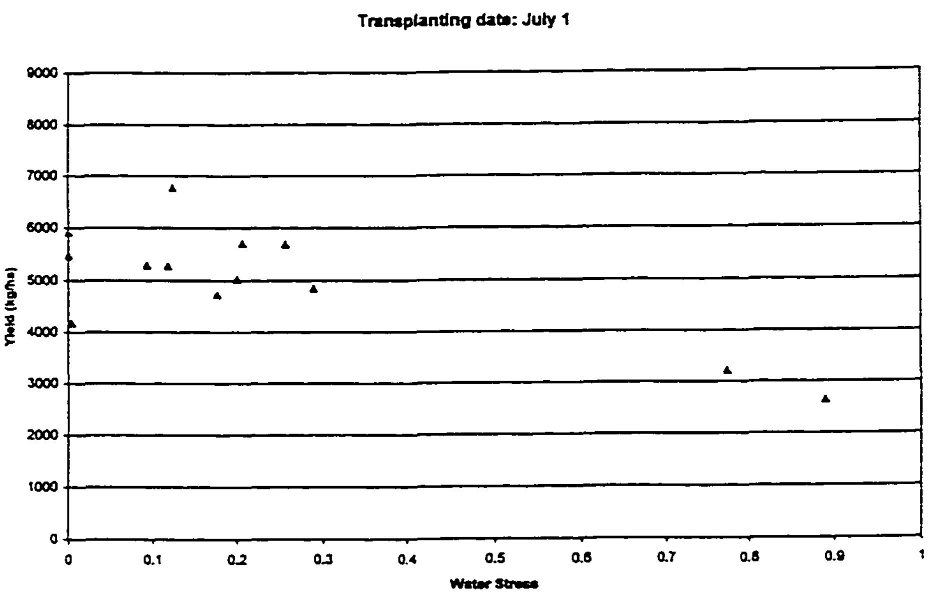
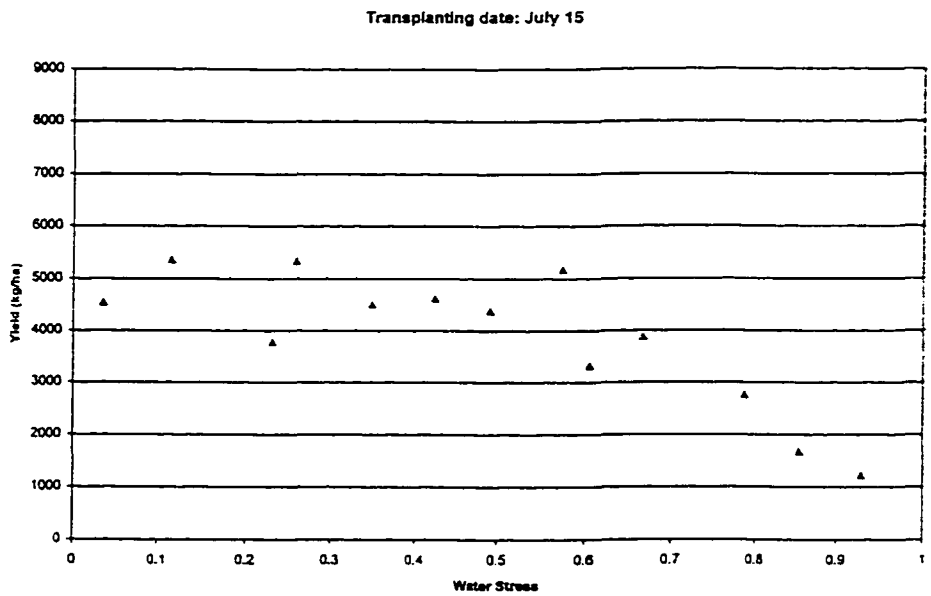
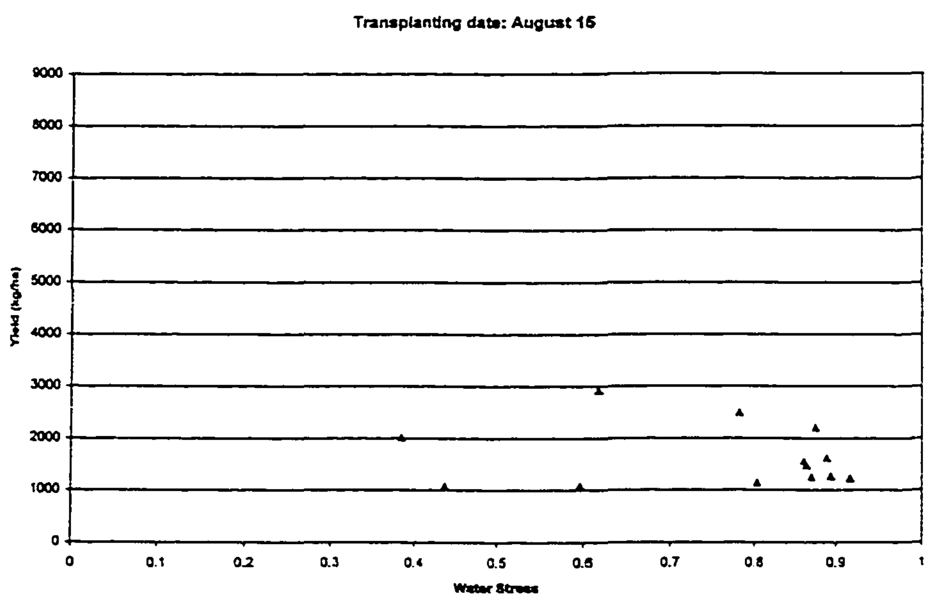


Figure 7.8a-d. Sylhet: Water stress during the maturing stage and yield.

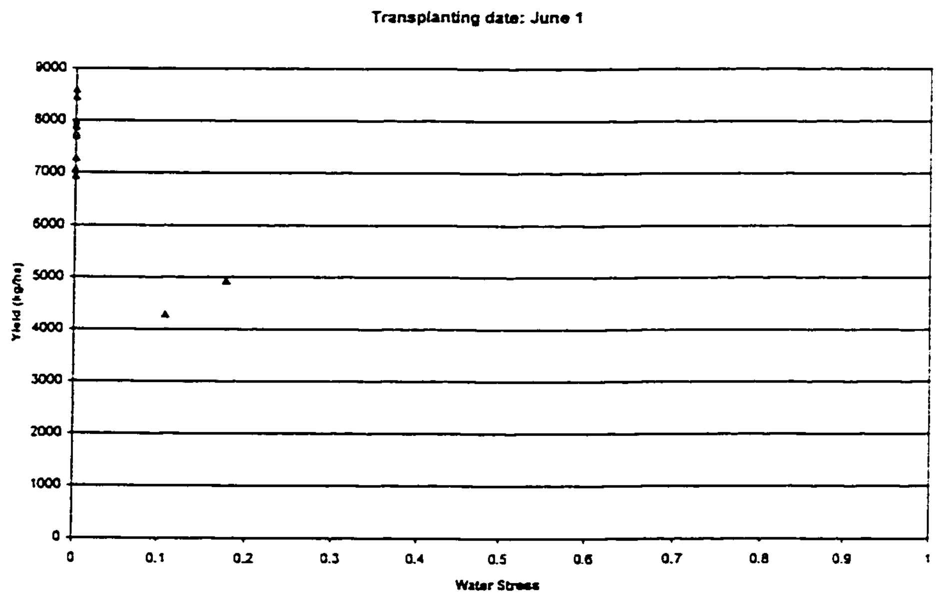
c)


Transplanting date: July 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

d)


Transplanting date: August 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

a)



b)

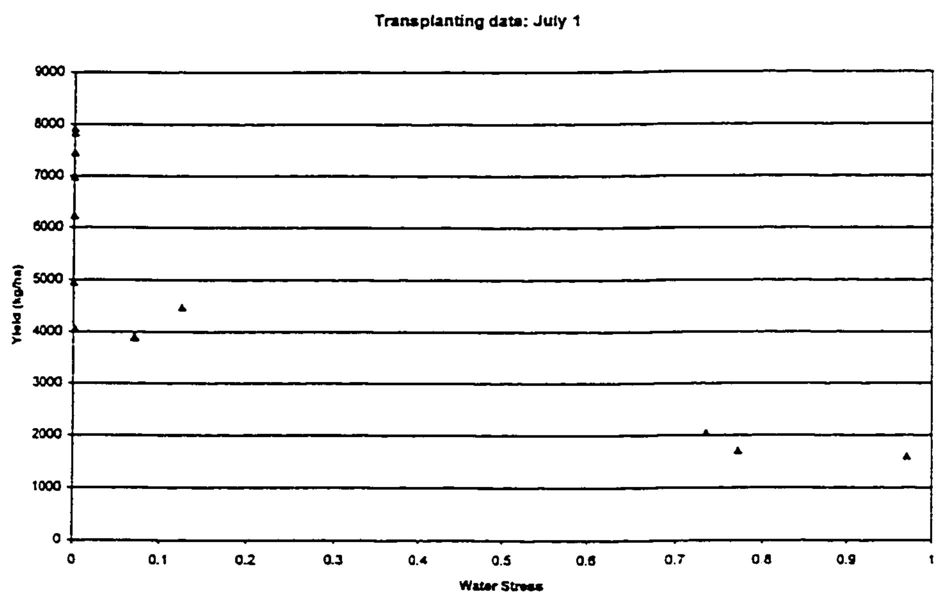
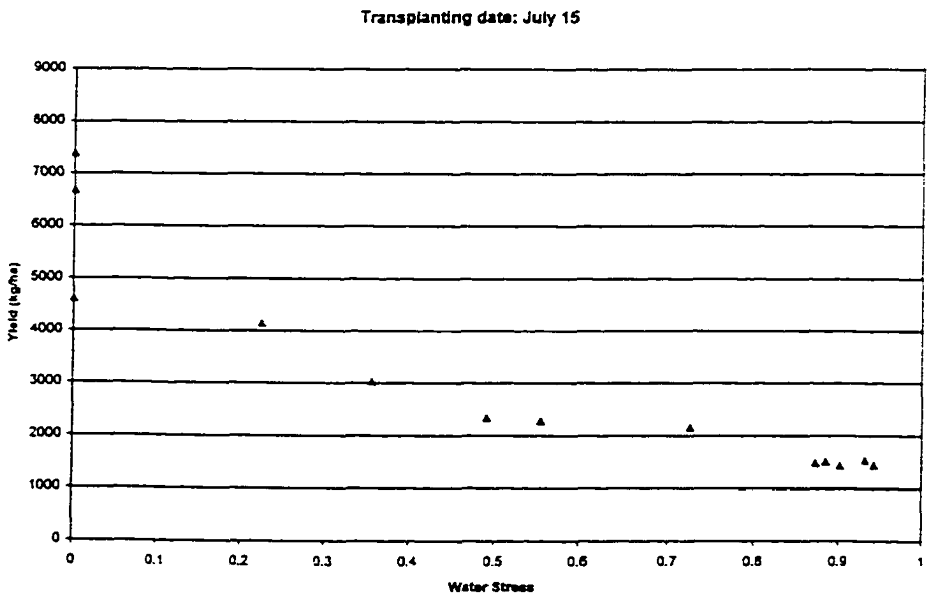
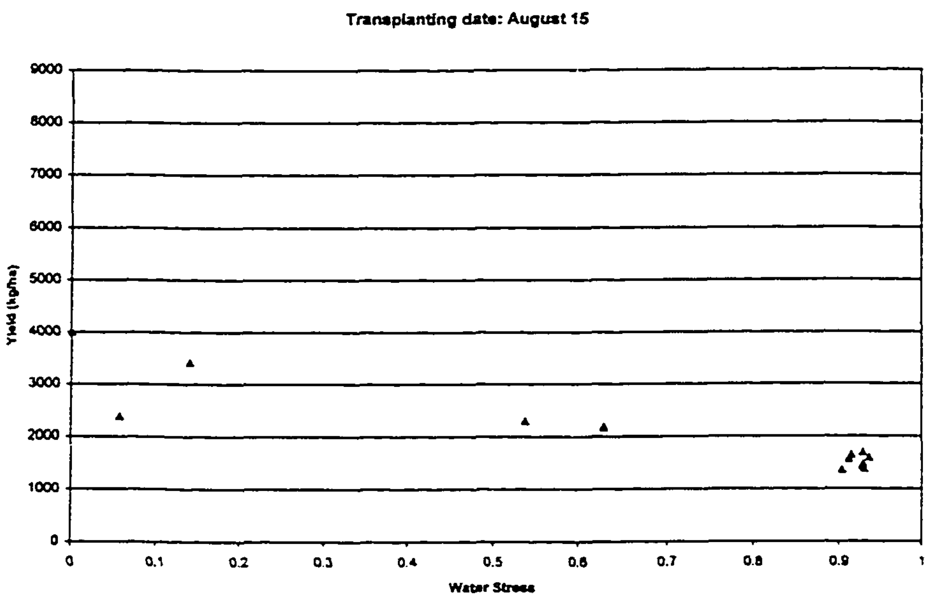


Figure 7.9a-d. Chandpur: Water stress during the flowering/heading stage and yield.

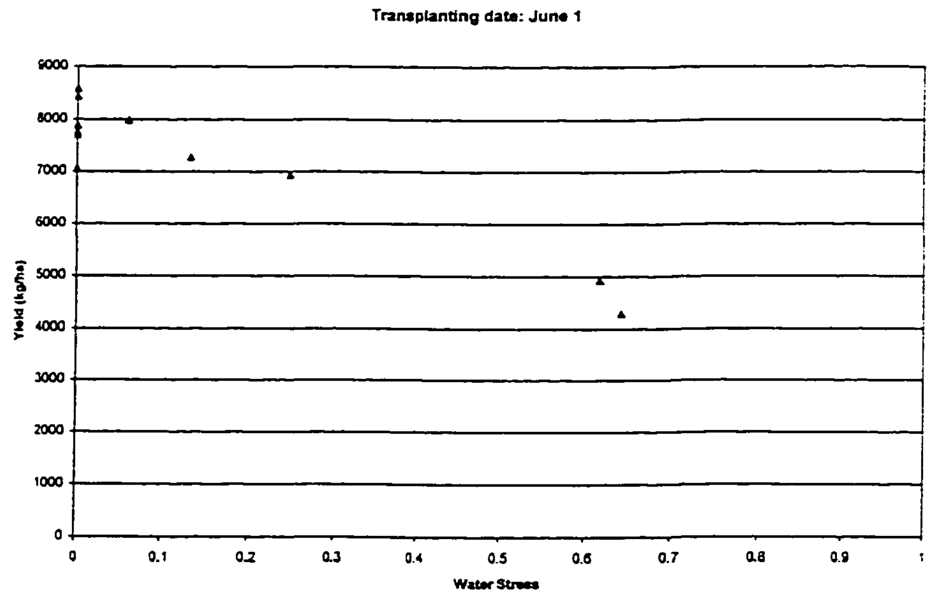
c)


Transplanting date: July 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

d)


Transplanting date: August 15
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Yield (kg/ha)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

a)



b)

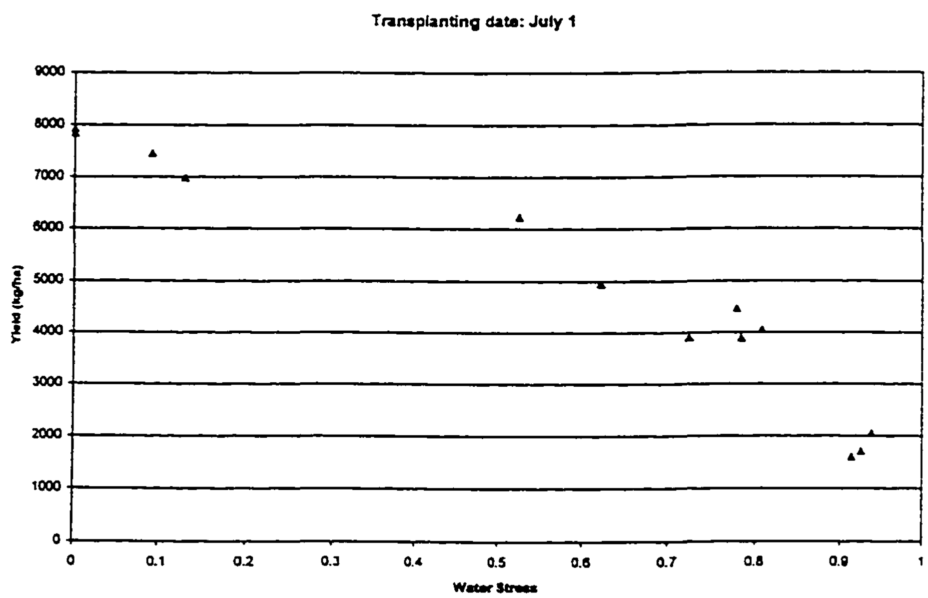
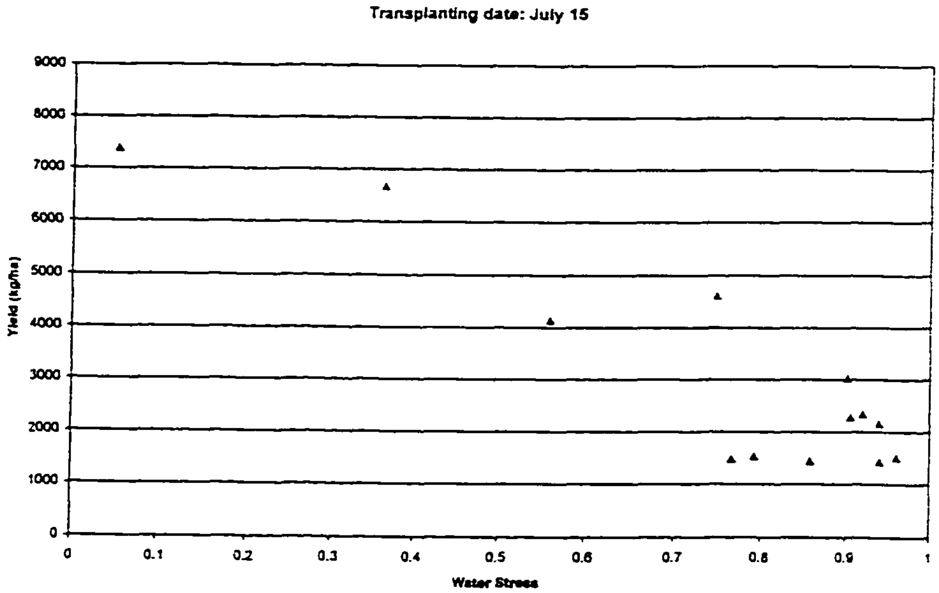
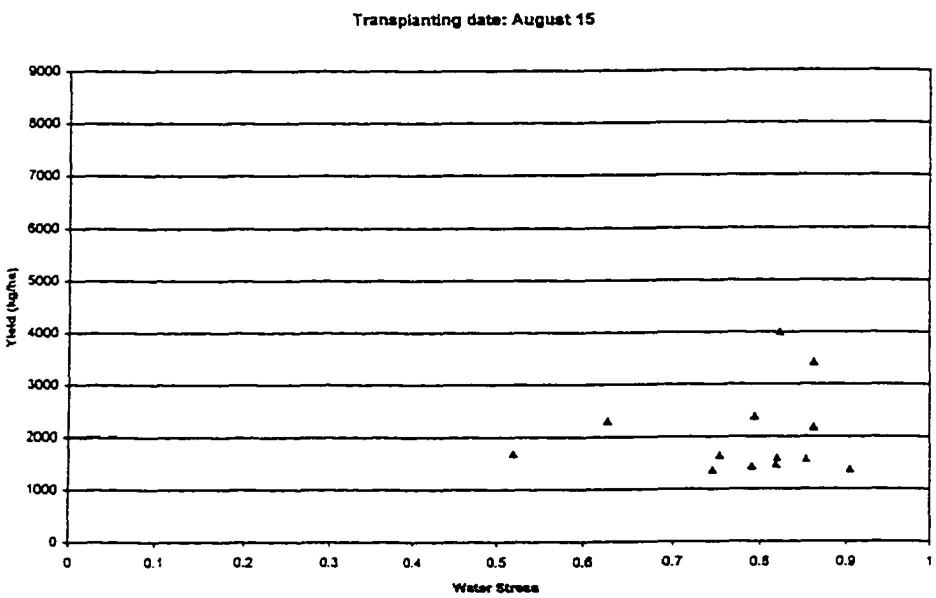


Figure 7.10a-d. Chandpur: Water stress during the maturing stage and yield.

c)


Transplanting date: July 15
Yield (kg/ha)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

d)


Transplanting date: August 15
Yield (kg/ha)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Water Stress

Tables B. 1-4 (Appendix B) suggest that the regional variations in yields are not very strikingly different in Bangladesh. In other words, a moderate region-to-region variation exists. For the June 1 transplanting date, the highest and the lowest yields under low water stress conditions during stages 4 and 5 range between 7694 to 6031 kg ha^{-1}. Yield range is between 7694 to 7416 kg ha^{-1} for Dhaka, Dinajpur, and Chandpur while Jessore and Sylhet fall in the lower end. For the July 15 and August 15 transplanting dates yields range between 6522 to 4718 kg ha^{-1} and between 4215 to 2576 kg ha^{-1}, respectively, for low water stress conditions during the flowering/heading and maturing stages. Moreover, under high water stress conditions at stages 4 and 5, yields range between 4564 to 2290, 2237 to 1486, and 1265 to 1657 kg ha^{-1} for the June 1, July 15, and the August 15 transplanting dates, respectively. Dhaka consistently recorded relatively higher yields under combined low water stress conditions for transplanting dates shown in the Tables (Appendix B. 1-4). This occurs possibly due to the season-wide well distribution of rainfall and the absence of extreme weather conditions. The model-estimated yields for Jessore and Sylhet are frequently low compared to the yields for other stations. Smaller rainfall amount in Jessore results in such a low yield. On the other hand, excessive rainfall and low solar radiation and soil conditions possibly caused lower yields in Sylhet.

7.2. Transplanting date and yield vulnerability

The coeffcient of variation (CV) has been calculated for 16 stations as a measure to estimate yield variability and vulnerability (Table 7.4). The higher and lower variability represents the higher and the lower vulnerability. All stations, except Mymensingh, show the lowest variability in yield for the June 1 transplanting date. Rangpur, Rangpur, Dhaka, Sylhet, Ishwardi, Ishwardi, Rangpur, and Bogra show the lowest variabilities in yield for the June 1, June 15, July 1, July 15, August 1, August 7, August 15, and August 23 transplanting dates, respectively. On the other hand, Mymensingh, Mymensingh, Mymensingh, Chandpur, Maijdi Court, Jessore, Satkhira, and Feni show the highest variabilities in yield for the June 1, June 15, July 1, July 15, August 1, August 7, August 15, and August 23 transplanting dates, respectively. It is important to note that higher and lower CVs for various stations do not represent higher and lower yields. Rather it helps us to understand crop yield vulnerability of a particular region and allow crop planners to devise strategies to minimize crop and financial loss of individual farmers. From the table, that crop yield variability increases during the Bangladesh Rice Research Institute (BRRI) recommended optimum transplanting period which starts in July 15 and ends in August 15. Relatively, lower variability in the end and after the end of this period results from steady country-wide low yield.

Table 7.4. Coefficient of Variation (%) of yields for eight transplanting dates.

Station	June 01	June 15	July 01	July 15
Dhaka	13.84	16.21	18.70	36.00
Rangpur	5.84	9.81	25.96	41.67
Jessore	20.03	31.83	46.59	57.50
Khulna	10.00	24.70	38.50	55.16
Chandpur	17.57	33.41	46.98	66.04
Comilla	29.93	42.97	47.48	56.04
Faridpur	14.65	31.80	45.70	53.92
Mymensingh	42.67	50.97	59.74	57.39
Maijdi Court	7.62	18.59	32.01	48.49
Feni	24.01	32.27	40.93	55.44
Sylhet	10.46	13.78	22.30	34.01
Satkhira	18.11	29.01	34.31	60.03
Barisal	5.90	11.77	39.04	45.87
Bogra	23.03	27.17	37.72	54.44
Dinajpur	23.58	27.54	41.13	57.10
Ishwardi	26.49	28.78	37.38	60.83

Station	August 01	August 07	August 15	August 23
Dhaka	45.95	49.56	51.61	35.44
Rangpur	46.27	63.46	8.68	17.42
Jessore	52.28	72.69	58.05	42.80
Khulna	56.09	31.38	56.53	48.23
Chandpur	57.37	49.31	40.77	22.54
Comilla	50.60	54.63	50.23	40.20
Faridpur	53.66	60.68	41.42	27.81
Mymensingh	34.94	53.32	49.71	22.81
Maijdi Court	72.33	69.59	54.16	38.89
Feni	64.97	69.54	64.55	59.69
Sylhet	38.85	36.22	36.13	36.33
Satkhira	44.64	61.61	68.17	49.21
Barisal	51.96	46.48	23.59	21.68
Bogra	31.57	26.34	12.71	13.73
Dinajpur	39.55	43.69	42.47	32.05
Ishwardi	31.32	17.76	16.56	14.30

Thus, it is clear from the discussions in Chapters 6 and 7 that early transplanting of *aman* rice is the key to success. It allows plants to obtain sufficient moisture from the soil during the flowering/heading and maturing stages which leads to a higher yield. As reported in the baseline estimates, yield sharply declines after the July 15. Therefore, wherever land is unoccupied by another crop, farmers should transplant rice plants during the early part of the monsoon season. Early transplanting also results in less variability in yield which reduces crop vulnerability.

CHAPTER 8

DECISION MAKING BY FARMERS UNDER VARIABLE WEATHER CONDITION IN BANGLADESH

Decision making and planning under uncertain weather conditions has always been a difficult task for farmers and policy makers. As a result, a large number of methods have been developed to cope with uncertain environmental conditions and their impacts on agriculture (*cf.*, Thornton and Wilkens, 1998; Davis *et al.*, 1997; Muchow and Bellamy, 1991; Barry, 1984; and Eddy and Shanon, 1975). In addition, many of these methods are based on a Game Theoretic approach. These methods largely address the issues related to multiple-cropping agriculture where farmers can choose from a series of crops depending on the weather of a particular area. Moreover, in some cases, these methods are suitable for capital-intensive farming (*cf.*, Larson and Mapp, 1997; Teague *et al.*, 1995). The land use and farming practices in Bangladesh during monsoon season are different from these situations. Agricultural activities are largely subsistence in nature and land use is predominantly under a monoculture category. In other words, farmers of Bangladesh cultivate rice under any type of weather condition for their survival and their choices are restricted (Mapp, 1999). Moreover, applications of a variety of risk and vulnerability assessment techniques may be inappropriate (Mapp, 1999). The results of this study show that in a given year farmers would obtain higher yields if they transplanted rice during the early part of the monsoon season. However, inter-seasonal variations in the yields for all eight transplanting dates have been recorded.

Thus further assistance can be given to farmers in Bangladesh to estimate what would be the potential loss under a particular monsoon season. This would also allow farmers to re-allocate their resources for their most efficient use. In the context of the restricted choices available to the Bangladeshi farmers, Savage's game theory-based method was modified (*cf.*, Ilberry, 1985; Anderson *et al.*, 1977; and Halter and Dean, 1971) to estimate the annual yield loss for a certain monsoon season. This method allows farmers to estimate the amount of aggregated potential loss that they may experience if they had known future monsoon season weather conditions. Savage's method appears sufficiently cautious and conservative enough to fairly represent the mindset of a subsistence farmer.

The unreliability of long-lead forecast has already been noted at the very beginning of this dissertation. However, it is important to note in the past long-lead monsoon forecast were made by using the sea surface temperature (SST), the Southern Oscillation Index (SOI), Eurasian snowfall and snow cover, and various other parameters of large-scale atmospheric circulation (Krishnamurti and Surgi, 1987). Among these, SOI based forecasts show certain degree of promise (Morrissey, 1999). These forecasts largely predict the strength of the monsoon (below normal, above normal, normal seasonal rainfall). These forecasts can play an important role in farmers' decision making since end-of-the growing season soil water availability largely determines yield. For this analysis, it has been assumed that each monsoon season to be a scenario (thus 13 scenarios) in which they may re-appear in the future. Thus, if farmers know the strength of a future monsoon, the results would help them to know the potential loss that may occur. Moreover, this early estimation will help them to decide how they will invest their resources in the future.

The calculation procedure of the modified Savage's method is straight-forward. Each yield estimate has been subtracted from the highest estimate for each transplanting date for each thirteen scenarios. Thus, potential loss estimates for each transplanting date were calculated as well as 104 potential yield loss estimates for each station. Yield loss estimates for eight transplanting dates for each scenario are added to calculate seasonal total potential yield loss. This is also known as total regret. Table 8.1 presents the estimates of seasonal total regret for each year/scenario for all 16 stations. It shows that 1986 was a good year for farmers of Bangladesh. During this year, 11 of 16 stations recorded the lowest total regret while 5 stations recorded the second-lowest total regret. Eleven stations which record the lowest total regret are Dhaka, Jessore, Khulna, Comilla, Faridpur, Mymensingh, Maijdi Court, Satkhira, Bogra, Dinajpur, and Ishwardi. On the other hand, 1981 was not a good year for the farmers. During this year, 6, 3 and 3 stations record the highest, the 2nd highest, and the 3rd highest total regret, respectively. In other words, if a long-lead forecast resembles a scenario like

1986, then farmers can be assured that they will get a good return and their investment will be assured. In addition, if a forecast resembles 1981, then farmers should start thinking about how they are going to plan for the next season and if possible, an individual farmer consider for an alternative investment activity.

For further analysis, Figures 8.1a-b have been prepared to present the highest and the lowest minimum regret value for each station. The Figure 8.1a shows that the highest minimum regret generally increases as the transplanting date moves well into the monsoon season. This corroborates earlier findings of yield loss (see chapter 6 and 7). The lowest minimum regret also increases up to the early August transplanting dates (Figure 8.1b). The difference (range) between the highest and the lowest minimum regret decreases rapidly for August transplanting dates (Appendix C. 1). This results from the consistantly low yields for these transplanting dates.

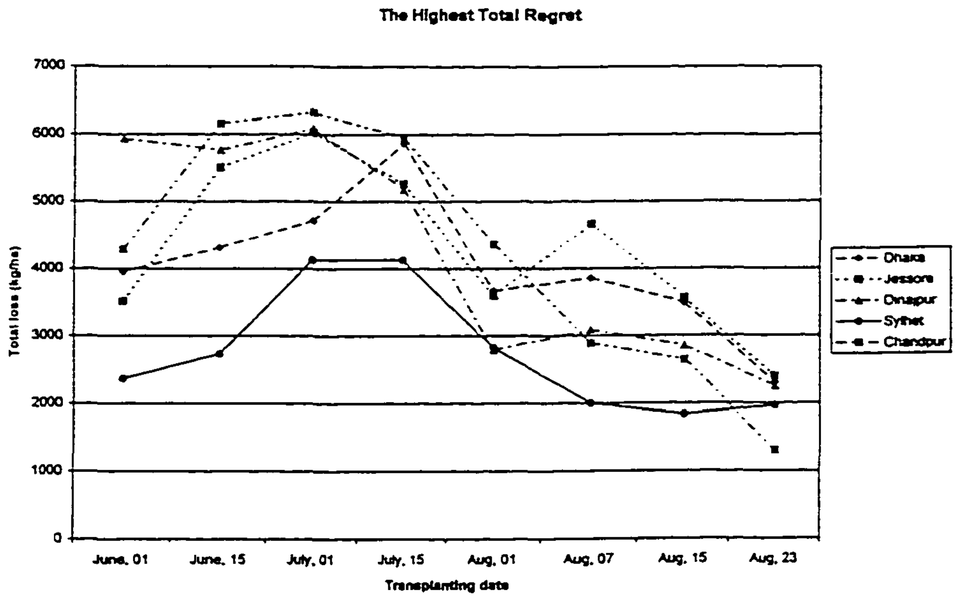
In view of the above discussion, I believe that an impacts analysis with a modified game theoretic approach, and the use of the results in conjunction with long-lead forecasts may significantly improve decision making and proper resource allocation by the farmers of Bangladesh.

Table 8.1. Estimated total regret (kg ha^{-1}) for Bangladesh. (*cf.*, Illberry, 1985, for the definition of total regret).

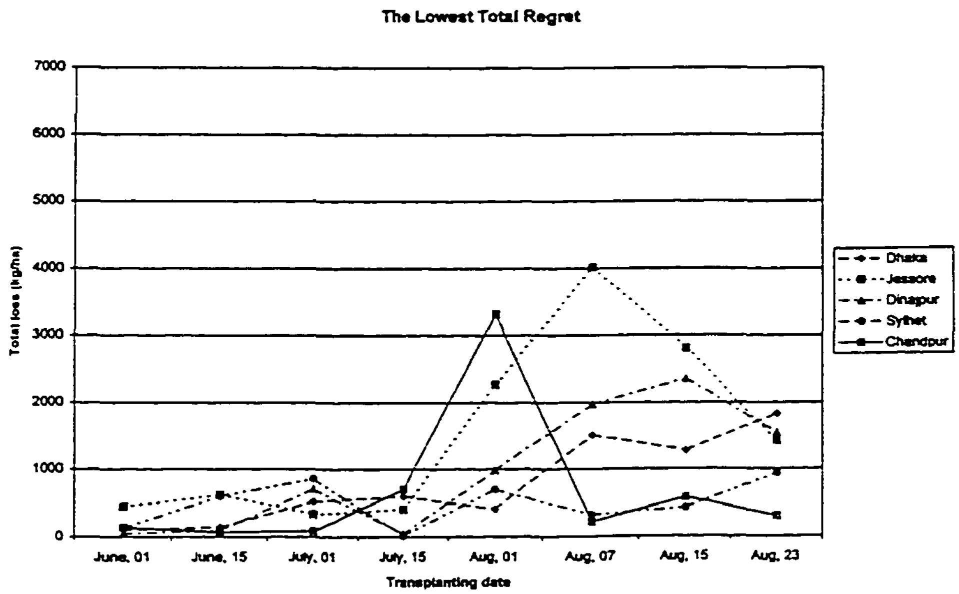
Station	1975	1976	1977	1978	1979	1980	1981
Dhaka	8827	23439	19448	18682	16561	6901	21731
Rang-pur	8050	17707	12644	9403	9227	8958	17939
Jessore	22261	33585	27443	16979	18404	29903	25824
Khulna	25216	16911	36167	17890	26690	25526	29913
Chand-pur	32954	31153	23820	15757	19910	21181	27264
Comilla	7789	34628	27943	19201	16143	15650	32836
Farid-pur	10154	27236	20259	27423	21305	10386	24277
Mymen singh	35949	14403	18703	23800	28253	26566	28690
Maijdi Court	21243	22804	23841	21557	19559	17023	30863
Feni	351	22378	25290	22700	33169	43491	32690
Sylhet	7361	2338	10253	13708	15319	12103	20689
Satkhira	18801	30338	25679	13179	34172	32139	23989
Barisal	1424	14396	7698	12834	11335	5626	24563
Bogra	12585	14804	12399	29884	11871	15122	14278
Dinaj-pur	12512	23468	23968	20396	17410	22785	26243
Ish-wardi	16673	8655	20784	15542	12952	12280	11319

Station	1982	1983	1984	1985	1986	1987
Dhaka	10673	13633	27292	18808	3090	15365
Rang-pur	14362	1908	11751	9721	4029	2835
Jessore	33629	12645	25611	14218	3626	18581
Khulna	24580	9493	26231	21469	2154	19468
Chand-pur	19135	2397	22116	16336	5548	13923
Comilla	25442	9737	19896	23721	5545	9434
Farid-pur	28997	12666	18566	25226	1933	17445
Mymen singh	21243	11911	12736	11510	874	8266
Maijdi Court	23567	23042	23544	23150	8196	21091
Feni	26302	16016	25866	30817	12998	24649
Sylhet	18009	9675	9946	13188	7250	11337
Satkhira	23577	11755	25706	17149	1985	20327
Barisal	22209	7148	23375	13227	4642	14346
Bogra	21041	3726	12584	7309	3268	16440
Dinaj-pur	21950	10446	18236	8220	8129	11473
Ish-wardi	18989	2826	10892	10195	6584	10771

a)



b)



8.1. The highest (a), and the lowest total regret for the five representative stations (b).

CHAPTER 9

SUMMARY AND CONCLUSIONS

The CERES-Rice model was applied to determine the impacts of intra-seasonal monsoonal rainfall variability and soil water availability on the potential rainfed rice productivity in Bangladesh. The study assumed BRRI-recommended fertilizer supply and saturated and puddled soils during transplanting, and eight dates were used to identify optimum transplanting date(s) for rainfed rice. A method was developed by modifying Savage's game theory based approach to determine the highest and the lowest total regret which would help farmers make more efficient resource allocations if a long-lead forecast is provided. The CERES-Rice model was calibrated to represent agro-ecological conditions in Bangladesh. The model's performance was evaluated for yield estimation, length of growing season, phenology, harvest index, and evapotranspiration. From the evaluation, it appears that the model estimations are satisfactory.

The CERES-Rice model was applied to daily average climatic conditions for 16 representative stations in Bangladesh to obtain baseline estimates for the major growing regions. Baseline estimates reveal that rice yield decrease as the transplanting dates were moved well into the monsoon. The rate of decrease in yield is notable until July 15; thereafter, a very high decrease in yield occurs. On the average, for a July 15 transplanting date, yield loss is 20.9% compared to a

June 1 transplanting date. On the other hand, for an August 15 transplanting date, yield loss is 73.7% on the average compared to July 15 transplanting date.

To determine the impacts of intra-seasonal rainfall variability on rice productivity, a series of correlation analyses were conducted using six monsoon season precipitation parameters and yields for each date and each station. The monsoon season precipitation parameters that were used include standard deviation of daily rainfall, height of the largest and second largest rainfall squence, timing of these two sequences of rainfall, and the time delay between these two sequences. The correlation values are very low in most cases. Thus, intra-seasonal rainfall variability does not effect rainfed rice productivity.

The role of soil water also was investigated, since it is the medium from which plants obtain their moisture requirements for growth. It is known that the rice plant is very sensitive to water stress during the flowering/heading stage (stage 4) and the maturing stage (stage 5). As a result, correlation analyses were conducted to identify relationships between yield and water stress during these two stages. It became evident from this analysis that water stress at the end of the growing season plays a key role in the final yield estimation. Low (high) water stress during the flowering/heading and maturing stages for June (July and August) transplanting dates resulted in higher (lower) yields. Late transplanting pushes the flowering/ heading and maturing stages well into the dry winter season and thus causes water stress. Thus, end-of-season water availability, rather than intra-seasonal variability, plays the key role in determining final yield.

To further understand the combined role of water stress during stages 4 and 5 on yield, a series of contingency tables were prepared. These tables show that a higher yield can be obtained when rice is transplanted early in the monsoon season. Low or no water stresses at both stages help attain these yields. On the other hand, water stress at either one of the two stages (stages 4 and 5) reduced the yield noticeably. Water stress during both stages 4 and 5 reduced yields the most. The results from this study corroborate findings of various other field experiments.

The CERES-Rice model then was applied to a weather data set from 1975 through 1987. These applications were conducted for all 16 stations and 8 transplanting dates. The yield estimates are strongly correlated with the severity of water stress. Analyses of results also show that early transplanting produces higher yields due to low or no water stress during stages 4 and 5. On the other hand, water stress in both stages 4 and 5 results in the lowest yields. In short, the findings are similar to the analysis for baseline yield estimates.

The coefficient of variation of yields for each transplanting date and for each station also were computed. Higher and the lower variability of yields represent the higher and the lower vulnerability. Vulnerability in yields increase as the transplanting dates are moved further into the monsoon season.

Making decisions under variable weather conditions has always been a difficult task for the farmers and policy makers. In the case of Bangladesh, the underlying agro-ecological conditions for decision making during monsoon season are restrictive. The farming practice is subsistence in nature and land use is largely under a monoculture category. Moreover, this study shows that early transplanting generally ensures a higher yield. In this context, farmers can be assisted by providing information on the potential loss under a particular monsoon season. A modified version of Savage's game theory was used for the analysis; each year was considered as a scenario. Based on the lowest and the highest regret estimates for each region, a 'future year' like 1986 would be quite good for Bangladeshi farmers. On the other hand, a 'future year' resembling 1981 will cause potential crop loss. This type of estimation, in conjunction with an accurate long-lead time forecast, would allow Bangladeshi farmers to adopt a resource allocation plan that would help them more efficiently to overcome losses from unfavorable weather conditions.

Two future research areas have been identified. A data set for a longer time period should be obtained, which would provide a normal distribution of yields as predicted through application of the CERES-Rice model. This would allow for an improved risk assessment of rainfed rice productivity. One limitation of the CERES-Rice model is its inability to take into account the effect of long-lasting submergence of rice fields. As a result, this model is not applicable to deep-water rice yield simulation which is common in certain parts of Asia including Bangladesh. Research involving improvement of this particular aspect also would be worthwhile.

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APPENDIX A.

Table A. 1. Yield vs. water stress during growth stage 4 (flowering/heading) and 5 (maturing)

Station	Yield June 01 kg ha^{-1}	Growth stage 4 June 01	Growth stage 5 June 01	Yield June 15 kg ha^{-1}	Growth stage 4 June15	Growth stage 5 June 15
Dhaka	7168	0	0	6932	0	0
Rangpur	7695	0	0	7556	0	0
Jessore	8045	0	0	7854	0	0
Khulna	8271	0	0	8131	0	0
Chandpur	7910	0	0	7495	0	0
Comilla	7904	0	0	8113	0	0
Faridpur	8144	0	0	7885	0	0
Mymensingh	7415	0	0	7381	0	0
Maijdi Court	8168	0	0	7262	0	0
Feni	7336	0	0	7192	0	0
Sylhet	5374	0	0	5497	0	0
Satkhira	8209	0	0	8107	0	0
Barisal	8396	0	0	7841	0	0
Bogra	7600	0	0	7319	0	0
Dinajpur	8413	0	0	8067	0	0
Ishwardi	7917	0	0	7760	0	0

Table A. 1. Continued... Yield vs. water stress during growth stage 4 (flowering/heading) and 5 (maturing).

Station	Yield July 01 kg ha^{-1}	Growth stage 4 July 01	Growth stage 5 July 01	Yield July 15 kg ha^{-1}	Growth stage 4 July15	Growth stage 5 July 15
Dhaka	6714	0	0	6335	0	.087
Rangpur	6960	0	0	6700	0	.116
Jessore	7688	0	0	6221	0	.394
Khulna	7479	0	0	6640	0	.132
Chandpur	7068	0	0	5776	0	.416
Comilla	7605	0	.043	5600	0	.523
Faridpur	7391	0	0	6312	0	.328
Mymensingh	7007	0	.050	5020	0	.582
Maijdi Court	6579	0	0	6168	0	.159
Feni	6679	0	0	6364	0	.139
Sylhet	5357	0	0	5737	0	0
Satkhira	7454	0	0	6839	0	.140
Barisal	7350	0	0	7075	0	.034
Bogra	7164	0	0	5725	0	.436
Dinajpur	7506	0	0	5993	0	.419
Ishwardi	7227	0	.108	4797	0	.690

Table A. 1. Continued... Yield vs. water stress during growth stage 4 (flowering/heading) and 5 (maturing).

Station	Yield Aug 01 kg ha^{-1}	Growth stage 4 Aug 01	Growth stage 5 Aug 01	Yield Aug 15 kg ha^{-1}	Growth stage 4 Aug 07	Growth stage 5 Aug 07
Dhaka	3818	.068	.746	2752	.319	.865
Rangpur	3708	.045	.823	2319	.502	.844
Jessore	1988	.675	.868	1940	.733	.938
Khulna	3825	.141	.793	2462	.481	.889
Chandpur	2086	.583	.812	1993	.697	.896
Comilla	1969	.834	.804	2099	.653	.919
Faridpur	2600	.508	.800	2316	.609	.932
Mymensingh	2000	.591	.903	1686	.801	.872
Maijdi Court	3150	.136	.840	2075	.463	.938
Feni	3586	.011	.780	2319	.396	.891
Sylhet	3831	0	.676	2755	.208	.796
Satkhira	3741	.147	.799	2421	.470	.896
Barisal	4409	0	.772	2932	.225	.950
Bogra	2148	.516	.930	1552	.877	.941
Dinajpur	2759	.398	.869	1851	.812	.869
Ishwardi	1581	.888	.899	1594	.833	.936

Table A. 1. Continued.... Yield vs. water stress during growth stage 4 (flowering/heading) and 5 (maturing)

Station	Yield Aug 15 kg ha^{-1}	Growth stage 4 Aug 15	Growth stage 5 Aug 15	Yield Aug 23 kg ha^{-1}	Growth stage 4 Aug 23	Growth stage 5 Aug 23
Dhaka	1876	.645	.867	1312	.938	.859
Rangpur	1586	.870	.845	1465	.893	.810
Jessore	1553	.775	.865	1318	.957	.867
Khulna	1835	.713	.880	1451	.924	.878
Chandpur	1491	.796	882	1377	.911	.849
Comilla	1434	.912	.914	1329	.951	.904
Faridpur	1900	.648	.893	1431	.954	.894
Mymensingh	1380	.934	.865	1299	.925	.828
Maijdi Court	1403	.876	.970	1256	.923	.995
Feni	1664	.703	.880	1340	.897	.869
Sylhet	1553	.767	.832	1339	.851	.832
Satkhira	1982	.706	.864	1452	.929	.868
Barisal	1698	.822	.986	1453	.936	.999
Bogra	1352	.947	.903	1262	.961	.901
Dinajpur	1556	.904	.845	1431	.900	.793
Ishwardi	1324	.864	.920	1269	.960	.887

APPENDIX B

Table B. 1a. Yield (kg ha^{-1}) estimates for Jessore (1975-87) for high and low water stress. Transplanting date: June 1.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	5856, 4913, 5835, 5894, 7566, 7327, 4335, 7561, 7090, 8083, 5820, 7634. Mean = 6493	4564 Mean = 4564
Stage 5: High water stress	None	None

Table B. 1b. Yield (kg ha^{-1}) estimates for Jessore (1975-87) for high and low water stress. Transplanting date: July 01.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	5856, 7354, 6277, 3276, 7690, 6516, 7297, 5690. Mean = 6244	None
Stage 5: High water stress	3530, 2672, 2886. Mean = 3029	1660, 1661. Mean = 1660

Table B. 1c. Yield (kg ha^{-1}) estimates for Jessore (1975-87) for high and low water stress. Transplanting date: July 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	5574, 6143, 5054, 6552, 3606. Mean = 5386	3873, 3505. Mean = 3689
Stage 5: High water stress	None	1295, 1418, 2572, 1431, 1294, 1688. Mean = 1616

Table B. 1d. Yield (kg ha^{-1}) estimates for Jessore (1975-87) for high and low water stress. Transplanting date: August 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	None	1612. Mean = 1612
Stage 5: High water stress	4419. Mean = 4419	1092, 860, 1238, 1353, 1199, 1134, 1305, 1339, 1579, 1511, 1295. Mean = 1265

Table B. 2a. Yield (kg ha^{-1}) estimates for Dinajpur (1975-87) for high and low water stress. Transplanting date: June 1.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	8179, 5541, 6337, 7938, 8227, 6180, 7928, 7512, 7621, 7924, 8024, 7583. Mean = 7416	
Stage 5: High water stress		2290. Mean = 2290

Table B. 2b. Yield (kg ha^{-1}) estimates for Dinajpur (1975-87) for high and low water stress. Transplanting date: July 1.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	6957, 7142, 6955, 7886, 7147. Mean = 7217	2653. Mean = 2653
Stage 5: High water stress	3694, 4172, 3781, 5421, 2472, 5415. Mean = 4159	1798. Mean = 1798

Table B. 2c. Yield (kg ha^{-1}) estimates for Dinajpur (1975-87) for high and low water stress. Transplanting date: July 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	4710, 6656, 6554, 6697, 6063. Mean = 4932	2680, 2722. Mean = 2701
Stage 5: High water stress	2482, 2391. Mean = 2436	1595, 1803, 2052, 1516. Mean = 1741

Table B. 2d. Yield (kg ha^{-1}) estimates for Dinajpur (1975-87) for high and low water stress. Transplanting date: August 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	4156. Mean = 4156	1569, 1531, 1670. Mean = 1590
Stage 5: High water stress	None	1580, 1516, 1462, 1321, 1305, 1779, 1479, 1797, 1585. Mean = 1536

Table B. 3a. Yield (kg ha^{-1}) estimates for Sylhet (1975-87) for high and low water stress. Transplanting date: June 1.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	6277, 7264, 5615, 5642, 5778, 4899, 6099, 6067, 5779, 5569, 6058, 7134, 6220. Mean = 6031	None
Stage 5: High water stress	None	None

Table B. 3b. Yield (kg ha^{-1}) estimates for Sylhet (1975-87) for high and low water stress. Transplanting date: July 1.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	5689, 6778, 5297, 5029, 4855, 4735, 5479, 5915, 5285, 5709, 4176. Mean = 5359	None
Stage 5: High water stress	2646, 3217 Mean = 2931	None

Table B. 3c. Yield (kg ha^{-1}) estimates for Sylhet (1975-87) for high and low water stress. Transplanting date: July 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	4515, 5180, 4544, 5344, 5362, 4628, 3787, 4388. Mean = 4718	None
Stage 5: High water stress	3327, 2769, 3886. Mean = 3327	1288, 1684. Mean = 1486

Table B. 3d. Yield (kg ha^{-1}) estimates for Sylhet (1975-87) for high and low water stress. Transplanting date: August 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	None	1082, 1080, 2022. Mean = 1394
Stage 5: High water stress	2212, 2922. Mean = 2567	1625, 1224, 1468, 1140, 1248, 1266, 1557, 2493. Mean = 1502

Table B. 4a. Yield (kg ha^{-1}) estimates for Chandpur (1975-87) for high and low water stress. Transplanting date: June 1.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	6941, 7711, 7764, 7990, 7284, 7882, 7901, 7055, 8447, 7068, 8589. Mean = 7694	None
Stage 5: High water stress	4295, 4934. Mean = 4614	None

Table B. 4b. Yield (kg ha^{-1}) estimates for Chandpur (1975-87) for high and low water stress. Transplanting date: July 01.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	7458, 7839, 6231, 7925, 6985. Mean = 7288	None
Stage 5: High water stress	3895, 4958, 4477, 4056, 3904. Mean = 4258	2057, 1604, 1712. Mean = 1791

Table B. 4c. Yield (kg ha^{-1}) estimates for Chandpur (1975-87) for high and low water stress. Transplanting date: July 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	7386, 6679, 4142. Mean = 6069	None
Stage 5: High water stress	4613, 2344, 2285, 3030. Mean = 3068	1449, 1515, 1538, 2158, 1435, 1489. Mean = 1597

Table B. 4d. Yield (kg ha^{-1}) estimates for Chandpur (1975-87) for high and low water stress. Transplanting date: August 15.

	Stage 4: Low water stress	Stage 4: High water stress
Stage 5: Low water stress	None	1693. Mean = 1693
Stage 5: High water stress	2293, 2382, 3424, 4005. Mean = 3026	1365, 1596, 1380, 1436, 1469, 1646, 1572, 2175. Mean = 1580

APPENDIX C

Table C. 1. The Highest and the lowest regret for the eight transplanting dates.

Station	06/01 Highest min. Regret Lowest min. Regret	06/15 Highest min. Regret Lowest min. Regret	07/01 Highest min. Regret Lowest min. regret	07/15 Highest min. Regret Lowest min. Regret
Dhaka	3955 102	4319 148	4716 524	5872 601
Rangpur	1698 142	2179 107	4532 49	5478 89
Jessore	3519 449	5508 624	6030 336	5258 409
Khulna	3058 222	5906 140	4791 109	5880 152
Chandpur	4294 142	6158 70	6321 86	5951 707
Comilla	6183 34	6871 591	6085 93	5152 420
Faridpur	3386 307	5671 194	6138 282	4861 207
Mymensingh	7162 132	6786 99	6315 525	5291 599
Maijdi Court	2325 195	5079 342	4135 87	5213 3169
Feni	6583 107	6554 22	5662 92	5386 388
Sylhet	2365 195	2738 603	4132 863	4134 18
Satkhira	3982 104	6355 135	4945 115	6099 507
Barisal	1855 15	2429 281	6418 129	6654 972
Bogra	4013 65	4462 280	5942 437	5006 1090
Dinajpur	5937 48	5767 94	6088 714	5181 41
Ishwardi	5002 298	4594 270	4736 316	4781 738

Table C. 1. Continued...

Station	08/01 Highest min. Regret Lowest min. Regret	08/07 Highest min. Regret Lowest min. Regret	08/15 Highest min. Regret Lowest min. regret	08/23 Highest min. regret Lowest min. regret
Dhaka	3675 411	3860 1512	3490 1278	2302 1832
Rangpur	2952 167	1532 46	340 4	1059 561
Jessore	3600 2272	4665 4018	3559 2807	2395 1424
Khulna	4146 1229	4719 2123	4389 3544	3326 2384
Chandpur	4368 3320	2890 220	2640 581	1309 303
Comilla	3811 2722	3323 185	2895 384	2189 181
Faridpur	3541 1304	4135 2873	2847 1601	1802 1116
Mymensingh	2362 771	3631 2244	3199 1874	1203 216
Maijdi Court	5213 3169	4302 1376	3064 859	1729 110
Feni	5316 2924	5408 2438	5105 2603	4400 3025
Sylhet	2826 705	2001 321	1840 429	1967 939
Satkhira	2458 123	4867 3011	4871 3733	3372 2675
Barisal	3772 791	3170 311	1492 426	1351 811
Bogra	1529 361	1371 310	685 210	506 27
Dinajpur	2792 987	3088 1978	2851 2359	2253 1547
Ishwardi	1576 693	782 8	765 24	749 73