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Irrigated agriculture in the northwest region of Bangladesh

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Acknowledgments

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In conducting this study, we have been benefitted from the help and advice of many people, too numerous to mention them all individually. We particularly appreciate the support provided by the Barind Multi-purpose Development Authority (BMDA), local offices of the Department of Agricultural Extension (DAE) and the authority of the Bangladesh Rice Research Institute (BRRI).

Executive summary

The main aim of this study is to provide a detail state of irrigated agriculture for the northwest region of Bangladesh based on the historical data and field observations at 535 farmers' plot over two years (2015-16 and 2016-17) across six locations in the region that will provide information to the policy makers for sustaining groundwater irrigation in the region. The study was undertaken by CSIRO in collaboration with Bangladesh Rice Research Institute and University of Southern Queensland as partners of the project 'Improving water use for season agriculture by marginal and tenant farmers in the Eastern Gangetic Plains'. The project was funded by the Australian Centre for International Agricultural Research (ACIAR).

Northwest region is at the forefront of the remarkable development in agriculture over the last few decades in Bangladesh. The region produces 34% of the country's total rice, 60% of the total wheat, and more than 2/3 of the total production of potato and maize and is considered as the food basket of Bangladesh. This was possible by substantial intensification of agriculture, particularly growing Boro rice in the dry season, using groundwater for irrigation. In recent years, there are serious concerns about the sustainability of groundwater use for irrigation since groundwater levels are falling in some parts of the region. Consequently, sustaining irrigation and groundwater usage is the utmost priority of the Government of Bangladesh. This study provides a comprehensive analysis of the current state of irrigated agriculture in the region that is expected to provide valuable information to the policy makers for the future sustainability of irrigated agriculture. This is also expected to help further development of irrigated agriculture in other parts of the Eastern Gangetic Plains. The key findings of the study are:

1. The cultivated area of Boro rice remains steady over the last few years. Area of maize is increasing rapidly mostly at the expense of other crops except rice. Total paid-out cost, gross benefit, and gross income of rice significantly differ among the locations, types of pumps used for irrigation, varieties of rice, and transplanting dates; these also differ from year to year. The price of rice, which varies significantly from year to year, determines the overall profitability of its cultivation.
2. Average cost of irrigation was 25% of the total cost of production in 2015-16 and 20% in 2016-17. Due to different price models (e.g., area based, fixed-charge based on area plus diesel by the farmer, crop sharing, etc.), irrigation cost varies from location to location.
3. There is significant variation in yield among different locations and rice varieties. Hybrid rice and BRRI dhan29 produced higher yield (6.0 to 7.5 tonne/ha). The variation in yield is less in BRRI dhan29. The probability of achieving a yield of 8.0 tonne/ha for Hybrid rice is only 20%.
4. Potato is the most profitable crop, but initial investment is very high. Maize has similar initial investment of rice but much higher profit. The risk of growing potato may be higher.
5. Crop evapotranspiration for rice varies from 283 mm to 545 mm. Evapotranspiration for maize varies from 276 to 528 mm. So, for water saving, maize may not be a good replacement for rice.
6. Farmers are, in general, very efficient in applying water to rice. In Shallow Tube Well (STW) sites, water applied by the farmers were very close to actual requirements, but rice plots in DTW sites had some over application.
7. The general perception of overuse of water to the extent of 3,000 to 5,000 lit to produce one kilogram of rice is nowhere near the reality in the field. The average irrigation water supplied to grow one kilogram of rice was 1,402 lit in 2015-16 and 1,086 lit in 2016-17. However, not all water supplied to the rice plots are consumed by the plants. Percolation and seepage water return to the underlying aquifer as return flow. The real water usage by the plants is the actual crop evapotranspiration. Based on these facts, the water required to grow one kilogram of rice was 661 lit and 584 lit, respectively for 2015-16 and 2016-17 crop seasons.

The study recommends examining all the factors that influence declining of groundwater levels in some parts of the region and their relative magnitudes and the impacts of different 'water saving' and 'conservation' practices on the local and regional water balance and groundwater recharge.

1 Introduction

1.1 Background

Bangladesh has made remarkable development in agriculture over the last few decades and gained self-sufficiency in rice production. With a population of 76 million in 1977, total production of rice was 11.6 million tonnes (152 kg/capita). The total production of rice has increased to 34 million tonnes (222 kg/capita) for an increased population of 168 million in 2019. It is not only rice, there is significant increase in production of other crops such as wheat, maize, vegetables and fruits over the last few decades. Thus, agriculture has become a leading contributor to poverty reduction in Bangladesh since 2000 (World Bank, 2016).

Increase in production has resulted from a substantial intensification of agriculture rather than from the increase in land area available for cultivation. The overall cropping intensity for the country has increased from 148.9% in 1977 to 194% in 2016 (BBS, 2016) with an increasing proportion of land being double- or triple- cropped. This growth in intensity was driven by increased cultivation during the dry season (October–April) that was made possible by the growing availability of irrigation facility. *Boro* rice is the major crop grown in the dry season that currently contributes more than 55% of the total rice production of the country from about 42% of the total cultivated area of rice. Most of the non-rice crops such as wheat, maize, potato, tomato, summer and winter vegetables, pulses, and oilseeds are also grown in the dry season with irrigation. *Aman* rice is the predominant crop (~70% of total cultivated area) in the wet season.

There was an impressive growth in irrigation development in Bangladesh over the last 3 decades. The total irrigated area has increased from 1.52 million ha in 1983 (18% of the net cultivable area) to 5.5 million ha in 2015, (64% of the net cultivable area). This growth was driven by the growing use of groundwater through rapid increase in the adoption of shallow tubewells (STWs). Currently, groundwater covers 79% of the total irrigated area of the country. The number of STWs has increased from 93 thousand to 1.52 million during this period. The number of deep tubewells (DTWs), which also pump groundwater, has increased from about 14 thousand to 36.7 thousand. The northwest region of the country has the highest percentage of net cultivable area irrigated (around 85% in 2012-13) and has the most intensive use of groundwater; over 97% of the total area was irrigated by groundwater in 2012-13. The region produces 34% of the country's total rice, 60% of the total wheat, and more than 2/3 of the total production of potato and maize. This region is considered as the food bowl of Bangladesh. Groundwater is the main driver for this development.

In recent years, there are serious concerns about the sustainability of groundwater use in the northwest region. Many studies (Samsudduha et al., 2009; Rahman and Mahbub, 2012; Aziz et al., 2015, Mojid et al., 2019) show that groundwater levels are falling in some parts of the region and that the use of shallow aquifers for irrigation in the area is unsustainable. Boro rice is the predominant irrigated crop in the dry season. There is a general perception with the researchers and policy makers that farmers waste water by applying excessive quantity (Rahman, 2018; Hoque, 2018) in the rice field than is required. So, 3,000 to 5,000 litres of water are required to produce one kilogram of rice (Reddy et al., 2014; Tuong, 2008). These perceptions are based on the surface water irrigation system where delivery of water was done through highly inefficient earthen canals and the on-farm water management was also poor. The return flows (seepage and percolation) from the rice fields goes to aquifer or to other sources from where they are not used or cannot be used (in case of saline aquifer). We could not find any literature about the actual water usage by the farmers in the rice field, and on the amount of water required to produce one kilogram of rice in the northwest region. Yet the current response to the declining groundwater levels is based on this perception without any detail investigations in the field.

The current (2018) population of Bangladesh is 168 million and is projected to increase to 194 million by 2050 (UN medium variant population projection). To feed this extra population, Bangladesh must increase food production substantially (Mainuddin and Kirby, 2015) and this will require further intensification of production from a land base that is in rapid decline due to urbanization and industrial development. Considering the current trend, it is expected that this extra food will come from further augmentation of the productivity of both rainfed and irrigated agriculture. So, the availability of water for irrigation is crucial for maintaining the current and future growth in agricultural production. Sustaining groundwater irrigation while maintaining the current growth in production, particularly in the northwest region, is of utmost priority of the government. This requires a clear understanding of the current state of irrigated agriculture in the region.

The northwest region is part of the Eastern Gangetic Plains (broadly, Bihar and northern West Bengal in India, the Terai in Nepal and Northwest Bangladesh) within the Ganges Basin. Eastern Gangetic Plains are believed to have significant potential for intensification of agricultural production and to offer underutilised opportunities to improve livelihoods of smallholder farmers. As mentioned above, the northwest Bangladesh has been more successful in tapping into this potential than the biophysically similar neighbouring states in India, and Nepal Terai (Kirby et al., 2013). This raises the question about the nature of social and institutional constraints to rural development holding back smallholders in India and Nepal.

1.2 Aim and objectives

The main aim of this study is to provide a detail state of irrigated agriculture for the northwest region based on the historical data and field observations that will provide information to the policy makers for planning sustaining groundwater irrigation in the region. This information is also expected to help further development of irrigated agriculture in the other parts (areas in India and Nepal) of the Eastern Gangetic Plains. The specific objectives of the study are:

1. To analyse the historical trends of cultivated area, yield, production and irrigation development in the region.
2. To understand the variation in water and land productivity from plot to plot, location to location, and by different modes of irrigation. To know the reasons of productivity variations and to identify the ways for their improvement.
3. To draw key messages for the sustainable and equitable management of groundwater resources that may be applicable in Nepal and Bihar.

The study is based on historical data available mainly from the Bangladesh Bureau of Statistics (BBS), primary data collected through intensive field observations in 7 locations across the region during the dry seasons of 2015-16 and 2016-17, and the relevant modellings using field data and observations. To the best of our knowledge, this is the most comprehensive study on the irrigated agriculture on the northwest region and is expected to provide valuable information to the policy makers for planning sustainable irrigated agriculture for the future.

2 Current state of irrigation and agriculture in the northwest region

2.1 Topography and climate

The total area of the northwest region is 34,515 km^2, which is about 23.5% of the total area of the country (Figure 2.1). The area is divided into 16 administrative districts under two administrative Divisions (Rajshahi and Rangpur). The area is characterized by two distinct landforms viz. the Barind Tract-dissected and undulating, and the floodplains. The Barind Tract is a distinctive physiographic unit comprising a series of uplifted blocks of terraced land covering 8,720 km^2 in north-western Bangladesh between the floodplains of the Padma (known as the Ganges in India) and the Jamuna rivers (the main channel of the lower Brahmaputra) (Riches, 2008). It covers parts of Pabna, Rajshahi, Bogura, and Joypurhat districts of Rajshahi Division and some parts of Dinajpur, and Rangpur districts of the Rangpur Division.

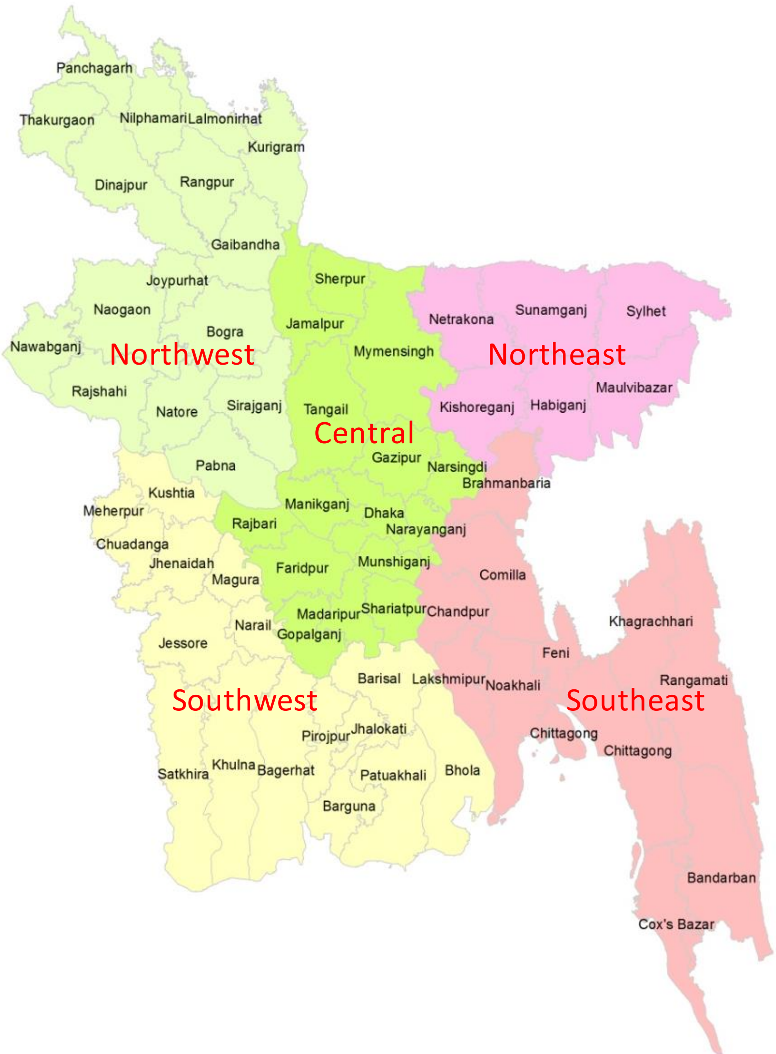

Figure 2.1 Five main regions of Bangladesh

Climatically, this region belongs to the dry humid zone with annual rainfall varying from 1,273 to 2,515 mm (average of 1985-2010). Among the regions, the northwest has the lowest average annual rainfall (1,927 mm; Figure 2.2). The average reference evapotranspiration (ETo, estimated by Penman-Monteith method) is 1,309 mm, which is close to the country's highest value; the highest ETo (1,334 mm) is in the southwest region. Thus, the region is the driest and has the 2nd greatest reference evapotranspiration.

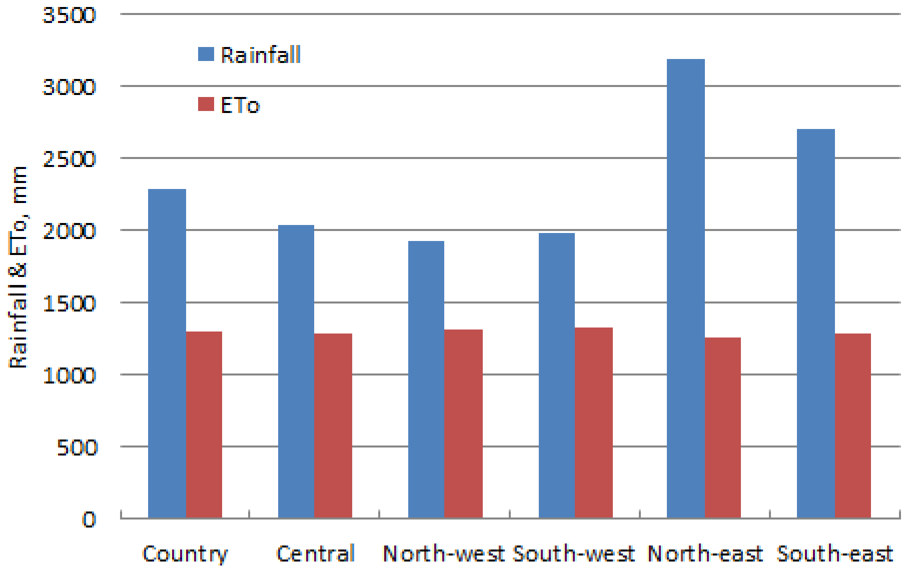

Figure 2.2 Average (1985-2010) annual rainfall and reference evapotranspiration (ETo) of the different regions of Bangladesh

There is significant variation of rainfall within the region (Figure 2.3). Barind area, represented by Rajshahi in Figure 2.3, has the lowest average rainfall (1,428 mm) and Rangpur has the highest rainfall (2,262 mm). Rainfall varies widely (with coefficient of variation, CV, of 20 to 24%) from year to year as well (Figure 2.3). There are spatial and temporal variation in ETo as well (Figure 2.4); however, the variation is much less (temporal CV of 6 to 8%) than the variation in rainfall. The highest average ETo is 1,366 mm for Ishurdi (within Pabna district) and the lowest is 1251 mm in Rangpur. The monthly distribution of rainfall and reference evapotranspiration is shown in Figure 2.5. Almost 82% of rainfall occurs during the monsoon season (May–October) and 18% of rainfall occurs during the dry season (November–May).

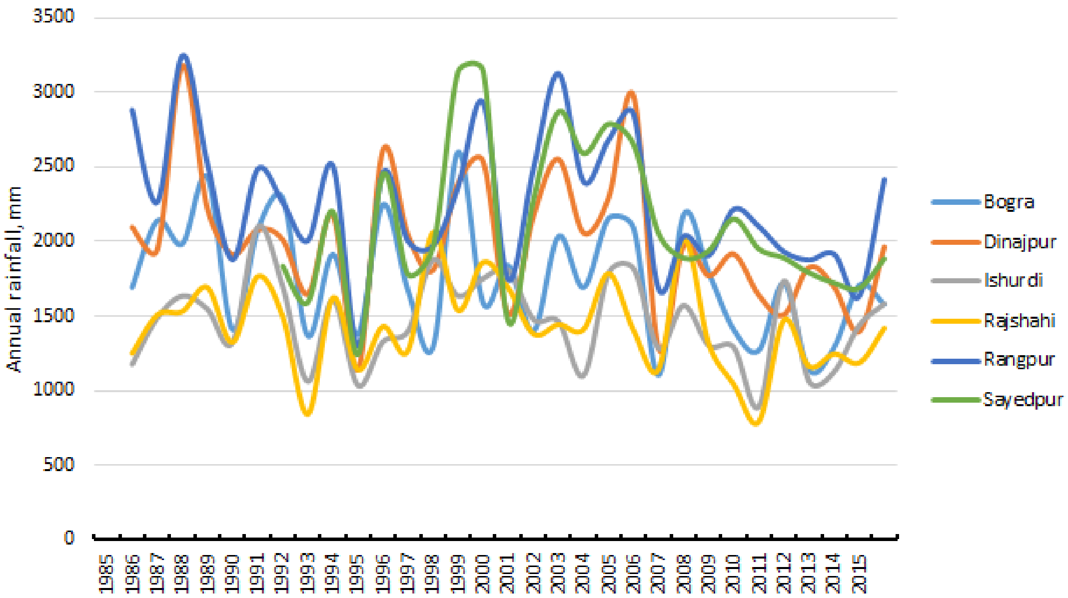

Figure 2.3 Annual variation in rainfall for the six main weather stations in the northwest region

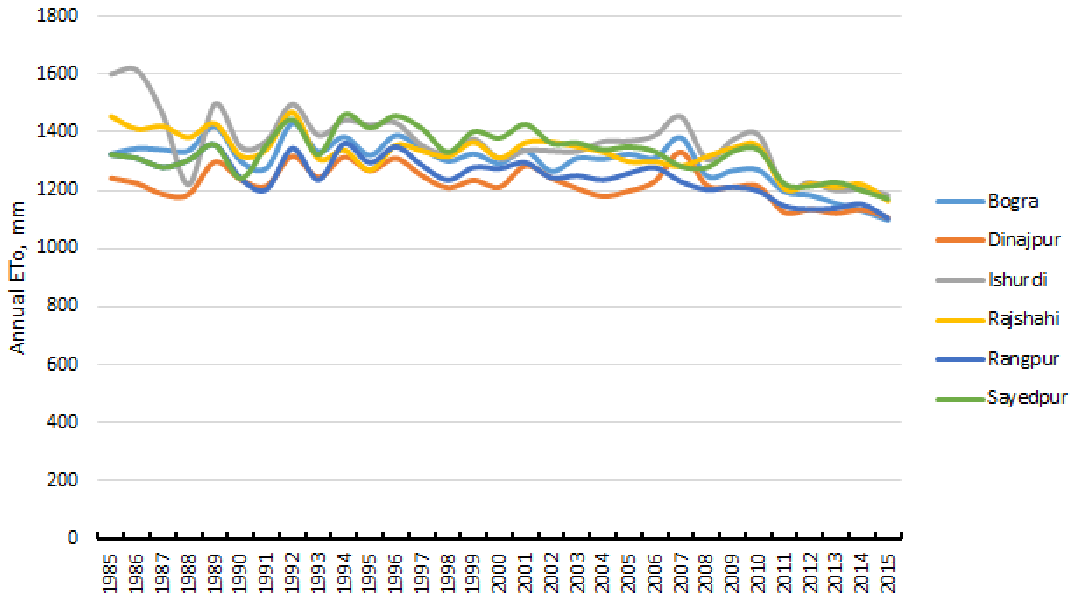

Figure 2.4 Annual variation in ETo for six main weather stations in the northwest region

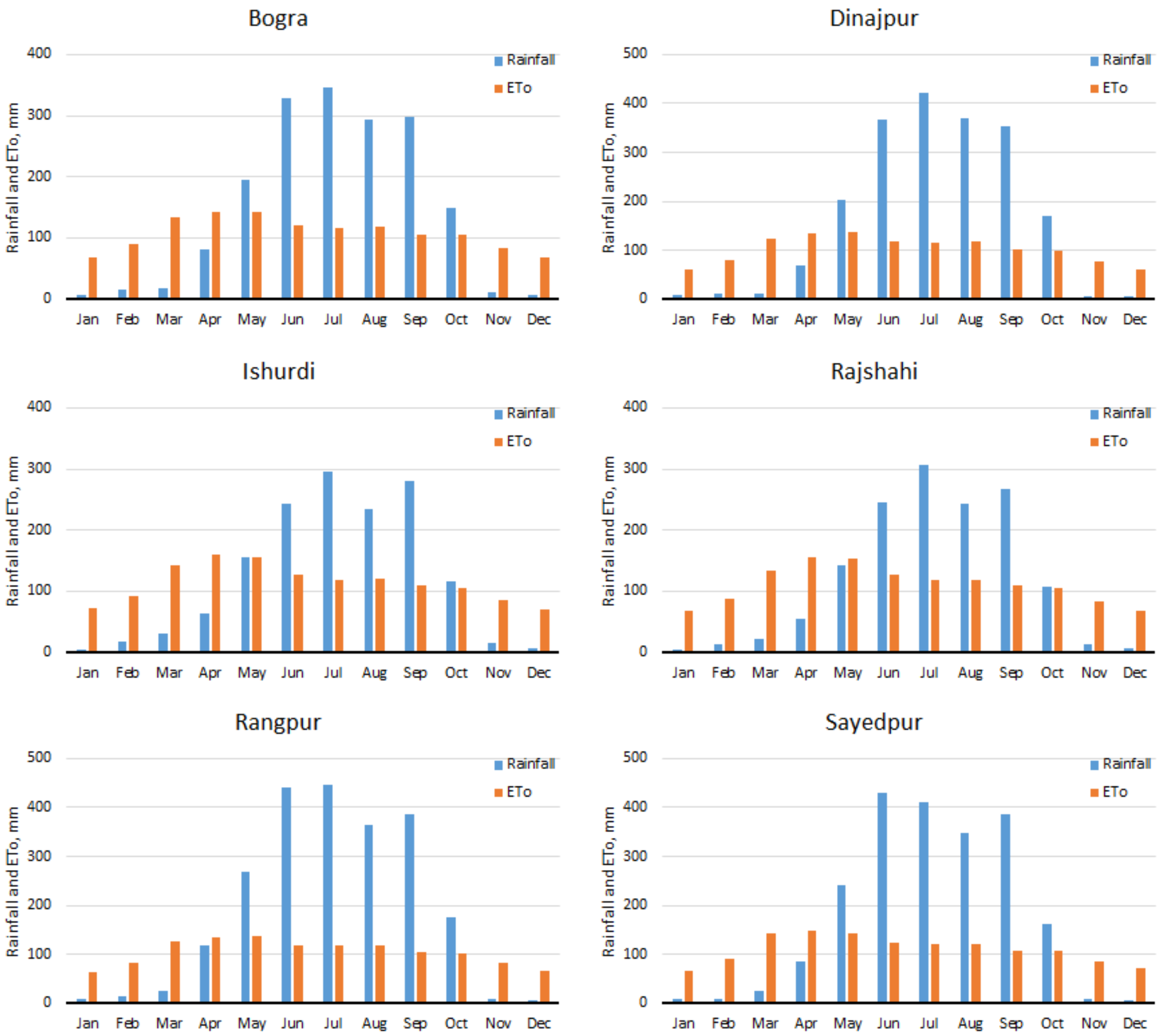

Figure 2.5 Comparison of average monthly rainfall and ETo in the northwest region (Ishurdi is in Pabna district and Sayedpur is another station within Rangpur district)

The monthly average temperature ranges from 25 to 35°C in the hottest season and 9–15°C in the coolest season. In summer, some of the hottest days experience a temperature of about 45°C or even more (Habiba et al., 2014). In the winter season, temperature goes down to 5°C in some places (Habiba et al., 2014). Maniruzzaman et al. (2017) reported that the average annual maximum, minimum and mean temperatures have increased by 0.001°C year^{-1}, 0.016°C year^{-1} and 0.009°C year^{-1} ($p<0.05$), respectively during 1971-2010. They also reported that dry season maximum temperature decreased by 0.013°C year^{-1} and seasonal minimum and mean temperature increased by 0.024°C year^{-1} and 0.006°C year^{-1}, respectively. On the other hand, wet season maximum and minimum temperatures are increasing by 0.0174 and 0.0083°C year^{-1}, respectively (Biswas et al., 2017). Average monthly humidity varies from 62% (in March) to 87% (in July), with a mean annual of 78% (Jahan et al., 2010).

2.2 Cropping season, area, and intensity

A wide range of crops are grown in Bangladesh. They are broadly classified into two groups according to seasons in which they are grown:

(i) Kharif crops

(ii) Rabi crops

Kharif crops are grown in the spring or summer season and harvested in late summer or in early winter (Figure 2.6, BBS, 2011). Kharif season is divided into Kharif-I (March to June) and Kharif-II (July to October). Rabi (November to February) crops are sown in winter and harvested in the spring or early summer (BBS, 2011). Kharif crops are mostly rainfed and partially irrigated as they are grown in pre-monsoon and monsoon seasons. Rabi crops are grown in dry season with very little rainfall. So, they are mostly irrigated.

Figure 2.6 Cropping season and the standard crop calendars for the major crops

Rice is the predominant crop in all seasons. Three types of rice are grown. They are Aus, Aman and Boro. Aus is grown in Kharif-I, Aman in Kharif-II, and Boro in Rabi season. Aman is the main rainfed rice and Boro is the fully irrigated rice. Aus, grown in very small areas nowadays, is not generally irrigated or partially irrigated (BBS, 2012). Aman rice covers about 87% of the total cropped area in the Kharif-2 season and Boro rice covers 61% of the total cropped area in the Rabi season (BBS, 2012).

The northwest is also a most diversified cropping region of the country (Mainuddin et al., 2014). Apart from rice, a wide range of crops are grown in Bangladesh. These are Jute, wheat, maize, other cereals, potato, tomato, pulses (lentil, mungbean, blackgram, etc.), oilseeds (mustard, soybean, sunflower, etc.), vegetables (both Kharif and winter vegetables), sugarcane, drugs and narcotics (tea, tobacco, betel nut and betel leaves, etc.), fibre, spices and condiments (chillies, onion, ginger, etc.), and fruits (BBS, 2011). The areas under different crops in 2011-12 are given in Figure 2.7.

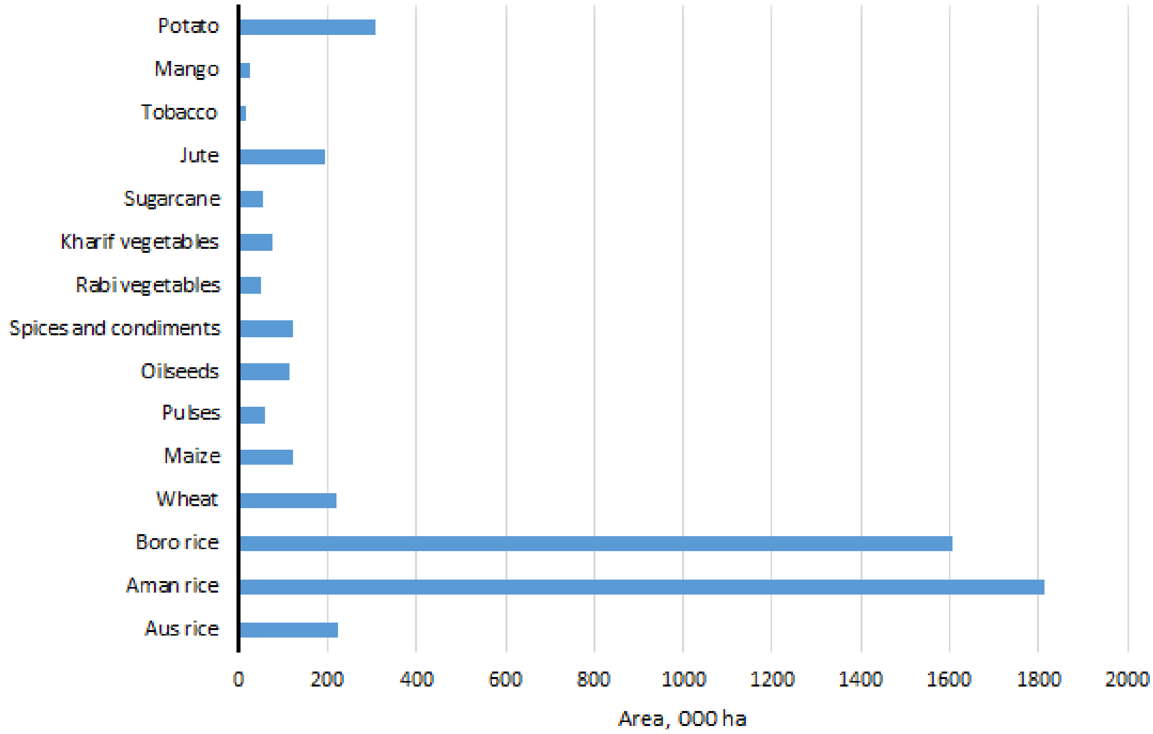

Figure 2.7 Areas under different crops grown 2011-12 in the northwest region

Northwest region is the most intensively cultivated region of the country. The region covers 23.5% of the total area of the country but has about 31% of the total cultivable area (2011-12). The average cropping intensity of the region in 2012 was 205% compared to the country average of 190%. In many areas, 3 to 4 crops are grown in a year. Within the region, the highest cropping intensity is in greater Bogura (Bogura and Joypurhat Districts) and the lowest is in greater Rajshahi (Rajshahi, Naogaon, and Nawabganj; Figure 2.8). All greater districts have cropping intensity higher than the country average. The cropping intensity is gradually increasing.

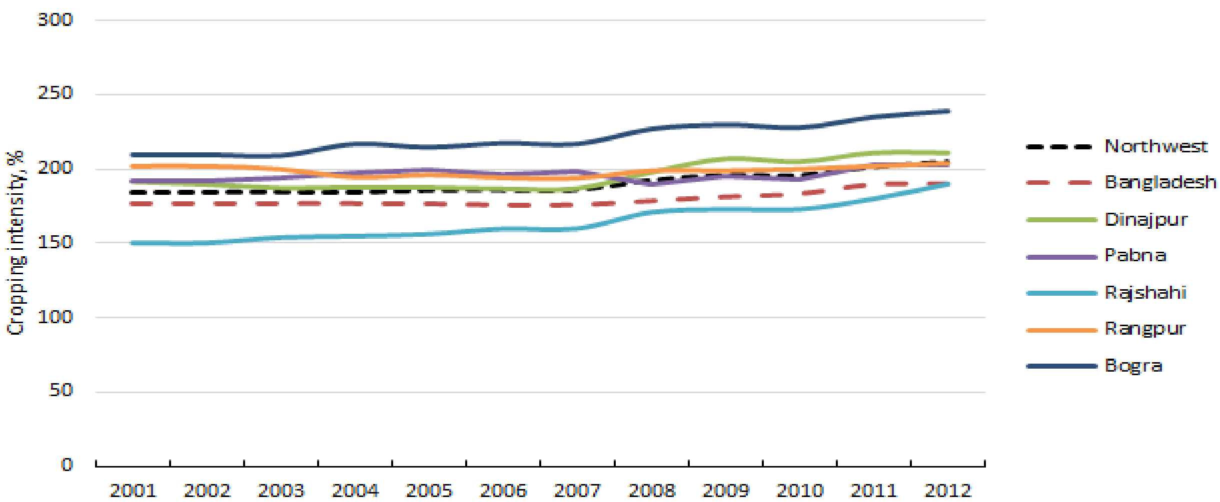

Figure 2.8 Cropping intensity (%) in the major districts of the northwest region along with the average of the region (black dotted line) and the country (red dotted line)

2.3 Trend in cultivated area of major crops

Over the last decades, there was phenomenal growth in Boro rice area (Figure 2.9) in the country. In the northwest region in 1979-80, the area was 116,000 ha, which has increased to 1.62 million ha in 2014-15; an increase of about 14 times. There was linear growth in the area until 2008-09 after which there was almost no growth. It seems the area of Boro has reached its peak in the region. Boro rice is fully irrigated, predominantly by groundwater (will be discussed later). Due to concerns of falling groundwater level, government is actively discouraging farmers to grow Boro rice and promoting to grow other non-rice crops. However, there is no decrease in area, but the growth has been stalled. Among the greater districts, the area of Boro rice has decreased from the peak of 384,122 ha in 2008-09 to 371,330 ha (a decrease of 3.3%) in 2010-11 and then again increased to 379,101 ha in 2014-15 in Rajshahi (the most water-stressed area).

The increase in Boro rice area was due to a decrease in areas of other crops such as Aus (Aus season overlaps with the Boro season) and other Rabi crops cultivated in the same season (Figure 2.6). The net cropped area during this period has also decreased due to urbanization and industrial development. The Aus area in the region has declined gradually, from the maximum of 968,000 ha in 1983-84 to the minimum of 110,000 ha in 2004-05 (Figure 2.10). Over the last 5 years, the area has increased to over 200,000 ha. The government's policy is to increase the Aus area and reduce the Boro area. But there is no noticeable growth of the Aus area at the regional level over the last 7 years. Only in Rajshahi, there is noticeable growth in Aus area, which has risen to 162,000 ha in 2011-12 from 59,000 ha in 2001-02. In 2014-15, the area was 143,000 ha. Aus is a climate-vulnerable crop and its flowering time coincides with high temperature period, which negatively affects the yield. The harvest time coincides with rainfall period, making is difficult for the farmers for threshing, drying and winnowing.

The planting of Aman rice depends on the onset of monsoon season as lot of water is needed to prepare the land for transplanting. Aman is also affected by floods and seasonal droughts, which sometimes damage the crop. So, the area of the crop slightly varies from year to year within the range of 1.7 to 1.9 million hectares in the region as shown in Figure 2.11. The Aman area remains also steady within the greater districts.

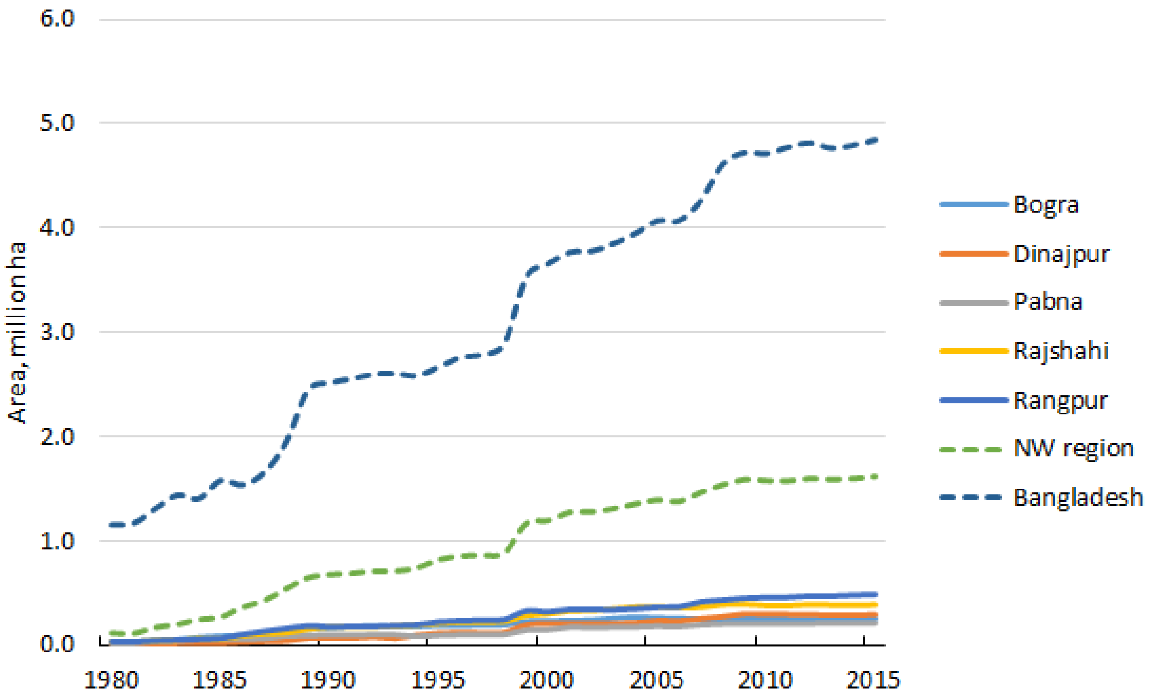

Figure 2.9 Trend in cultivated area of Boro rice in different districts of the northwest region along with the regional and country mean trend

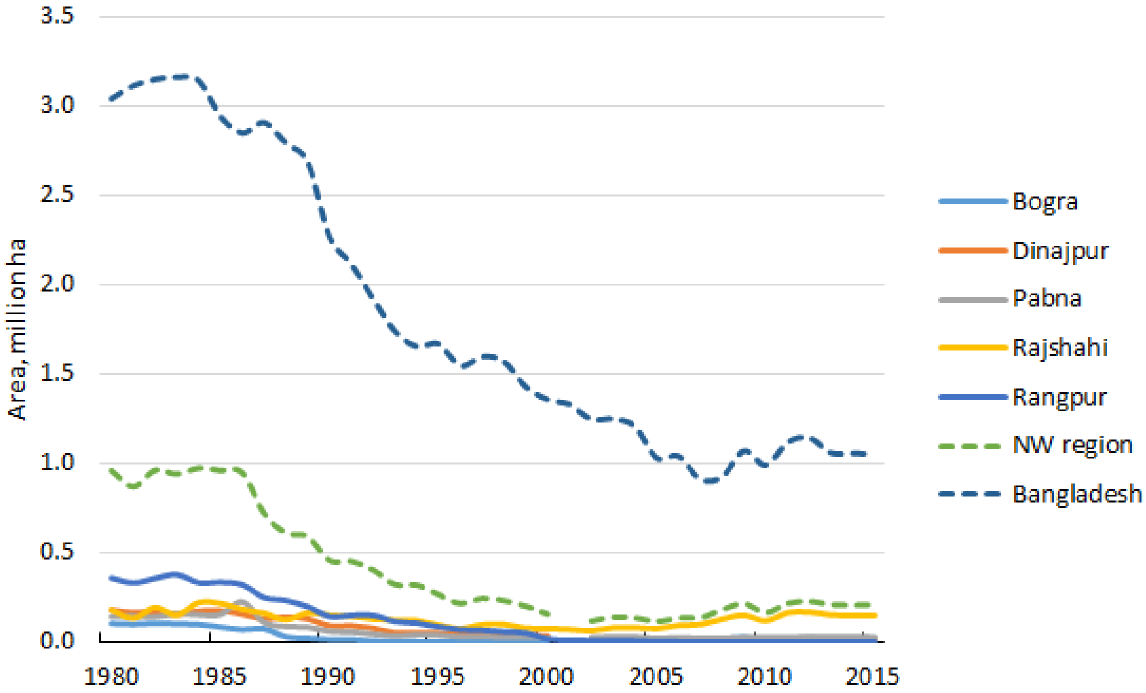

Figure 2.10 Trend in cultivated area of Aus rice in different districts of the northwest region along with the regional and country mean trend

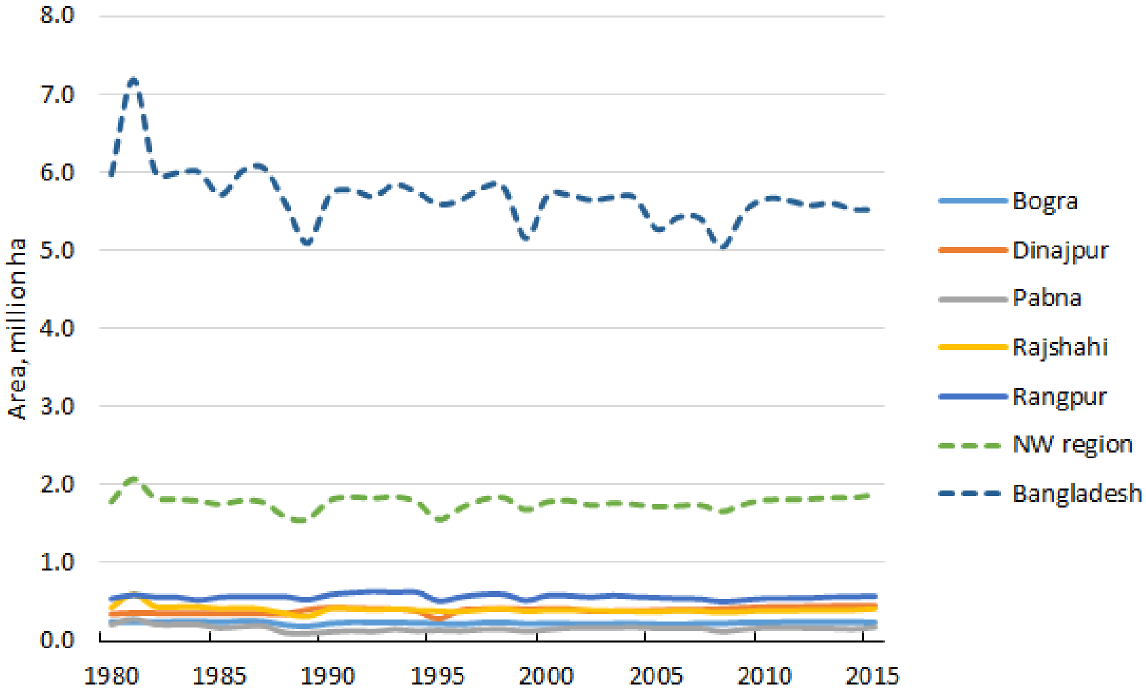

Figure 2.11 Trend in cultivated area of Aman rice in different districts of the northwest region along with the regional and country mean trend

The northwest region has more than 60% of the country's total wheat area. However, the area has reduced from its peak of 467,000 ha in 1998-99 to the minimum of 217,000 ha in 2011-12 (Figure 2.12). Currently (2014-15) the area is about 272,000 ha. Dinajpur (35% of the total area of the region), Rajshahi (38%) and Pabna (17%) are the major wheat-growing areas of the region as well as of the country.

The decrease in the cultivated area of wheat can be partly attributed to the increase in the cultivated area of maize. The area of maize has increased exponentially with a dip in 2008-09 and 2009-10 (Figure 2.13).

The area has increased from 7,000 ha in 2001-02 to 148,000 ha in 2007-08 but reduced to 99,000 ha in 2009-10. Since then, the area has increased exponentially again to 211,000 ha in 2014-15 (Figure 2.13). The region has 65% of the country's total maize cultivated area. Dinajpur (46.2% of the total area of the region) and Rangpur (33.4%) are the major maize-growing areas followed by Rajshahi (12.3%) in the region. Northwest region is also the major producer of potato (71.4% of the country's total area producing 67% of total production), mango (77% of area and 64% of production), sugarcane (51% of area and 63% of production), spices and condiments (38% of area and 33% of production), pulses, and oilseeds (Table 2.1).

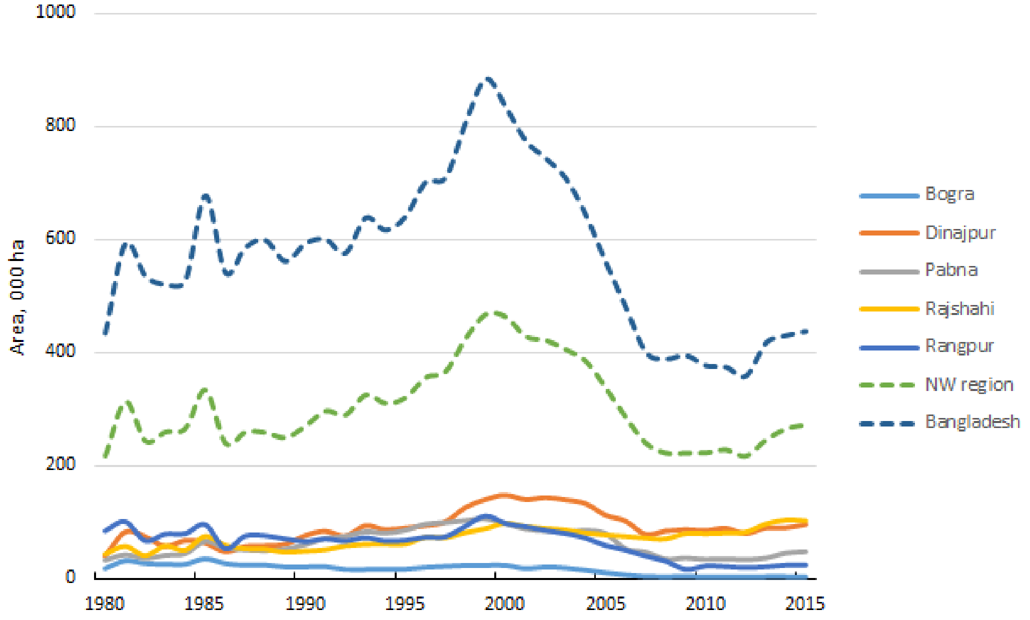

Figure 2.12 Trend in cultivated area of wheat in different districts of the northwest region along with the regional and country mean trend

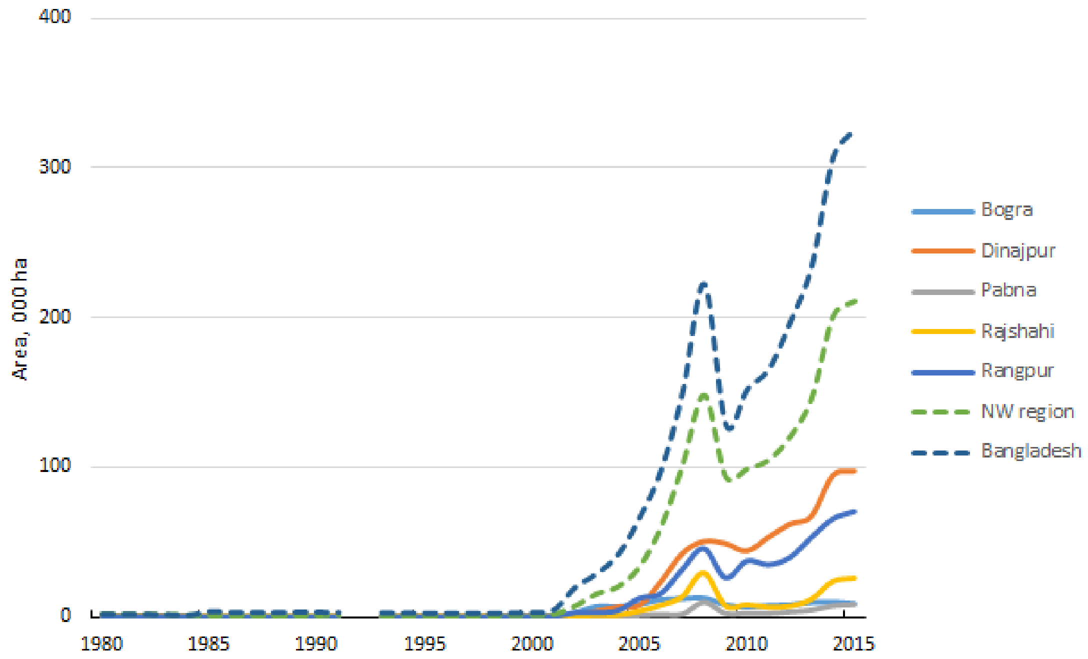

Figure 2.13 Trend in cultivated area of maize in different districts of the northwest region along with the regional and country mean trend

Table 2.1 Basic statistics of the northwest region for 20014–15

ITEM	COUNTRY	NORTHWEST
Total area (km²)	146,589	34,515 (23.5%)
Net cultivable area (NCA, million ha)	8.268	2.572 (31.1%)
Area irrigated (million ha)	5.218	2.079 (39.8%)
Area irrigated as % of NCA	63.1%	80.8%
Area irrigated by groundwater (million ha)	4.127	2.021 (49.0%)
Area irrigated by groundwater as % of total irrigated area	79.0%	97.2%
Crop area (million ha)		
Total rice	11.416	3.698 (32.4%)
Aus rice	1.045	0.204 (19.5%)
Aman rice	5.530	1.870 (33.8%)
Boro rice	4.840	1.624 (33.6%)
Wheat	0.437	0.272 (62.3%)
Maize	0.211	0.325 (64.8%)
Potato (2011-12)	0.430	0.307 (71.4%)
Pulses (2011-12)	0.270	0.059 (21.9%)
Oilseeds (2011-12)	0.349	0.115 (32.8%)
Spices and condiments (2011-12)	0.326	0.123 (37.7%)
Vegetables (2011-12)	0.465	0.125 (26.9%)
Tobacco (2011-12)	0.051	0.018 (35.0%)
Sugarcane (2011-12)	0.108	0.055 (50.7%)
Jute (2011-12)	0.760	0.192 (25.3%)
Mango (2011-12)	0.031	0.024 (76.9%)
Crop production (million tonne)		
Total rice	34.710	12.051 (34.7%)
Aus rice	2.328	0.505 (21.7%)
Aman rice	13.190	4.907 (37.2%)
Boro rice	19.192	6.639 (34.6%)
Wheat	1.348	0.856 (63.5%)
Maize	2.272	1.415 (62.3%)
Potato (2011-12)	8.205	5.490 (66.9%)
Pulses (2011-12)	0.240	0.052 (21.9%)
Oilseeds (2011-12)	0.353	0.116 (33%)
Spices and condiments (2011-12)	1.756	0.769 (43.8%)
Vegetables (2011-12)	1.489	0.357 (24%)
Tobacco (2011-12)	0.085	0.023 (26.8%)
Sugarcane (2011-12)	4.603	2.896 (62.9%)
Jute (2011-12), Million Bales	8.003	2.206 (27.6%)
Mango (2011-12)	0.945	0.600 (63.5%)

Source: BBS (2011), BADC (2010). Numbers in parenthesis show % of the country's statistics

2.4 Trend in yield and production of major crops

Bangladesh has been making remarkable advance in rice production. At the country level, total rice production increased from 12.5 million tonnes in 1979-80 to 34.71 million tonnes (277%) in 2014-15. In the northwest region, total production of rice during this period increased from 3.28 million tonnes to 12.051

million (367%) tonnes. During this period, average yield of rice increased from 1.23 to 3.04 tonne/ha at the country level. Increase in production has resulted from substantial intensification of rice cultivation through introduction of Boro rice during the dry season (Figure 2.14) and from the increase in yield for all types of rices (Figure 2.15) due to replacement of low-yielding local varieties with the high-yielding and hybrid (recently introduced) varieties, increased application of inputs (such as fertilizer, pesticides, etc.) and better management of the crop. Boro cultivation has been made possible by the growing availability of irrigation by groundwater through rapid increase in the adoption of shallow tubewells, STWs. The increase in production out-weighed the growth in population. In the early nineties, with the total population of 106 million, the net import of food gain was around 3 million tonne/year (Islam and Mondal, 1992). In 2012-13, with the population of 152 million, Bangladesh has gained self-sufficiency in rice production (The Daily Star, 2013).

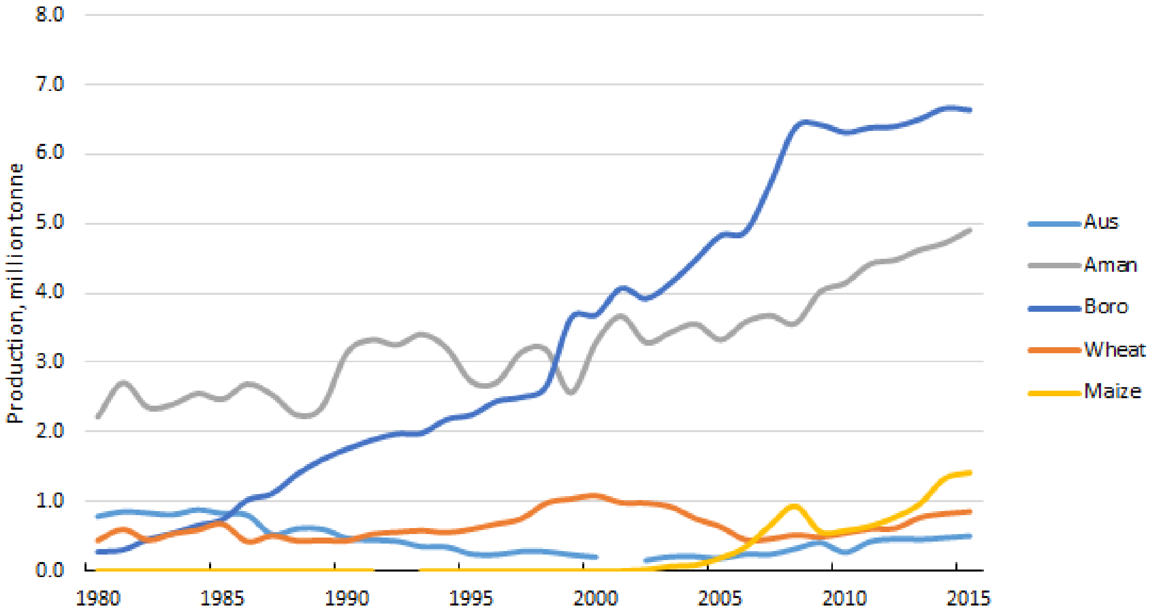

Figure 2.14 Trend in total production of major crops in different districts of the northwest region

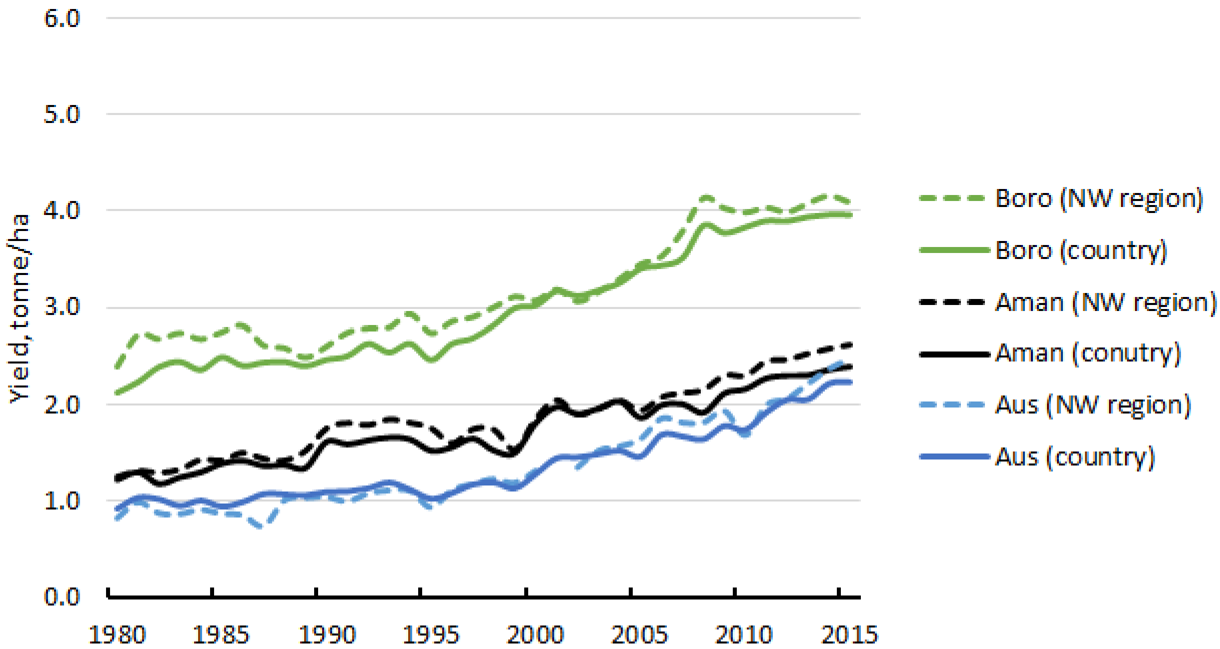

Figure 2.15 Average yield of rice in the northwest region (dotted lines) and at the country level (solid lines)

The average yields of Aus, Aman and Boro rice have increased consistently all over the country, with some fluctuations as shown in Figure 2.15. However, the average yield is higher in the northwest region compared to average yield at the country level for all 3 types of rice. The average yield of Boro rice is much higher than that of Aman and Aus rice. Boro is a fully irrigated crop, so the risk of this crop being suffered from water stress is much less than Aman and Aus rice, which are rainfed. Due to variation in rainfall over space and time, Aus and Aman rice suffer from in-seasonal water stress, which is the main reason of their low yield and yield growth (Islam and Mondal, 1992; Jensen et al., 1993). In addition, Aus and Aman rice (particularly Aman) also suffer damage due to inundation and flood from heavy rainfall (Roy, 2013).

There is significant spatial variation at the district level in the yield and growth in yield of Aus rice. According to the data of the last nine years (2006-07 to 2014-15), in general, the yield of Aus rice is higher in the greater districts of Rajshahi, Dinajpur and Bogura and lower in Pabna and Rangpur (Figure 2.16). The yield fluctuates from year to year but, in general, it is increasing. The average yield for the region has increased from 1.82 tonne/ha in 2006-07 to 2.48 tonne/ha in 2014-15.

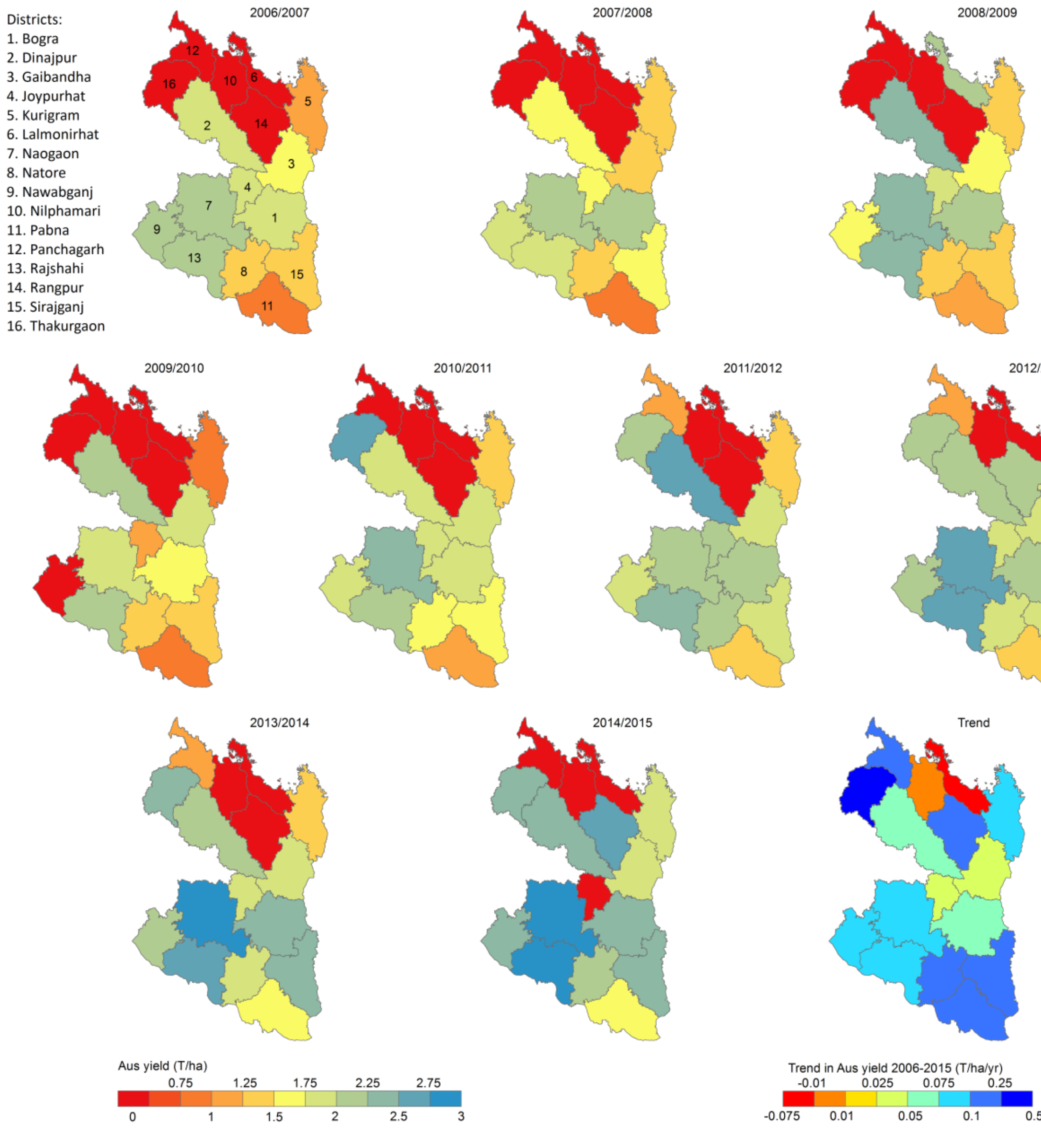

Figure 2.16 Spatial variation and trend in the yield of Aus rice during 2006-07 to 2010-11 in the northwest region

The variation in the yield of Aman rice among the districts is like that of Aus within the region (Figure 2.17). Currently (2014-15), the average yield is higher and almost similar in the greater districts of Bogura, Rangpur, Rajshahi, and Dinajpur. The lowest yield was in Pabna. In all the districts, the average yield has increasing trends. For the region, the average yield has increased from 2.12 tonne/ha in 2006-07 to 2.62 tonne/ha in 2014-15.

The spatial variation in the yield of Boro rice is much lower compared to that of Aus and Aman rice (Figure 2.18). The coefficient of variation, CV, of the average yield for the districts varies from 4.4 to 6.4% over the last 10 years (2005-2015). CV was 10.7 to 26.0% for Aus and 8.8 to 11.4% for Aman. There is no growth in the yield over the last 8 years (2007-2015). The average yield during this period varied from the minimum of 3.98 tonne/ha to the maximum of 4.16 tonne/ha.

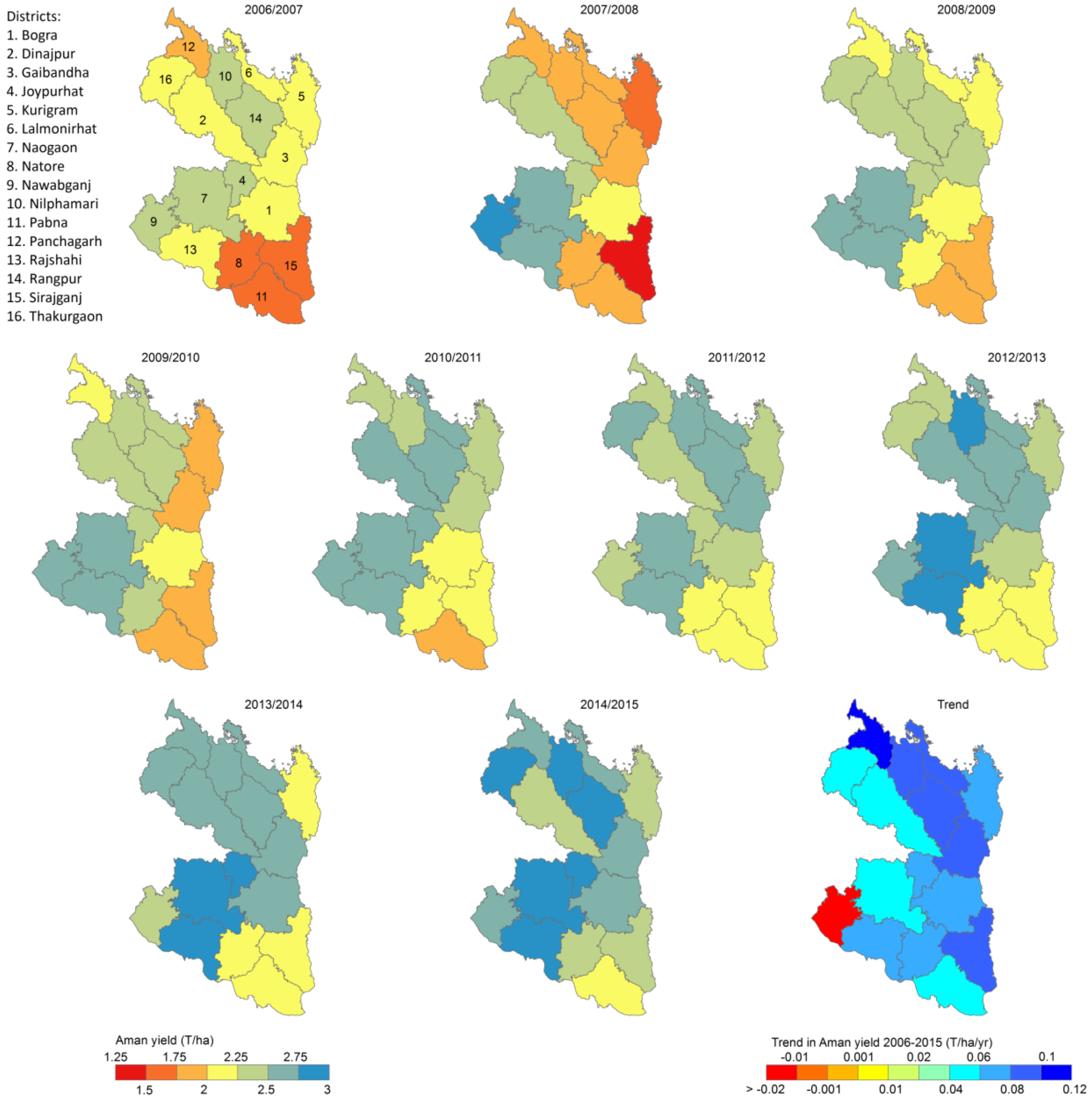

Figure 2.17 Spatial variation and trend in the yield of Aman rice during 2006-07 to 2010-11 in the northwest region

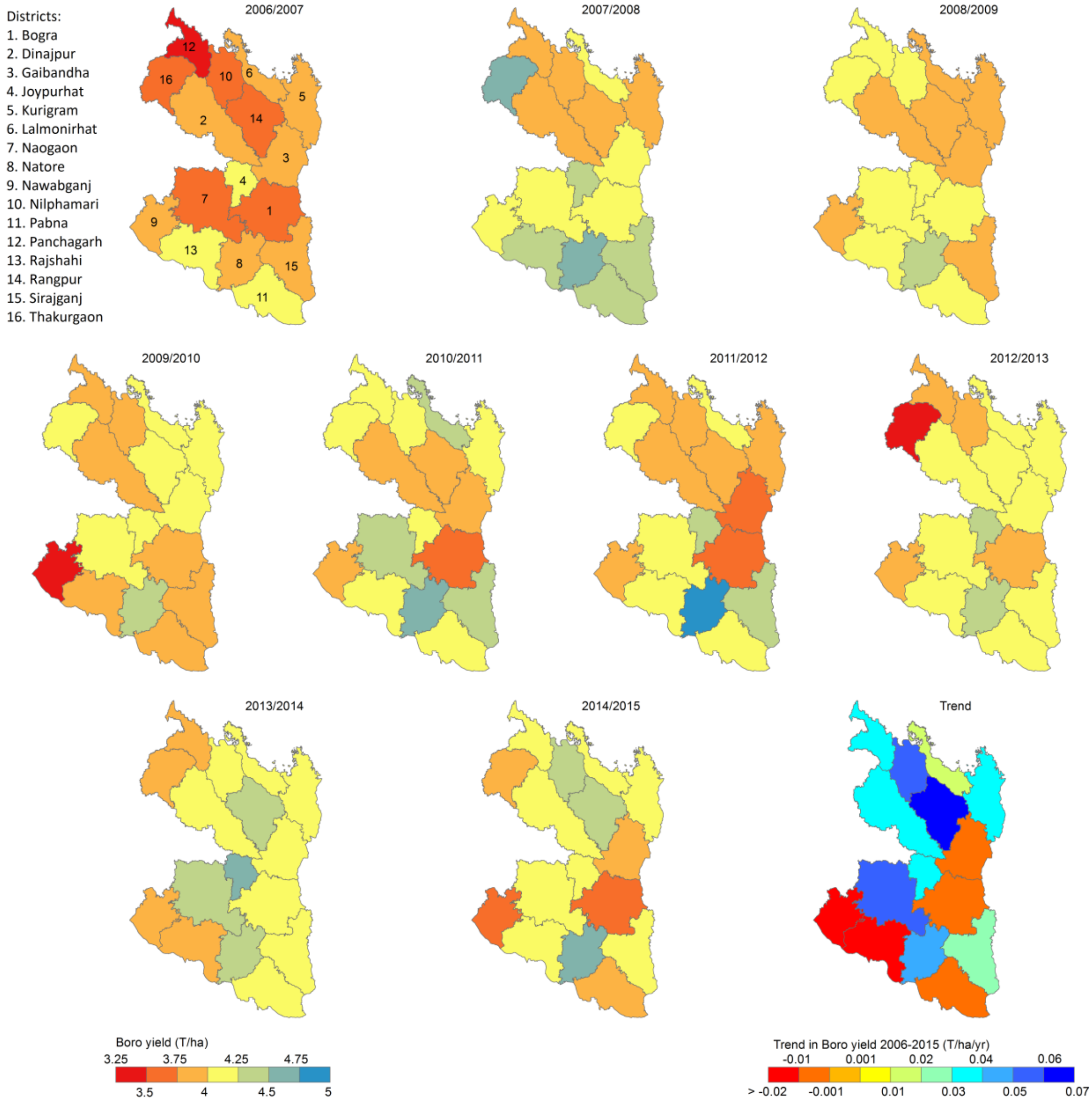

Figure 2.18 Spatial variation and trend in the yield of Boro rice during 2006-07 to 2010-11 in the northwest region

While there was linear growth in rice production and yield, wheat production and yield were going through fluctuations (Figures 2.14 and 2.19). At the country level, the maximum production of 1.9 million tonnes was in 1998-99. In the northwest region, this was 1.085 million tonnes in 1999-00. In 2014-15, the production of wheat in the northwest region was 0.856 million tonnes (Figure 2.14). The increase in total production up to 2008 was mainly due to the increase in total area for the crop as the yield has been varying around 2.0 tonne/ha over that period (Figure 2.19). However, over the last 6 years, there was significant increase in yield; yield increased from 2.02 tonne/ha in 2009 to 3.15 tonne/ha in 2015 in the northwest region. The average yield was slightly higher in the region than the country average.

The total production of maize has dramatically increased since 2001 (Figure 2.14); in the northwest region, it was 3,430 tonnes in 2001 and increased to 1.415 million tonnes (412 times) in 2015. This is due to both increase in area and yield. Over this period, the area increased from 1,314 ha to 210,997 ha (161 times) and the yield increased from 2.61 tonne/ha to 6.71 tonne/ha (2.57 times). This is because of the strong demand from the poultry and aquaculture sectors. The average yield of maize in the region is at par with the country average yield (Figure 2.19).

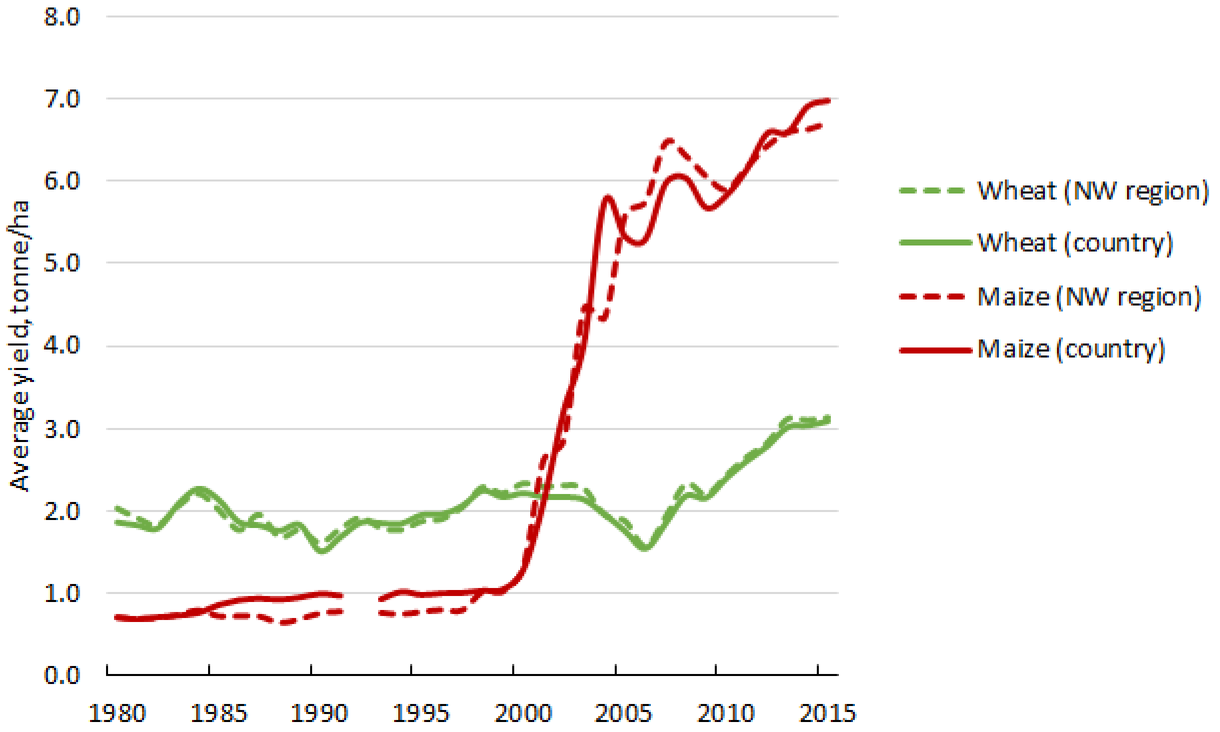

Figure 2.19 Average yield of wheat and maize

The growth in cropping intensity (discussed in Section 2.2) and the manyfold increase in rice production driven by increased cultivation during the dry season, particularly Boro rice, were made possible by the growing scope of irrigation with groundwater. Boro rice currently (2015) contributes 55% to the total annual rice production of the country. The large increase in Boro rice production is a key factor in rice grain self-sufficiency of the country. Other cereals such as wheat and maize, and other crops including potato, tomato, sunflowers, pulses, oilseeds and major vegetables are also grown in the dry season using irrigation.

2.5 Irrigation

There was outstanding growth in irrigation development over the last 3 decades. According to the Minor Irrigation Survey Report prepared by BADC under the Ministry of Agriculture, total irrigated area increased from 1.52 million ha in 1983 (18% of the net cultivable area, NCA) to 5.45 million ha in 2015 (61.2% of the net cultivable area) (Figure 2.20). This growth was driven by the growing use of groundwater through rapid increase in the adoption of STWs (Figure 2.20). The number of STWs has increased from 93,000 to 1.55 million during this period. The number of DTWs, which also pump groundwater, increased from about 14,000 to about 37,000. There was almost no growth in use of surface water for irrigation (0.9 million ha in 1983 to 1.22 million ha in 2015. Currently, about 79% of the total area (4.22 million ha) is irrigated using groundwater sources.

The growth in irrigation, more specifically groundwater irrigation, was not uniform over the whole country. The northwest region is the most intensively irrigated area of the country. Currently, 83% of the NCA is irrigated in the northwest region compared to 61.2% at the country level (Figure 2.21). Despite having 30% of the NCA area of the country, the region has more than 40% of the total irrigated area. Of the irrigated area, 97% are irrigated with groundwater (Figures 2.22 and 2.23). On average, there are more than 28 STWs and 1 DTW per 100 ha of cultivable area of the region.

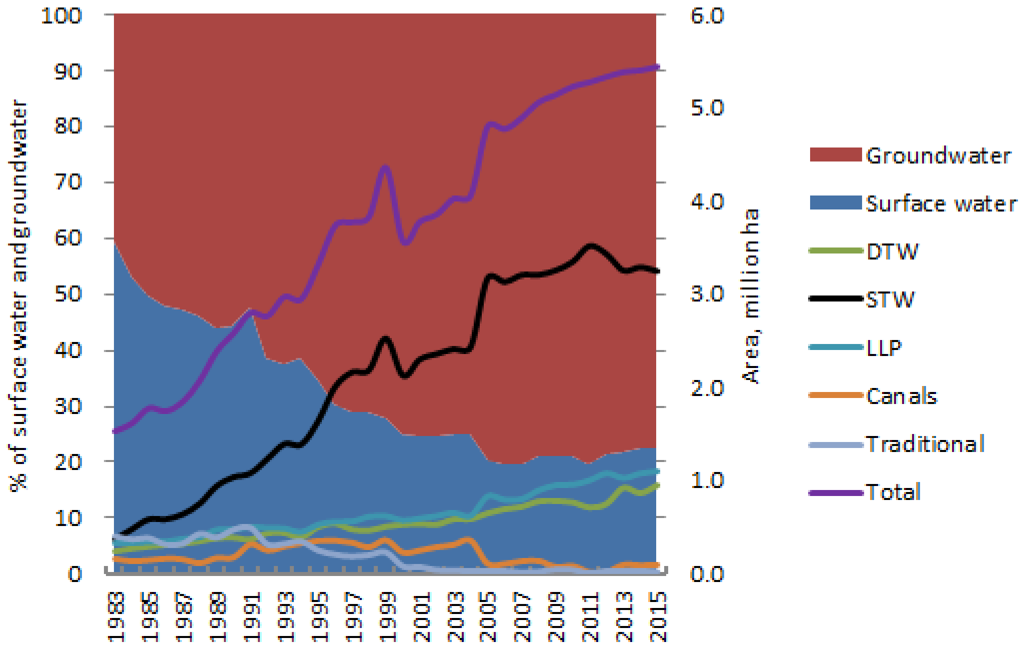

Figure 2.20 Area irrigated by different technologies and sources of water in Bangladesh (Data source: BADC)

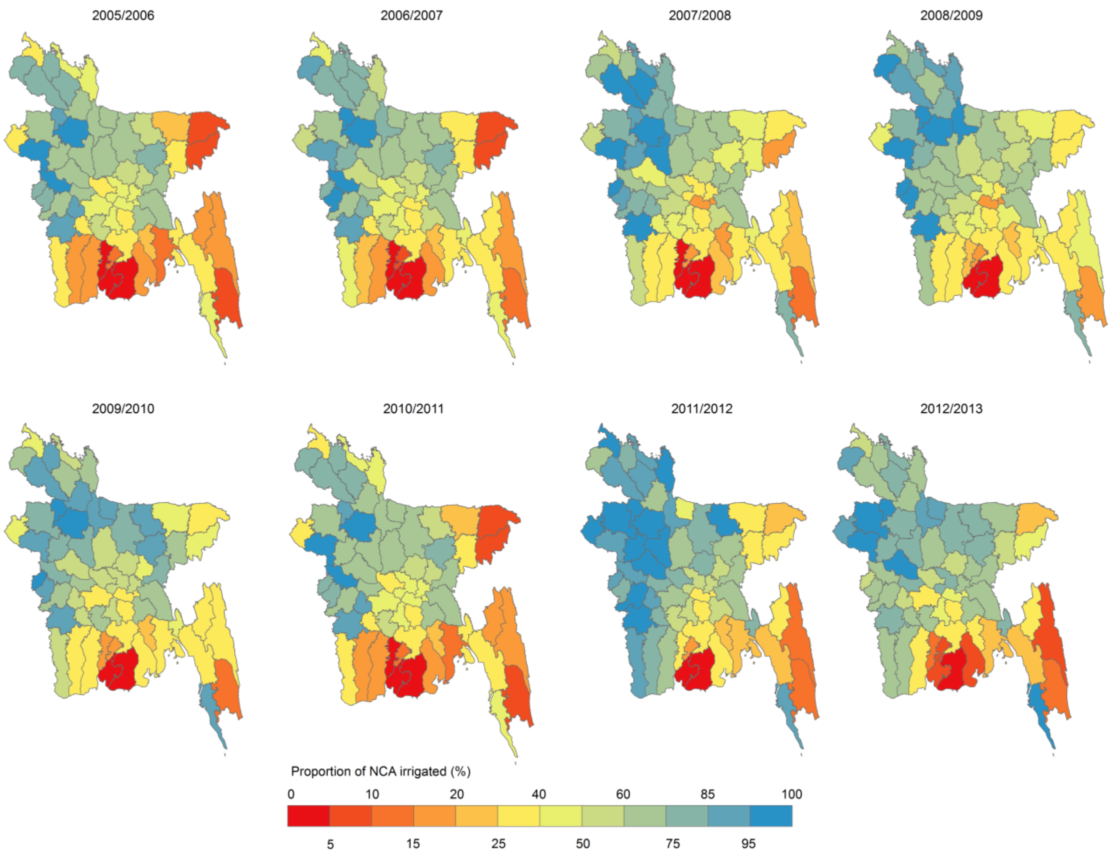

Figure 2.21 Proportion of net cultivable area (NCA) irrigated (Data source: BADC)

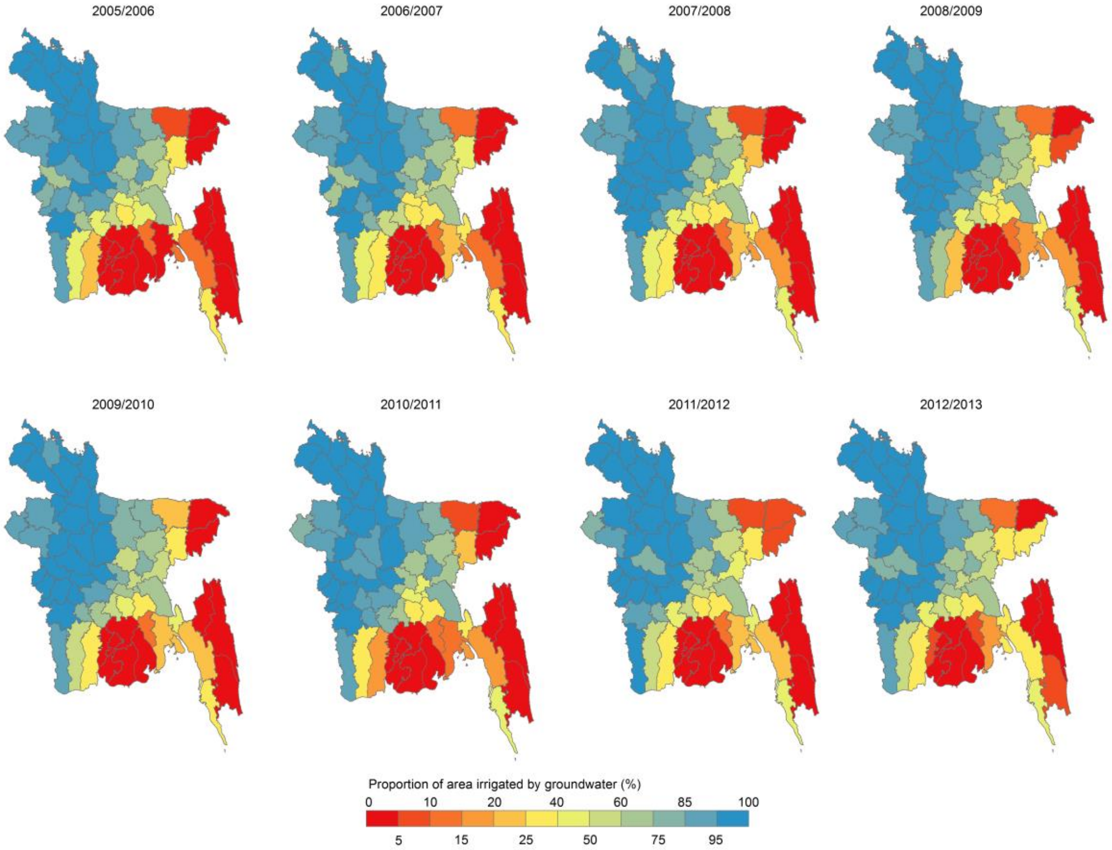

Figure 2.22 Proportion of net cultivable area (NCA) irrigated by groundwater during 2005–06 to 2012–13 (Data source: BADC)

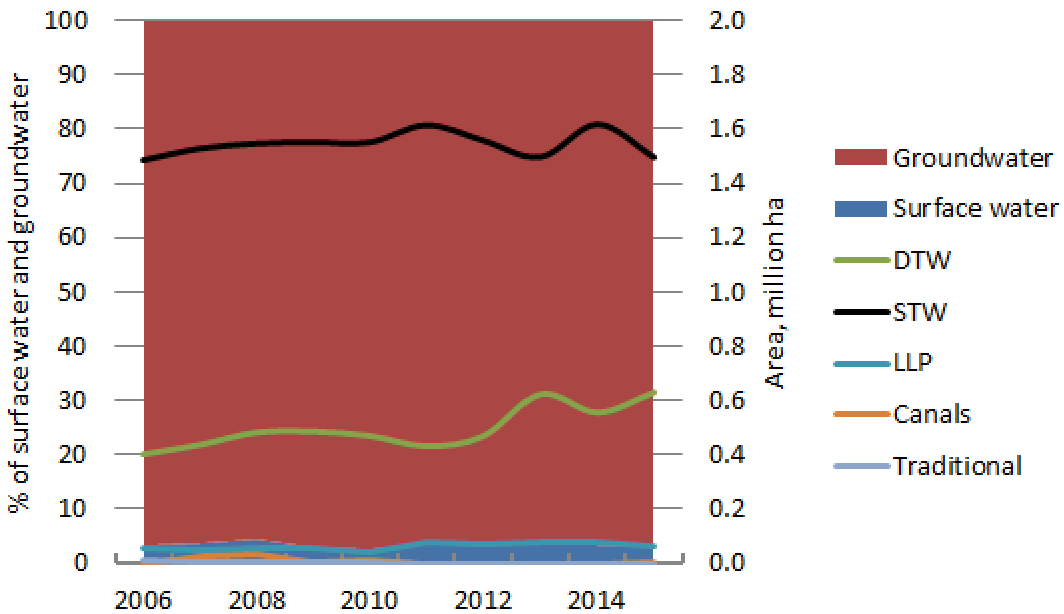

Figure 2.23 Area irrigated by different technologies and sources of water in the northwest region

The growth in irrigation appears to have slowed down in recent years (Figure 2.24). At the country level, the observed slight growth in area is due to the increase in surface water irrigation. There is no growth in groundwater irrigation. In the northwest region, the irrigated area appears to be steady with a slight downward trend in 2015. It seems, groundwater irrigation may have reached the maximum limit of groundwater use under the current bio-physical and infrastructure conditions. Boro rice covered more than 65% of the total irrigated area in 2012 in the northwest region. Other major irrigated crops are maize, wheat, potato, tomato, vegetables, pulses, and oilseeds. Due to higher irrigation requirements of Boro rice, 91% of the total water used for irrigation is for Boro rice (Mainuddin et al., 2015).

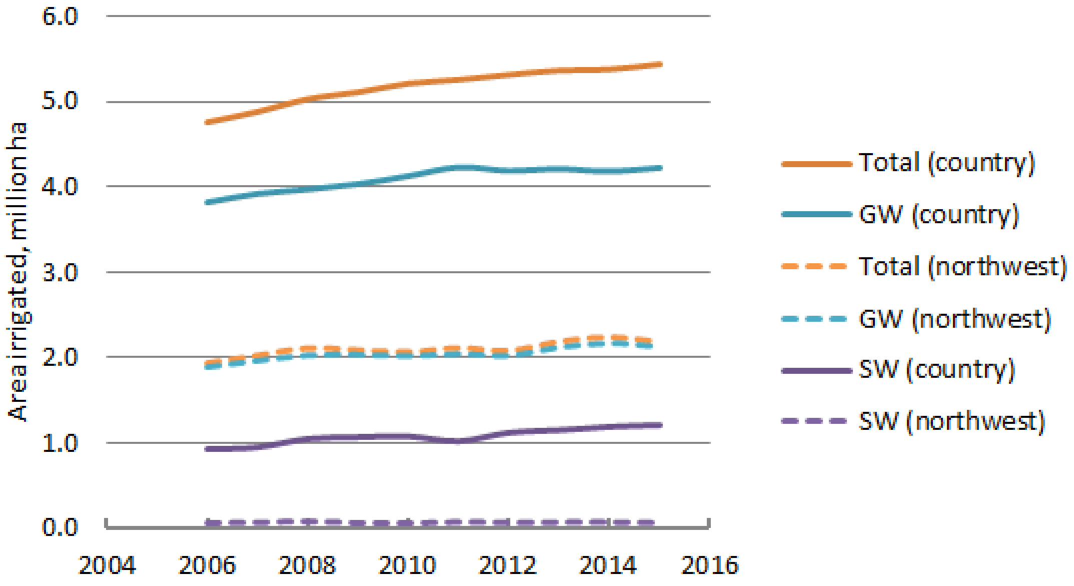

Figure 2.24 Trend in irrigated area in recent years for the country and the northwest region

2.6 Sustainability of groundwater irrigation

There are serious concerns about the sustainability of groundwater use, particularly in the Barind area (western part of the northwest region). Shamsudduha et al. (2009), Jahan et al. (2010), Shahid and Hazarika (2010), Rahman and Mahbub (2012), Aziz et al. (2015), Qureshi et al. (2015), Sumiya and Khatun (2016), Hasanuzzaman et al. (2017), and Salem et al. (2017) all showed that groundwater levels are falling in the Barind Tract and that current abstraction is unsustainable. Imon and Ahmed (2013) and Mojid et al. (2019) also showed that groundwater levels are falling generally in the Barind area, but in some small parts, they are steady or rising. Shamsudduha et al. (2009) and Kirby et al. (2014, 2015, 2016), MacDonald et al. (2016), concluded that the use of shallow aquifers for irrigation in some areas, particularly in the Barind tract is unsustainable.

The shallow groundwater table rises nearly to the surface across Bangladesh during the wet season, as the abundant rain and flooding rivers recharge the aquifers. Water tables fall during the dry season, when pumping for use and discharge to the rivers (which are at low levels in the dry season) deplete the aquifers. The deepest groundwater conditions are during April to May 15, i.e. in pre-monsoon, whereas the shallowest water tables are in November, i.e. in post-monsoon periods. Analysis done as part of the preceding ‘Bangladesh Integrated Water Resources Assessment Project’ shows that the time-series average regional groundwater depths (except for the eastern hills region) for pre- and post-monsoon conditions fluctuates within top 10 metres (CSIRO et al., 2014). The groundwater table in the northwest and north-central regions (with or without Dhaka district) is deeper than in the other regions. The spatial variation in pre-monsoon groundwater depth is shown in Figure 2.25 (CSIRO et al., 2014). This figure shows the areas of deeper water tables towards the end of dry season. The declining water tables could be due to a reduction in rainfall, increase in groundwater consumption, or changed recharge from or discharge into rivers.

Hodgson et al. (2014) also analysed the groundwater trends in 704 monitoring boreholes across Bangladesh (excluding the Eastern Hill Tracts). Some wells showed stable water levels, and others showed declining water levels. 56% of the wells showed declining water levels and 44% showed stable water levels. Some areas, such as the Barind Tract, are dominated by wells with declining groundwater levels (Figure 2.26). Other areas, such as the northern part of northwest region, are dominated by wells with stable groundwater levels.

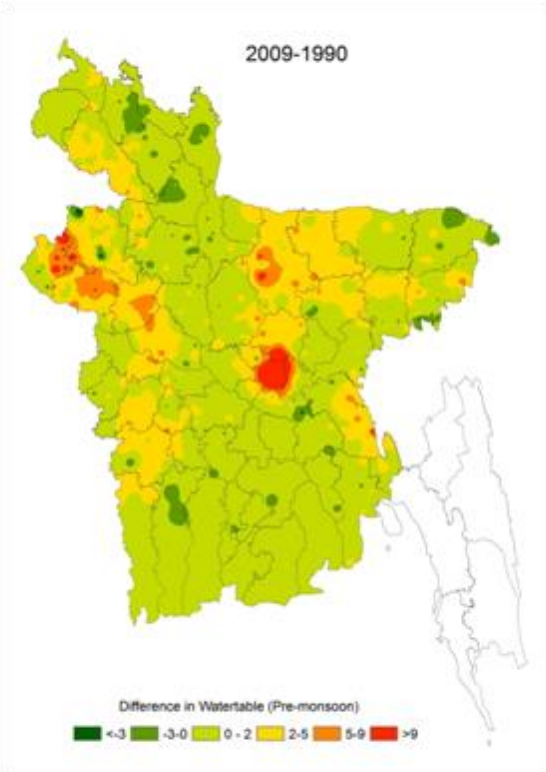

Figure 2.25 Spatial variation (difference in water table between 2009 and 1990) in pre-monsoon groundwater depth (m) across Bangladesh. The Eastern Hill Tracts in south east Bangladesh were excluded from the analysis (source: CSIRO et al., 2014)

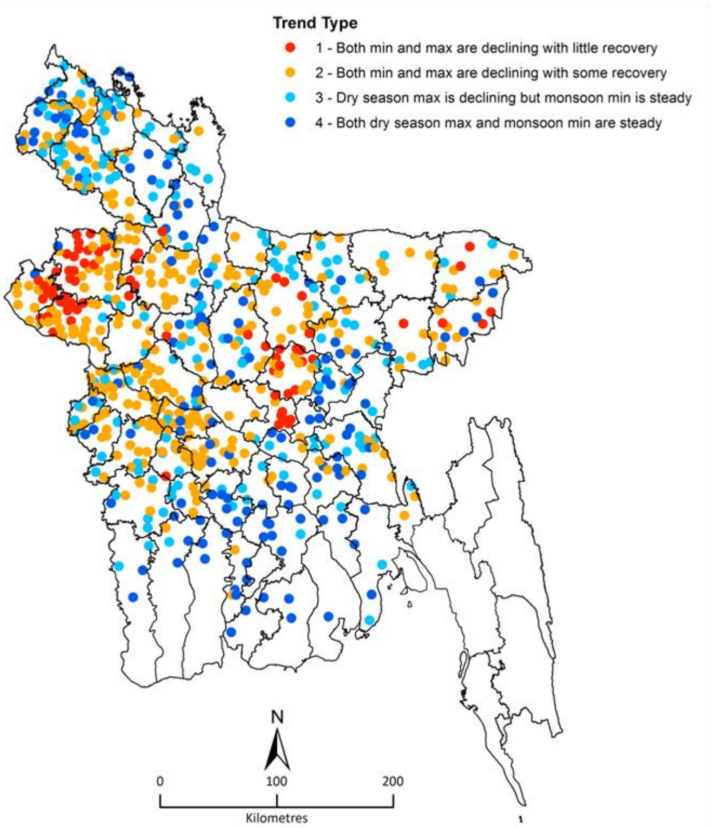

Figure 2.26 Distribution of wells of different trends in groundwater level. The Barind Tract, in the western region of Bangladesh, is dominated by a concentration of wells with declining trend of groundwater level (indicated by red points). (Source: Hodgson et al., 2014)

Hodgson et al. (2014) also noted that the water table in many wells falls below a critical threshold of about 8 m, particularly at the end of the dry season in March, April and May. Water tables below the threshold leaves regular suction-mode pumps (e.g., STW) and hand pumps inoperative (they cannot lift water higher than 8 m), leading to a lack of access to water for drinking and irrigation. There are many such STWs in the northwest region, particularly in Bogura district. So, to ensure irrigation supply to the crops, farmers install the STWs' pumps below the ground level (Figure 2.27). Falling groundwater level below the suction limit of the hand tubewells during the dry summer months of March to May, in some areas, is seriously affecting easy access to water for household purposes. People, particularly women, often need to walk up to 2 km to collect fresh water (Haq, 2013) for drinking and other household activities. Traditionally, women are responsible for collecting water for household uses. Their time, spent on this physically-demanding task, limits many other development opportunities.

Figure 2.27 STW installed below the ground level to pump water during the driest period

Nonetheless, the area irrigated by groundwater is rising in the northwest (Figure 2.28) region, but the area irrigated by shallow tubewells has declined (Figure 2.28) slightly in recent years. The reason for this could be declining of groundwater level below the suction limit of the STWs that has resulted in farmers now installing more DTWs instead of STWs. In our monitoring site in Bogura (discussed in the next Chapter), we have found that farmers have installed a DTW replacing STW due to problem with pumping groundwater during the driest months.

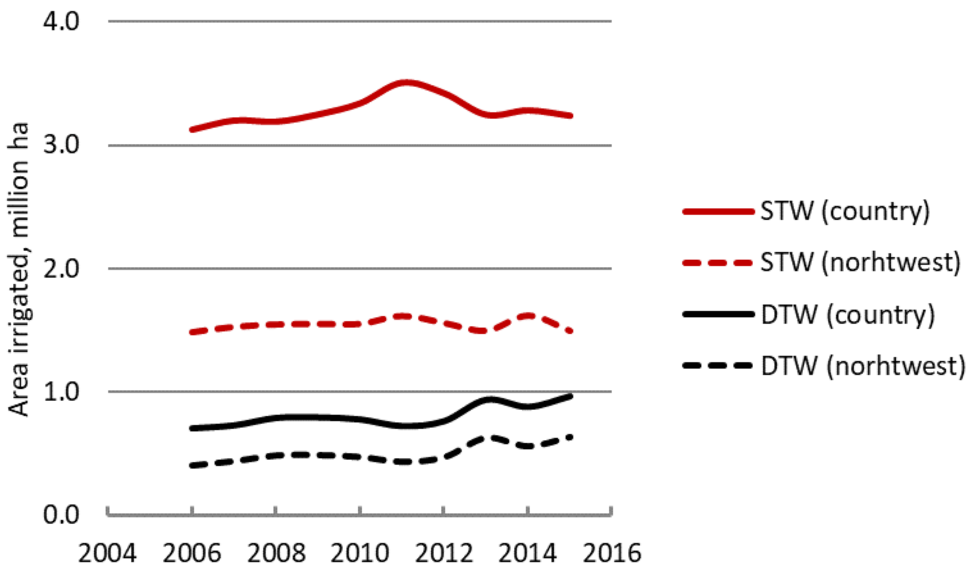

Figure 2.28 Area irrigated by shallow tubewells (STW) and deep tubewells (DTW) in the northwest region and in the country

2.7 Conclusion

The northwest region of Bangladesh is at the heart of the current agricultural development of the country and produces most of the country's main agricultural products (Table 2.1). However, due to the concerns of the sustainability of groundwater use, the Government of Bangladesh intends to reduce dependence on groundwater by increasing the use of surface water for irrigation, reducing pumping through crop diversification, and replacing B*oro* rice with other non-rice crops, particularly wheat (GoB, 2010).

Due to risk of floods and other natural disasters in the monsoon season, dry season is the most productive, risk free and diversified cropping season. Therefore, the yield of B*oro* rice is the highest among the three types of rice grown in Bangladesh as shown in Figure 2.15. Currently, the contribution of B*oro* rice to total rice production is 55-60%. Apart from B*oro* rice, other cereals such as wheat and maize, potatoes, tomatoes, pulses, oilseeds and a wide range of winter vegetables are grown only in the dry season. This makes Bangladesh not only self-sufficient in rice production but also self-sufficient in the production of potatoes, tomatoes and vegetables. The population in Bangladesh is projected to increase to 185 million in 2030 and 202 million in 2050 (UN Population Division, 2012) for medium variant population growth. Mainuddin and Kirby (2015) showed that this will require an additional 12.4 and 21.0 million tonnes of rice respectively by 2030 and 2050. Based on current trends, it is expected that most of the additional requirement will come from irrigated B*oro* rice. The demand of other crops will also increase with the increase in population. Thus, sustaining and further increasing dry season crop production is essential for this region.

3 Field monitoring and data collection

3.1 Site selection

The objective of this study is to understand the bio-physical, socio-economic and institutional aspects of groundwater irrigation in the northwest region of Bangladesh. This was done through intensive monitoring of groundwater irrigation by the farmers in the region. We used following criteria for the selection of specific sites (Figure 3.1) for data monitoring:

1. A good geographical spread within the northwest region (one site in each of Rajshahi, Pabna, Bogura, Rangpur, Dinajpur and Thakurgaon districts)
2. Each site will have a group of deep tubewells (DTWs) or shallow tubewells (STWs) covering a considerable area (10–20 ha), and a suitable area is bounded by the village homes.
3. Two DTW sites and four STW sites; DTW sites can be in Rajshahi and Thakurgaon Districts.
4. Both diesel and electric pumps (1 DTW site and 2 STW sites in each)
5. Irrigation is done for rice and other crops (e.g., potato, tomato, wheat and maize) as well. STW-site in Bogura for potato, STW-site in Dinajpur for wheat, DTW-site in Rajshahi for mix crops, including tomato.
6. Different water pricing mechanisms (share of crop as water charge, fixed land area-based water charge, smart card, diesel + fixed charge, etc.).
7. Convenient for communication (but not biased).

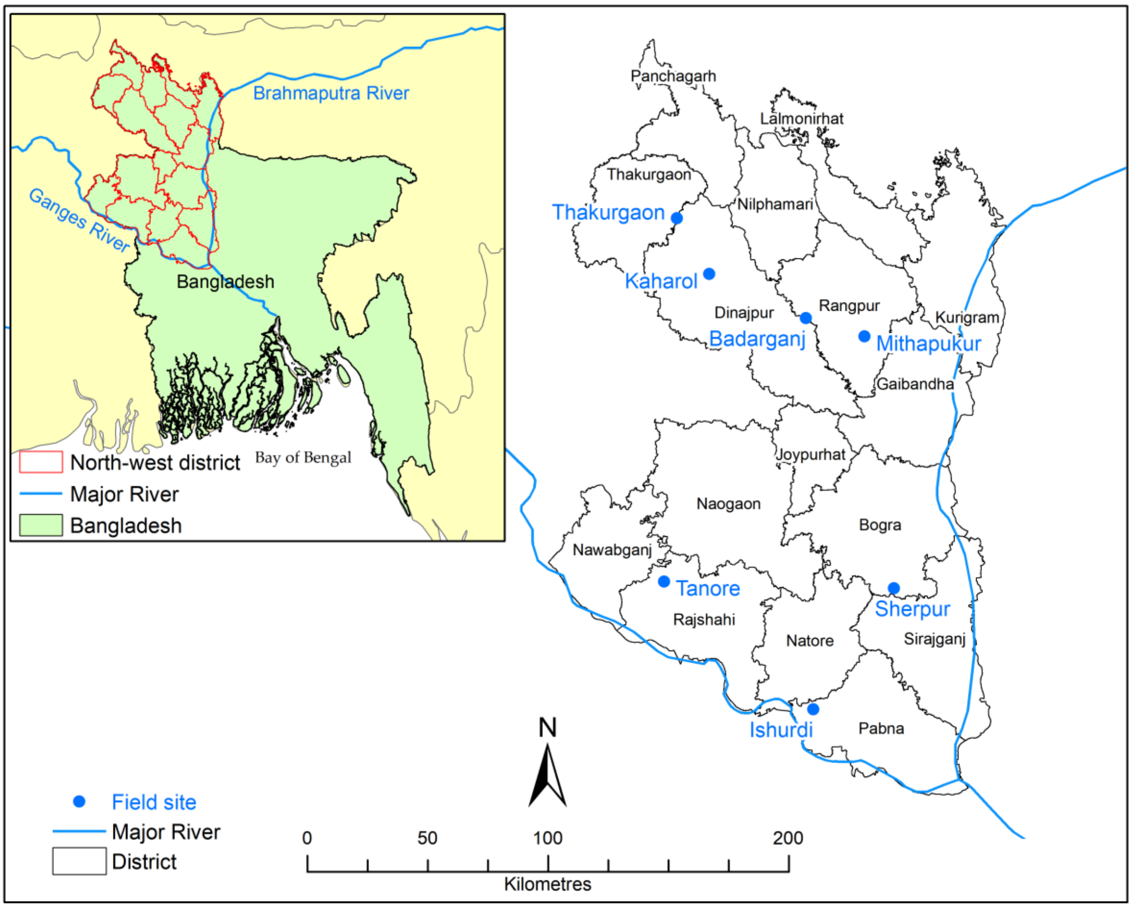

Figure 3.1 Location of the selected sites for monitoring and data collection

We extensively visited the fields in six districts of the region and selected sites for monitoring and data collection (Figure 3.1). Rajshahi and Thakurgaon were selected as DTW irrigation zone. STW irrigation is the main mode of irrigation in the other four sites though both DTW and STW are being used for irrigation in these areas. The common characteristics of all these sites are: i) Irrigation water selling is considered as a business, ii) Most of the farmers are marginal and tenants, and iii) Rice is the main dry season crop of the area. The main features of irrigation of each site are described in the following sections.

Thakurgaon: We visited about eight DTWs and finally selected three electricity operated DTWs in the villages of Dhandogaon and Jogonnathpur (Figure 3.2) based on the selection criteria. The main mode of irrigation in the area is DTW (force mode submersible pumps) though static water levels remain within the suction limit of STWs (centrifugal pumps) throughout the year. Most of the farmers under the DTW in Dhandogaon village are tribal that also represents the special demographic character of the area. There is a significant coverage of maize, wheat, mustard and potato in the area though rice is the main crop in the dry season. All the DTWs represent the crops cultivated and cropping patterns practiced in the area. There are large number of marginal and tenant farmers in the area.

Figure 3.2 DTW sites at Thakurgaon Sadar, Thakurgaon

Dinajpur: Both STWs and DTWs are used for irrigation as the static water levels remain within the suction limit of centrifugal pumps throughout the year. But coverage of STWs is higher in the area. We visited about 15 STWs at Birganj and Kaharol Upazila to find out the diesel operated and electricity operated STWs and finally selected 5 STWs at Gurnurpur village of Kaharol Upazila (Figure 3.3). Two of the selected STWs are operated by electrical motor and the other 3 are diesel operated. There is significant coverage of maize, mustard, potato and wheat in the area though rice is the main crops in the dry season. Many tribal people live in this area. There are large number of marginal and tenant farmers in this area as well.

Figure 3.3 STW sites at Kaharol Upazila, Dinajpur

Rangpur: We visited about 20 STWs at Pirganj and Mithapukur Upazila to find out the diesel operated and electricity operated STWs and finally selected 6 STWs at Ramnatherpara village of Mithapukur Upazila, of which 1 STW is electricity driven and 5 STWs are diesel operated (Figure 3.4). Maize, mustard, potato, wheat, vegetables, spices and pulses are grown in the area though rice is the main crops in the dry season.

Figure 3.4 STW sites at Mithapukur Upazila, Rangpur

Bogura: We visited 12 STWs at Sherpur Upazila to find out the diesel operated STWs and finally selected 5 diesel operated STWs in the Arongshail village of Mirzapore union, Sherpur Upazila based on the selection criteria (Figure 3.5). Rice is the main crop of the area.

Figure 3.5 STW sites at Sherpur Upazila, Bogura

Pabna: We visited 25 STWs at Pabna Sadar, Chatmohar and Ishurdi Upazila to find out the diesel and electricity operated STWs and finally selected 5 STWs at Baliadangi village of Muladoli union, Ishurdi Upazila, of which 3 STWs are electricity driven and 2 STWs are diesel operated (Figure 3.6). Irrigated rice is the main dry season crop of the area. The static water level crosses the suction limit of STWs during the dry season. Therefore, the pump and power unit of the STWs are installed 1-2 m below ground surface by digging a pit.

Figure 3.6 STW site at Ishurdi Upazila, Pabna

Rajshahi: DTW irrigation is practiced in Rajshahi since static water level is far below the suction limit of STW coverage. We visited 10 DTWs and Mini-DTWs at Tanore Upazila to find out suitable multi-crops oriented DTWs and finally selected 3 DTWs in the villages of Chinasho and Pachondor (Figure 3.7). Most of the DTWs here were installed by the Barind Multipurpose Development Authority (BMDA). Some low capacity private DTWs (Mini-DTW) are also used for irrigation. All DTWs are electricity operated. Irrigated rice is the main dry season crop of the area. But maize, wheat, potato, spices, oil seeds and pulses are also cultivated. There are large number of marginal and tenant farmers in the area.

Figure 3.7 DTW site at Tanore Upazila, Rajshahi

In total, we selected 22 STWs and 6 DTWs in six sites for monitoring, which started in 2015-16 dry season. For monitoring, we considered all the plots under the command area of the STWs. Command area of the DTWs are quite large. Irrigation water is supplied to the field through underground pipes/buried pipes with outlets at certain intervals through which farmers take water in the field. We have selected command area of 3 outlets in each DTW for monitoring and data collection. The details of each STW and DTW and their command area are given in Table 3.1. In 2016-17, we discontinued monitoring of Tanore in Rajshahi and Kaharol of Dinajpur. But we added one site at Badarganj Upazila of Rangpur district where solar energy is used for irrigation pump operation. In addition, we also reduced the number of STWs in the other sites for monitoring in 2016-17 dry season.

3.2 Data monitoring at farmers' fields

We monitored all the plots within the command areas of STWs. In DTW irrigation systems, plots belonging to specific outlets were considered for monitoring. In each DTW, three outlets: at head, middle and tail end were considered for the study. We have recorded all the activities done by the farmer in his/her plot using predesigned forms. The data include name of the farmer, ownership, area (in decimal), cropping patterns, years of cultivation, land type, soil type, crop grown, date of seeding, date of transplanting, date of flowering, etc. Various inputs used (amount of seed, fertilizers, herbicides, pesticides, irrigation, labourer, etc.), costs and revenue, and output achieved (crop and biomass) in the cultivation were also recorded. The discharges of the irrigation units were measured during the initial, middle and later parts of crop growing season. Amount of water applied in each irrigation event was calculated using the discharge rate and irrigation time of the specific period. The cost for irrigation was calculated. Daily rainfall data were collected from adjacent meteorological stations.

3.3 Irrigation water pricing

There are variations in irrigation water pricing among different areas of Bangladesh. There is also variation in mode of charge within a specific area. But for a single irrigation unit, irrigation charge is similar for all the water users.

Area-based water pricing: This is the widely used irrigation water pricing system in Bangladesh. In this system, a certain amount of irrigation cost is fixed a priori for a unit area (1 bigha comprising 33 decimals or approximately 1336 m^2) for the whole season (e.g., for Boro rice) or for each irrigation event (e.g., for Aus rice, Aman rice and non-rice crops). For Boro rice, it is independent of irrigation frequency and fuel/energy requirement. Most of the STWs use this system of water pricing for rice irrigation in Boro season.

Time-based water pricing: In this system, a fixed charge is taken for unit time of operation of the irrigation pump. BMDA-managed DTWs use this irrigation system for both rice and non-rice crops irrespective of the cropping seasons. Most of their DTWs are pre-paid card metering system. Some STWs also use this irrigation charge system for non-rice crops and supplementary irrigation of Aman and Aus rice. The cost of energy or fuel is included within the charge.

Crop sharing: Another system of pricing irrigation water for Boro rice is sharing of the harvested crop. About 19-25% of the crop is charged for irrigation cost. Generally, the water seller harvests the sharing portion (area) of crop with his own labour cost.

Mixed charge: This system combines area-based charge with actual fuel consumption. A fixed charge per unit irrigated area is taken in addition to the fuel used for irrigation. Water users bring their fuel and irrigate as long as they wish. The money fixed per unit area is the charge for the irrigation unit and locally termed as "handle charge". The irrigation water pricing used in the selected locations are given in Table 3.2.

Table 3.1 Necessary information of the selected shallow tubewells (STWs) and deep tubewells (DTWs)

Site	Types of tubewell	Power sources	Discharge capacity (lit/s)	Command area (ha)	Total no. of plots	Number of farmers	Major crops
Thakurgaon	DTW-1	Electric	58.0	24.3	100	60	Rice, wheat, maize, potato
	DTW-2	Electric	38.5	16.5	85	46	Rice, wheat, maize
	DTW-3	Electric	36.8	13.8	78	43	Rice, wheat, maize, potato
Kaharol	STW-1	Electric	13.2	2.02	8	2	Rice
	STW-2	Diesel	8.91	0.50	5	3	Rice
	STW-3	Electric	14.0	1.80	11	6	Rice
	STW-4	Diesel	8.78	0.95	9	5	Maize
	STW-5	Diesel	8.85	0.81	1	1	Maize
Mithapukur	STW-1	Electric	14.82	2.77	65	23	Rice, jute, maize, wheat, potato
	STW-2	Diesel	8.77	1.17	13	10	Rice
	STW-3	Diesel	9.43	1.17	10	8	Rice
	STW-4	Diesel	9.87	2.41	17	10	Rice, maize
	STW-5	Diesel	8.45	1.42	16	11	Maize, wheat, brinjal, tomato, cauliflower
	STW-6	Diesel	8.89	3.00	20	15	Maize, potato, brinjal, onion
Sherpur	STW-1	Diesel	7.13	1.28	10	4	Rice
	STW-2	Diesel	7.24	1.84	13	3	Rice
	STW-3	Diesel	7.32	3.04	29	5	Rice
	STW-4	Diesel	7.12	0.62	8	5	Potato, mustard
	STW-5	Diesel	7.04	0.30	4	4	Wheat
	STW-6	Diesel	7.20	0.31	3	1	Maize
Ishurdi	STW-1	Electric	12.86	1.87	6	6	Rice
	STW-2	Diesel	14.0	2.94	19	12	Rice
	STW-3	Electric	15.02	4.60	25	22	Rice
	STW-4	Diesel	8.12	1.63	11	11	Wheat, lentil
	STW-5	Diesel	8.56	2.13	17	15	Wheat, lentil, okra
Tanore	DTW-1	Electric	17.0	16.0	84	56	Rice, wheat, potato, lentil
	DTW-2	Electric	20.0	20.0	98	72	Rice, wheat, potato
	DTW-3	Electric	21.5	20.0	108	84	Potato, rice
Badarganj	STW	Solar	9.04	2.47	20	20	Rice

The irrigation water pricing used in the selected locations are given in Table 3.2.

Table 3.2 Current irrigation water pricing systems in the selected locations

Area	Crop	Mode of irrigation charge	Charge	Measurements
Mithapukur, Rangpur	Rice	Area basis (STW with electric motor) Mixed (STW with diesel engine)	Tk. 1800-2500/bigha Tk.24-26/decimal + Fuel	1 bigha =50 decimal
	Non-rice	Area basis (STW)	Tk. 600/irrigation/bigha	1 bigha =50 decimal
Badarganj, Rangpur	Rice	Area basis	70 Taka/decimal or 7,000 Taka/acre for rice	
	Non-rice	Area basis	6 Taka/decimal/irrigation or 600 Taka/acre/irrigation	1 acre = 100 decimal
Kaharol, Dinajpur	Rice	Area bases (STW with diesel engine) Area bases (STW with electric motor) Mixed	Tk. 3500/bigha Tk. 2500-3000/bigha Tk.26-28/decimal + Fuel	1 bigha =50 decimal
	Non-rice			
Thakurgaon Sadar, Thakurgaon	Rice	DTW (BMDA) STW (with diesel engine) STW (with electric motor)	Tk. 110-140/ hr Tk. 20/decimal+Fuel Tk. 1200-1500/bigha	1 bigha =50 decimal
	Non-rice	DTW (BMDA) STW (with diesel engine)	Tk. 110-140/hr Tk. `40/hr+Fuel	
Tanore, Rajshahi	Rice	Area based (private DTWs) DTW (BMDA)	Tk. 2000-2200 /bigha Tk. 120-140/ hr	
	Non-rice	DTW (BMDA and private)	Tk. 100-140/ hr	
Ishurdi, Pabna	Rice	Crop share (25% of unharvested crop)	Tk. 3500-4000/bigha	1 bigha = 33 decimal
	Non-rice			
Sherpur, Bogura	Rice	DTW STW (with diesel engine)	Tk. 2000 /bigha Tk. 3000-3200 /bigha	1 bigha = 33 decimal

3.4 Estimation of irrigation water requirements of crops

We collected daily historical climate data such as rainfall, maximum and minimum temperature, maximum and minimum humidity, daily wind speed and total sunshine hour from the Bangladesh Meteorological Department (BMD) for the six stations located near our monitoring sites. These stations are Rajshahi (representing Tanore), Ishurdi, Bogura (for Sherpur), Rangpur (for Mithapukur and Badarganj), Dinajpur (for Kaharol) and Sayedpur (representing Thakurgaon). Using these data, we estimated reference crop evapotranspiration (ET_o) based on FAO-56 Modified Penman-Monteith Method using a software called REF-ET (Allen, 2011). FAO-56 Modified Penman-Monteith Method, which uses maximum and minimum temperature, maximum and minimum humidity, daily wind speed, and sunshine hour, is the recommended method by FAO (Allen et al., 1998) for estimating ET_o.

To estimate the daily potential evapotranspiration and irrigation requirements, we have used a Soil Water Balance (SWB) model which is similar to the FAO (Food and Agriculture Organization) CROPWAT 8.0 model (http://www.fao.org/nr/water/infores_databases_cropwat.html). The model gives identical results under the same conditions. The main advantage of this model over the CROPWAT model is that it loops automatically through several climate regions, soils, crops and irrigation rules to save the tedium of manually setting up and running many input files. The basis of the crop coefficient approach is described in Allen et al. (1998) and Doorenbos and Kassam (1979). More detail about the SWB model can be found elsewhere (Mainuddin et al., 2014; Mainuddin et al., 2015). The model has been used to estimate the crop evapotranspiration and irrigation requirements of all the major crops grown in Bangladesh for all districts and to study the impact of climate change (Mainuddin et al., 2014; Mainuddin et al., 2015).

Several soil properties (field capacity, wilting point, water holding capacity, percolation rate, etc.) are important parameters for the SWB model. Based on field observations, we have found that silt loam soil is most dominant soil in the monitoring sites. Silt loam soils are found in Ishurdi, Sherpur, Kaharol and in parts of Tanore. Mithapukur has sandy loam soil and Thakurgaon has clay loam soil. Parts of Tanore have clay loam soil. Mainuddin et al. (2014) collected soil data (percentage of sand, silt and clay) for the 3 major soil series (covering maximum area) in each district from Soil Resources Development Institute (SRDI). Using these data, they have determined the soil textural classes and other model parameters such as saturation point, field capacity, and wilting point using US Soil Triangle Hydraulic Properties Calculator (http://www.pedosphere.ca/resources/texture/triangle_us.cfm). These data were used to parameterize the model. Crop coefficients, and yield response factors were taken from the FAO Irrigation and Drainage Paper 56 (Allen et al., 1998), which was also used by Mainuddin et al. (2015). The duration of the cropping period for different crops was used from the field observation. The lengths of the growth stages were taken primarily from the FAO Irrigation and Drainage Paper 56 but were adjusted based on the actual duration of the crops in the field.

The rate of percolation is an essential component of water balance in the rice fields. The irrigation requirement varies significantly based on the rate of percolation used in estimation. For this study, we set up small field lysimeters (one with open bottom and the other with closed bottom) to measure the actual rate of percolation from the field during two seasons. The detail is given in the companion report (Maniruzzaman et al., 2019). The percolation rates used in the water balance model are given in Table 3.3.

Water is supplied from the pump to the fields by various distribution systems such as buried pipes, lined and earthen channels, and polyethylene pipe. So, there are conveyance losses in the distribution systems. The amount of loss depends on the type of distribution systems used, their condition and the distance from the pump to the field; longer the distance of the field, higher is the loss. We did not measure the conveyance losses in the field. Instead, we used the information available in the literature. The type of distribution network in the selected sites and the conveyance losses used are also given in Table 3.3.

Table 3.3 Percolation rates and conveyance losses in the selected locations

Location	Percolation rate, mm/day	Distribution system	Conveyance losses
Ishurdi	2.80	There is a mixture of lined channel, polyethylene pipe and unlined channel. Lined channel in Ishurdi is made of brick wall with cement neat finishing	5% (Sayed et al., 2014)
Mithapukur	3.80	Earthen channel	24% (Sayed et al., 2014)
Sherpur	3.00		10%
Thakurgaon	2.40		7.5% (Rahman et al., (2011)
Kaharol	3.80	Here most of the plots were adjacent to the pump (as number of plots was few). So, loss was much less than the loss for Mithapukur	10%
Tanore	2.80		5.45% (Rahman et al., 2011)
Badarganj	3.80		24% (Sayed et al., 2014)

4 Observations, results and discussion

In this chapter, we present the results and observations based on the analysis of the data collected from the farmers' fields. We monitored 336 plots across six locations in 2015-16 and 195 plots across 5 locations in 2016-17. The size of plots ranged from 0.02 to 0.87 ha in 2015-16 and 0.02 to 0.47 ha in 2016-17. The mean and average plot sizes were 0.15 ha and 0.13 ha, respectively for the crop years. We compare the variation in input usage patterns and performance of crops at different levels such as plot to plot within a command area of the STW or outlet of a DTW, different STWs, STWs operated by diesel engine and electric motors, STW and DTW, crop to crop, and from location to location. We discuss the results of one site in detail and draws comparison with the other sites.

4.1 Farmers' socio-economic profile

At the beginning of the irrigation season in 2015-16, we recorded the socio-economic information of each farmer of the monitored plots. Table 4.1 presents classification of farm households in the selected locations for 2015-16 (Tanore, Ishurdi, Sherpur, Mithapukur, Kaharol, and Thakurgaon). We did not collect socio-economic information for Badarganj as the site was added for monitoring in 2016-17. Farm households are typified based on operating area of the farm and ownership of the operating land. On average, 91% of total farm households are small farm type. It is also the case that 100% of the total selected farmers are small and marginal in Kaharol (Dinajpur), Ishurdi (Pabna), Mithapukur (Rangpur) and Thakurgaon. This is higher than national average figure of small farm types (84% of total) as per agriculture census-2008 (BBS, 2015). Besides, nearly half of the farm households are owner tenant farmers followed by 35% are owner farmers. On average, about 66% of the total rural farm households in Bangladesh were owner-operated farm, followed by 24% of total were owner tenant-operated farm as per agriculture census 2008 (BBS, 2015). It can be noted that about 96% of total farm households are owner-operated farm despite 100% of them are small farm types in Kaharol (Dinajpur). This is followed by 55% of total farms are owner operated in Tanore (Rajshahi), whereas about 96% are small and marginal farmers. The striking feature of the results is that rented land for agriculture farming is not a popular livelihood option in Kaharol (Dinajpur) and Tanore (Rajshahi). This may be because of farming is less or non-profitable in the rented lands.

Table 4.1 Classification of farm households based on farm size and tenancy status at different locations

Farm types	Sherpur (n=12)	Kaharol (n=24)	Ishurdi (n=50)	Tanore (n=22)	Mithapukur (n=110)	Thakurgoan (n=18)	All (n= 36)
Farm size	% of total sample of the respective location						
-Marginal farm (≤0.02 ha)	8	0	6	23	7	11	8
-Small farm (0.02-1.0 ha)	83	100	94	73	93	89	91
-Medium farm (1.01-3.03)	0	0	0	0	0	0	0
-Large farm (≥3.04 ha)	7	0	0	4	0	0	1
Tenancy							
-Owner farm	17	96	28	55	24	33	35
-Owner tenant farm	58	0	58	36	64	56	53
-Tenant farm	25	4	14	9	12	11	12

Table 4.2 presents agricultural statistics of farm households. The mean family size (4 per household) of the selected farm household is smaller than the national average family size (4.7 per households) as per population and household census 2011 (BBS, 2015). Mean age of household head of the farm households is 47. This indicates that most of the heads of the selected farmers are under active age category as reported

by Kabir (2016). Farmers are highly experienced in farming, but their education is at primary level. The average farm size in the study locations is 0.70 ha, with a range of between 0.50 ha and 1.05 ha. Also, on average, 70% of total operated area of the farm household is own land. On the other hand, number of farm machineries per household (power tractor, pump and threshers) indicates that most of the farmers relied on service providers for tillage, irrigation and threshing of crops. The ownership of livestock, in particular cattle and poultry, per household indicates that livestock rearing is an important component of farming systems in the study villages.

Table 4.2 Agricultural statistics of farm households at different locations

Items	Sherpur	Kaharol	Ishurdi	Tanore	Mithapukur	Thakurgaon	All
Family size	3	4	3	4	5	3	4
Age of household head (years)	45	49	47	37	50	39	47
Farming experience of head (years)	26	34	34	21	27	26	28
Education of household head (years)	5	6	4	9	6	5	6
Homestead area (ha)	0.04	0.05	0.05	0.07	0.07	0.04	0.06
Orchard area (ha)	0.01	0.06	0.07	0.11	0.02	0.00	0.04
Own arable land (ha)							
– mean	0.78	0.86	0.35	0.67	0.44	0.34	0.49
– standard deviation	1.13	0.48	0.39	0.79	0.48	0.32	0.56
Farm size (ha)							
– mean	1.05	0.88	0.67	0.73	0.67	0.50	0.70
– standard deviation	1.07	0.45	0.37	0.86	0.47	0.24	0.54
Number of power tractor	0.33	0.29	0.00	0.41	0.06	0.39	0.14
Number of power pump	0.67	0.63	0.06	0.50	0.31	0.72	0.36
Number of power thresher	0.08	0.00	0.00	0.09	0.05	0.00	0.03
Number of cattle	3.2	3.5	1.7	2.0	2.5	2.7	2.5
Number of goats	0.6	2.7	1.1	1.4	1.2	2.2	1.4
Number of poultries	20	7	7	15	13	4	11

Table 4.3 presents annual income of farm households in the study locations. Household incomes of crop, livestock and aquaculture were estimated after subtracting the average paid out cost of the households for those farming systems' components from the gross benefit of the respective component. The contribution of the crops in the total household income is higher followed by livestock. Figure 4.1 shows that the representation of agriculture, including crops, livestock, and fisheries in the total household income is 78%. On average, contribution of the crops sector is 51% of the total household income followed by livestock (19% of total income). These results indicate that farm households mostly rely on agriculture for their livelihoods.

Table 4.3 Annual total household income of farm households at different locations

	Sherpur	Kaharol	Ishurdi	Tanore	Mithapukur	Thakurgaon	All
Crops	80,870	75,432	68,195	73,611	64,447	45,713	68,045
Livestock	23,875	21,208	45,320	26,295	22,743	21,833	26,879
Aquaculture	8,083	8,875	9,000	12,909	11,009	5,833	9,285
Off/non-farm work	16,667	8,667	14,400	14,000	7,655	12,389	12,296
Employed job	6,667	8,333	18,600	4,861	10,136	3,217	8,636
Business	10,333	4,667	12,600	15,818	7,227	3,333	8,996
Total	146,495	127,182	168,115	147,495	123,217	92,319	134,137

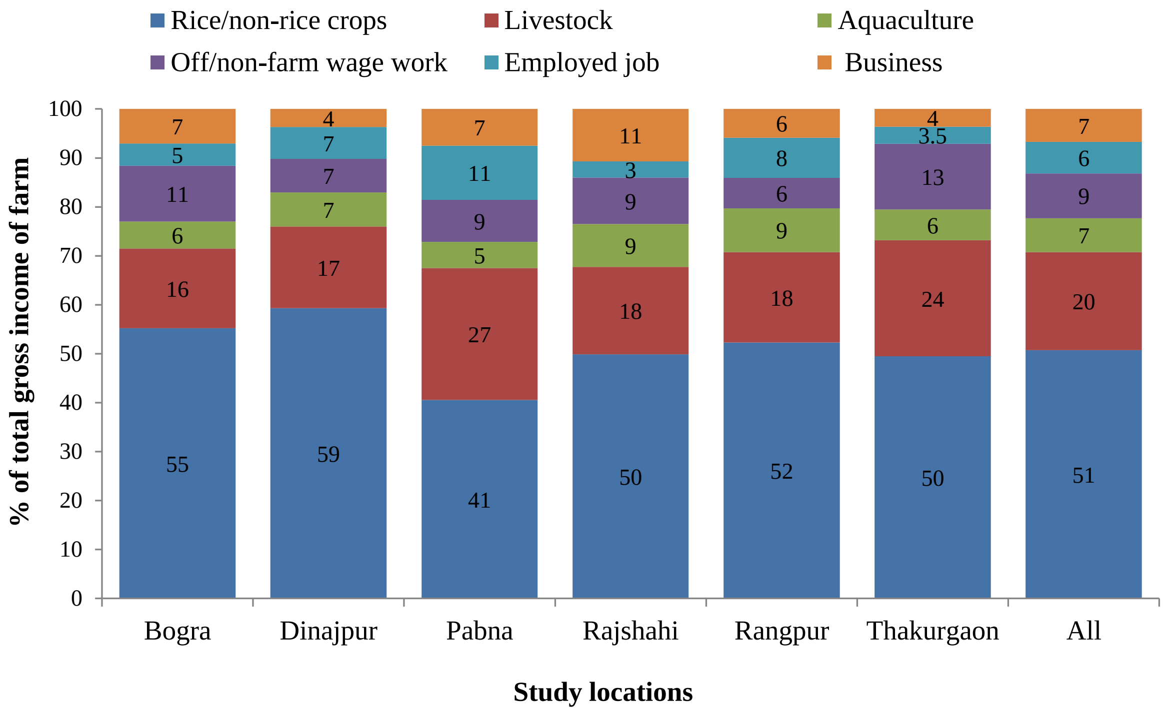

Figure 4.1 Representation of different income sources in the total household income of farm households at different locations (the district name represents the location within that district only)

4.2 Cultivated rice varieties

Rice is the predominant crop grown in all sites under investigation. Of the total 336 plots monitored in 2015-16, rice was cultivated in 235 plots (35.05 ha). Wheat, maize, potato, lentil, mustard, cauliflower and okra were grown in the remaining 101 plots (13.05 ha) across the six sites. So, 27% of the total area was under non-rice crops in 2015-16. In 2016-17, we concentrated our monitoring activities in four of the previous sites, excluding Tanore of Rajshahi and Kaharol of Dinajpur. We have also added one additional site at Badarganj in Rangpur where irrigation pumps are run using solar energy. We monitored 195 plots in these five locations of which only 10 plots were with crops other than rice.

Among the study areas, maximum number of rice plots (69 plots in 2015-16, 62 plots in 2016-17) were in Mithapukur and only 18 plots were in Thakurgaon (Table 4.4, see also Table 4.6 later). Average plots size was higher in Ishurdi, Kahrol, Tanore and Thakurgaon (0.18 to 0.21 ha in 2015-16). Mithapukur has the lowest average plot size (0.10 ha); plot size in Sherpur (0.12) was also similar to Mithapukur. In 2015-16, 83% of the total plots were irrigated by STW, of which 49% (of the total) were irrigated by diesel-operated STW; the rest were operated by electric motor driven STW. Only 17% of the plots were irrigated using DTW operated by electric motor. In 2016-17, 40% of the plots were irrigated by electirc motor driven STW, 39% by diesel engine driven STW, 10% by DTW and the rest 11% by solar power-operated pumps.

In 2015-16, six different rice varieties were grown in the sites (Table 4.4). They are Hybrid rice, BRRI dhan28*,* BRRI dhan29, *Minikit*, *Kajallata* and *Jirashail*. The variety name Minikit came from India. There was an intensive program of the farmers as a package/kit, which included some seeds of a rice variety, fertilizer and some management practices for improving their production level. From this source, the variety introduced in Bangladesh got familiar and popularly known as Minikit. The exact name of this variety is unknown. On the other hand, '*shail*' are usually Aman or Kharif-2 varieties grown in the monsoon period. The name of this variety is '*Jira*'; however, the farmers call it Jirashail and the name is popularly used.

In 2016-17, the varieties, Jirashail and Kajallata were not cultivated in the monitored plots. Jirashail was cultivated only in Tanore in 2015-16. Kajallata was cultivated in 2015-16 at Sherpur, Bogura.

It is evident from Table 4.4 that a maximum of two rice varieties (except Mithapukur where there were 4 plots with a third variety and Badarganj where there are 2 plots with a third variety) are grown in each location. BRRI-developed varieties (BRRI dhan28 and BRRI dhan29) are grown in half (50.2%) of the total plots in 2015-16. Minikit (13.2%), Kajallata (8.9%), and Jirashail (9.4%) are high yielding varieties but not released by BRRI. Hybrid varieties are commercially available varieties, which are getting popular because of their high yield with relatively lower growth duration. They are cultivated in 18.3% of the total plots mainly in Mithapukur of Rangpur in 2015-16.

Table 4.4 Number of plots with different varieties of rice at different locations

Variety	Ishurdi		Sherpur		Mithapukur		Thakurgaon		Tanore	Kaharol	Badarganj
	2015-16	2016-17	2015-16	2016-17	2015-16	2016-17	2015-16	2016-17	2015-16	2015-16	2016-17
BRRI dhan28				1	28	32	5			24	15
BRRI dhan29	44	18			4	4	13	18			3
Hybrid	6				37	26					2
Jirashail									22		
Kajallata			21								
Minikit		21	31	45							

In 2016-17, 86 plots (46%) were cultivated with BRRI dhan28 and BRRI dhan29. They were mainly in Ishurdi, Mithapukur, Thakurgaon and Badarganj. No BRRI rice varieties were grown in Sherpur; all the plots were with Minikit in 2016-17. It is clear that certain variety is dominant in certain location. BRRI dhan28 and Hybrid varieties are dominant in Mithapukur, BRRI dhan29 and Minikit (in 2016-17) are in Ishurdi, Minikit and Kajallata are in Sherpur, Jirashail is in Tanore, and BRRI dhan28 is in Kaharol and Badarganj. Farmers consider many factors such as local climatic conditions, total duration, market condition, availability of seed, crops grown before or after rice, prospective net economic benefit, own consumption or sell, etc. while choosing a variety to cultivate.

4.3 Rice transplanting time

Transplanting of rice started in late December and completed by the end of February in 2015-16. But, most of the plots (80.5%) were transplanted during the period of 16 January to 15 February (Figure 4.2). In 2016-17, 93% of the plots were transplanted during this period. Time of transplanting is also specific to location. In 2015-16, almost all plots of Ishurdi, Sherpur, Tanore and Thakurgaon were transplanted during 2nd half of January to the 1st half of February. Transplanting in Kaharol is done mostly in the 2nd half of February. Mithapukur has the longest transplanting period in 2015-16, starting in late December until almost the end of February. Farmers follow Boro-Fallow-T. Aman and Potato-Boro-T. Aman cropping patterns in this area.

Of the 39 plots in Ishurdi, rice was transplanted in 34 during 27 January to 5 February in 2016-17. All the plots in Sherpur were transplanted during 25 January to 3 February. In Thakurgaon, except 4 plots, all were transplanted on 14 February. In Badarganj, all the plots were transplanted during 1 to 9 February. Mithapukur had the longest transplanting period in this year also. The transplanting started around 15 January and completed in 15 February though most of the plots were transplanted during 1 to 15 February. Both BRRI dhan28 and BRRI dhan29 and the Hybrid rice are grown in this site. The duration of BRRI dhan29 is 20 days longer than the BRRI dhan28. So, BRRI dhan29 needs to be transplanted earlier so that harvesting can be done in time.

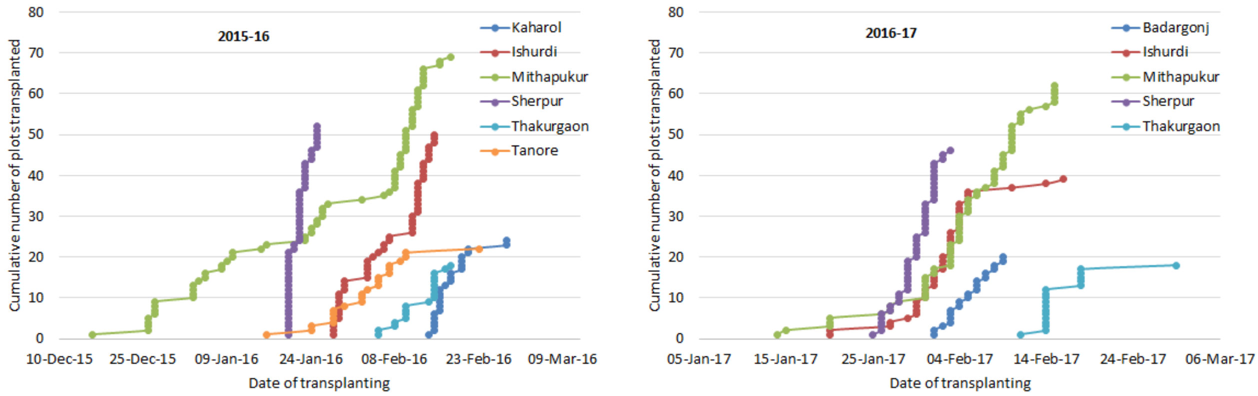

Figure 4.2 Transplanting period of rice at different locations (Note: x-axes are not same in the two charts of 2 years)

4.4 Input cost of production of rice

We recorded various inputs and labour used in every plot from nursery preparation to temporary storage of the production after harvesting. The paid-out cost of production was aggregated into following categories:

- Seed and nursery preparation
- Tillage and land preparation
- Seedling uprooting and transplanting
- Fertilizer application
- Herbicide application and weeding
- Pesticide application
- Irrigation application
- Harvesting and carrying
- Threshing, winnowing, and drying

Figure 4.3 shows the variation in total paid-out costs of different input categories per hectare for the plots monitored for the crop years 2015-16 and 2016-17. The average seedling cost per hectare was 3,403 Taka in 2015-16 and 4,036 Taka in 2016-17. The costs ranged between 1,420 Taka/ha and 6,693 Taka/ha in 2015-16 and between 2,410 Taka/ha and 9,139 Taka/ha in 2016-17. In 2014-15, substantial variation was observed in per hectare cost of fertilizer; it ranged from 4,141 to 20,400 Taka. Average irrigation cost per hectare was 16,459 Taka in 2015-16, which represents the highest proportion (23%) of total paid-out cost (TPC). This is followed by harvesting (crop cutting, transporting and threshing) cost (22% of TPC), and fertilizer cost (17% of TPC) of the total paid-out cost.

Average paid-out cost for different inputs used for rice cultivation varies slightly from STW to STW within a location. In 2015-16 season, 3 STWs (STW-1, STW-2, and STW-3) out of 5 STWs in Ishurdi (Table 4.5) were used only for rice cultivation and the rest 2 (STW-4 and STW-5) were used for wheat and lentil cultivation. Three of the STWs (1, 4 and 5) were operated by diesel engine and the rests (1 and 3) were operated by electric motors. In 2016-17, we monitored STW-1, STW-3 and STW-5 only. The detail information for each STW is given in Table 4.5.

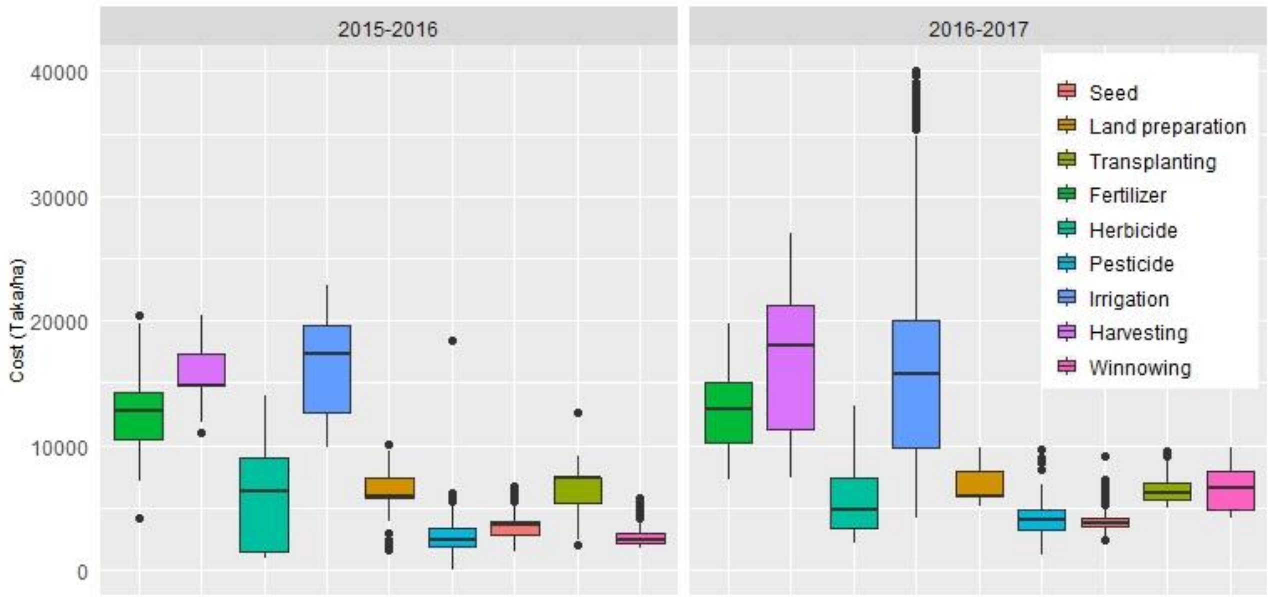

Figure 4.3 Variation of total paid-out costs for different inputs for growing rice

Table 4.5 Detail data of the STWs for Ishurdi

STW No.	Energy source	Discharge capacity (litre/sec)	Number of plots under each crop			Total cultivated area, ha
			Rice	Wheat	Lentil	
2015-16						
STW-1	Electric	12.9	6			1.87
STW-2	Diesel	14.0	19			2.94
STW-3	Electric	15.0	25			4.60
STW-4	Diesel	8.1		6	5	1.63
STW-5	Diesel	8.6		12	2	2.13
Total (2015-16)			**50**	**18**	**7**	**12.81**
2016-17						
STW-1	Electric		20			3.45
STW-3	Electric		19			3.97
STW-5	Diesel				1	0.13
Total (2016-17)						**7.55**

Figures 4.4 and 4.5 show the average per hectare total paid-out cost of different inputs for rice cultivation in Ishurdi for 2015-16 and 2016-17 season, respectively. Among the 3 STWs in 2015-16, the average cost of irrigation was lower (16,671 Taka/ha) under STW-1 compared to the costs in the other two STWs (> 21,000 Taka/ha). In 2016-17, average irrigation cost was substantially greater than in 2015-16; it was (37,550 Taka/ha for STW-1 and 35,669 Taka/ha for STW-3. In this location, irrigation cost is priced through crop (25% of total production). The pump owners irrigate other farmers' dry season rice fields as much as and/or when irrigation is required for the whole cropping season. When rice is ready to harvest, the field is divided into four equal parts and pump owners harvest one-fourth of each plot as fees for irrigation. Therefore, cost of irrigation in the location was estimated from the value of both rice and straw at the harvesting season. The fee thus varies from plot to plot due to the variation in yield. The cost of irrigation for 2016-17

was much greater than 2015-16 as the price of paddy rice was about 30% higher in 2016-17 compared to 2015-16. The key drawback of this pricing policy is that farmers pay higher for irrigation under good seasonal conditions (higher yield and paddy price). However, the benefit is that the risk of receiving lower return shared by both the pump owner and landlord under worst seasonal conditions (lower yield and price).

The cost of irrigation was the highest among the different input costs (fertilizers, pesticides, etc.) that was about 26% of the total cost in 2015-16 and about 35% in 2016-17. This is followed by cost of fertilizer (17% in 2015-16 and 13% in 2016-17), and labour for harvesting and carrying (17% in 2015-16, 10% in 2016-17). There is almost no variation in cost of different inputs for the cultivation of different rice varieties (Figure 4.4; comparison of different varieties under STW-3).

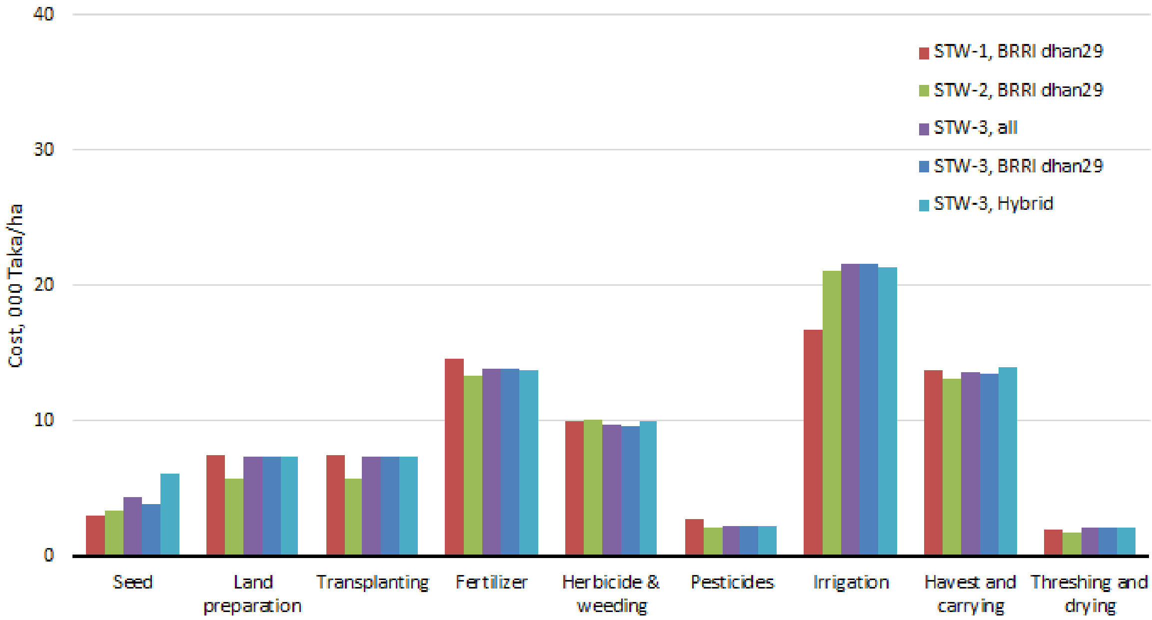

Figure 4.4 Mean total paid-out cost of different inputs for rice cultivation in Ishurdi for 2015-16

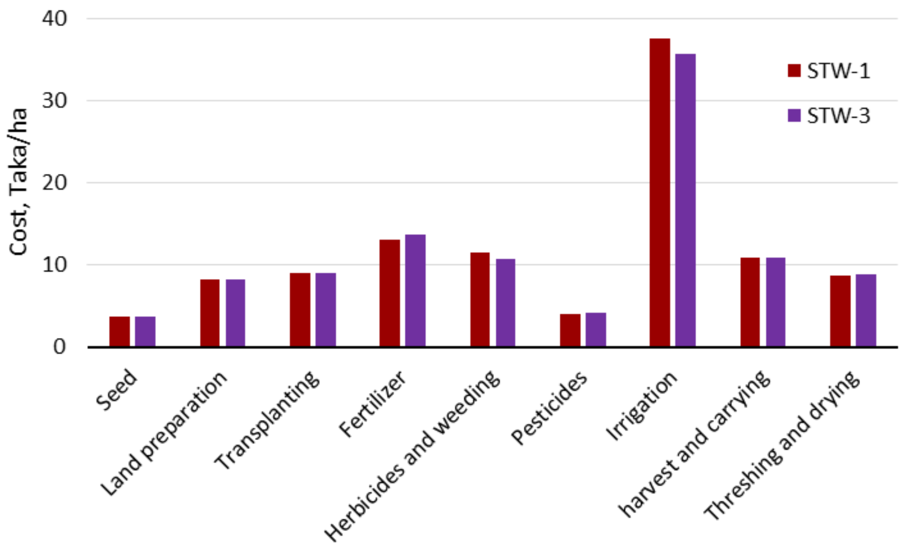

Figure 4.5 Mean total paid-out cost of different inputs for rice cultivation in Ishurdi for 2016-17

4.5 Gross benefit, gross income, and benefit over cost ratio of rice

'Gross benefit' of rice is the market value of grain and straw yields at current price and 'gross income' is the 'gross benefit' minus 'total paid-out cost'. Total paid-out cost is the sum of costs of all inputs described in section 4.4 above. The total paid-out cost, gross benefit and gross income of all the rice plots are shown in Figure 4.6. The variation in benefit-cost-ratio (BCR) is illustrated in Figure 4.7. These figures compare the averages (median) and variations (Interquartile range, IQR) in the variables across various types of pumps and across all locations.

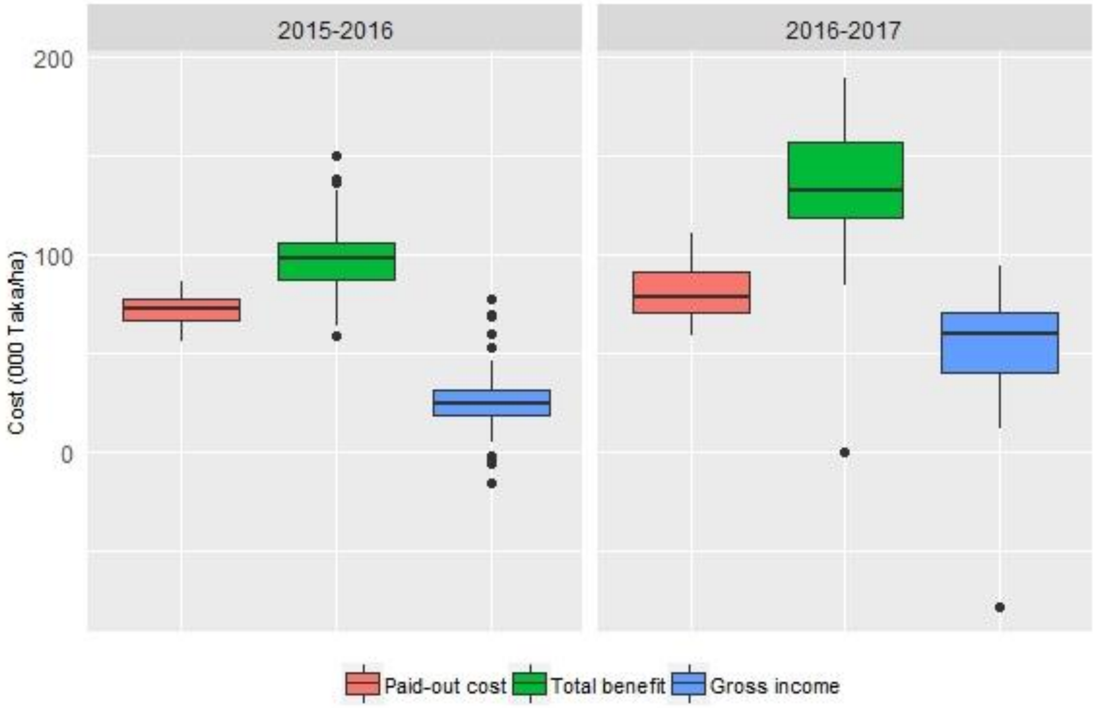

Figure 4.6 Variation of total paid-out cost, total benefit and gross income of rice cultivation for all plots of all locations

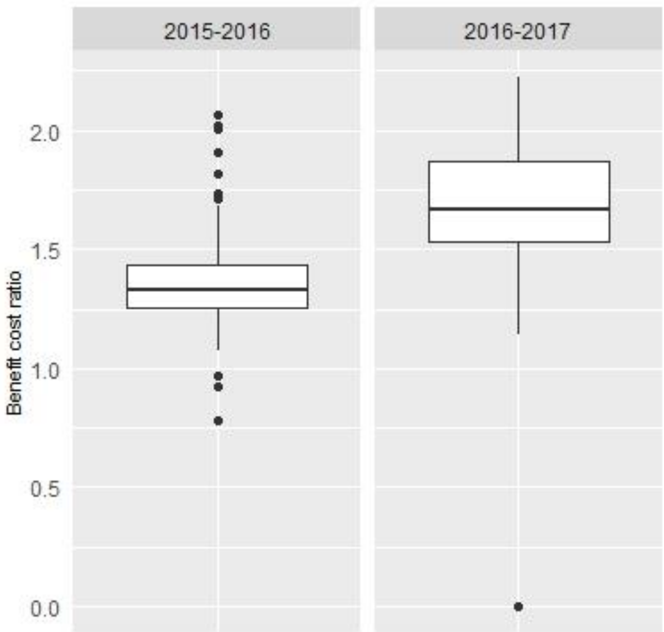

Figure 4.7 Variation in benefit-cost-ratio of rice cultivation for all plots of all locations

Considering all the plots, the mean gross benefit and gross income were respectively 97,360 Taka/ha and 25,080 Taka/ha in 2015-16 (Figure 4.6). The minimum value of negative gross income indicates loss from the specific plot, whereas the maximum gross income was estimated as 77,640 Taka/ha (Figure 4.6). Total paid-out cost, gross benefit and gross income varies due to location, type of tubewells and varieties of rice cultivated (Table 4.6).

Table 4.6 Number of plots, and mean of land area, yield, cost and profit for the rice plots by location, pump type, varieties, and date of transplanting

Item	2015-16					2016-17				
	No. of plots	Yield tonne/ha	Total paid out cost, Taka/ha	Gross benefit Taka/ha	Gross income, Taka/ha	No. of plots	Yield tonne/ha	Total paid out cost, Taka/ha	Gross benefit Taka/ha	Gross income, Taka/ha
Location										
Ishurdi	50	6.55	79,532	102,981	23,449	39	6.99	105,436	174,092	68,656
Kaharol	24	5.93	61,174	78,169	16,995					
Mithapukur	69	6.92	70,134	96,982	26,848	62	5.50	78,821	134,762	55,941
Sherpur	52	5.00	69,588	93,387	23,799	46	4.43	79,646	109,574	29,927
Tanore	22	5.04	76,373	106,663	30,290					
Thakurgaon	18	7.24	77,940	108,833	30,893	18	6.70	67,222	138,154	70,932
Badarganj						20	6.29	68,029	129,741	61,713
Pump type										
STW-Electric motor	80	6.62	70,975	107,640	25,317	74	6.11	90,558	152,923	62,365
STW-Diesel engine	115	5.89	71,519	96,291	23,000	73	5.00	81,662	121,492	39,830
DTW-electric	40	6.03	77,078	94,519	30,561	18	6.70	67,030	138,154	71,124
Solar power						20	6.29	68,029	129,741	61,713
Variety										
BRRI dhan28	57	6.14	66,559	88,074	21,515	48	5.33	74,468	125,903	51,435
BRRI dhan29	61	6.72	78,231	103,949	25,717	43	6.81	84,429	151,708	67,278
Hybrid	43	7.39	72,582	100,344	27,762	28	6.06	78,836	143,397	64,561
Jirashail	22	5.04	76,373	106,663	30,290					
Kajallata	21	4.87	71,880	91,076	19,196					
Minikit	31	5.09	68,034	94,952	26,918	66	5.18	88,154	131,223	43,068
Date of transplanting										
January	107	5.87	72,780	97,219	24,439	60	5.35	86,416	131,612	45,196
February first	104	6.49	73,683	100,579	26,896	113	5.92	80,831	138,965	58,134
February last	24	6.05	63,971	83,995	20,025	12	6.18	70,624	139,218	68,593

Note: Total cost is the 'total paid out cost', actual cost of purchase inputs, 'gross benefit' is the market value of grain and straw yield at current price and 'gross income' is 'gross benefit' minus 'total paid-out cost'

Analysis of Variance (ANOVA) was done for compairing mean cost, income, productivity, and profitibility of Boro rice across the locations, pump types, cultivars and transplaning dates. The ANOVA method assesses the relative size of variance among the group means (between group variance) compared to the average variance within groups (within group variance). The ratio between group variance to within group variance is called the F-ratio or F-value. The F-value along with the degrees of freedom produce P-value (probability of rejecting a true null hypothesis). Smaller P-value (smaller than 0.05) indicates statistically significant difference among the means of the groups. If any significant difference is detected by the 'overall F test', it is aimed to examine the specific pair of group means showing significant difference. This is done by using post-hoc multiple comparison test. Tukey's Honest Significant Difference (HSD) method has been adopted here for that purpose.

Table 4.7 provides the results of ANOVA test conducted to test if statistically significant ($p < 0.05$) differences exist in total paid-out cost among various locations, types of pumps, varieties of rice, and dates of transplanting. For the data obtained for 2014-15, smaller p-values (< 0.05) were observed for all the variables. This indicates statistically significant variations in mean cost among the categories of all the covariates. This means that total paid-out cost significantly differ among the locations, types of pumps used for irrigation, varieties of rice and transplanting dates. However, in 2016-17, the average paid-out costs did not differ much among the varieties of rice cultivated or the dates of transplanting. The costs were significantly different across the locations and types of pumps used for irrigation.

Table 4.7 ANOVA for total paid-out cost of rice cultivation (‘000 Taka/ha)

Source	2015-16				2016-17			
	df	MSS	F-value	P-value	df	MSS	F-value	P-value
Location	5	1,446	125.1	< 0.01	4	7,529	306.5	<0.01
Pump type	1	89	7.7	< 0.01	1	1,883	76.6	<0.01
Variety	3	104	9.0	< 0.01	3	65	2.6	>0.05
Transplanting date	2	183	10.1	< 0.01	2	21	0.9	>0.05
Residual	223	12			174	25		

In 2015-16, statistically significant variations in gross benefit were observed among the locations and varieties of rice (Table 4.8). In 2016-17, significant variations in gross benefit were observed among the locations, varieties of rice, and types of pumps used for irrigation. In both crop-years, differences in gross benefit were not statistically significant among the transaplanting dates. Types of pumps used for irrigation did not make significant variations in average gross benefit in the crop year 2015-16.

The results of ANOVA for gross income for the two crop seasons are presented in Table 4.9. While analysing data for the crop year 2015-16, significant ($p < 0.05$) vatiation in gross income were observed for the variables – locations, pump types and rice varieties. Transplanting date was not a significant factor in the variation in gross income (Table 4.9). In 2016-17 crop year, along with the transplanting date, types of pumps did not show a significant impact on gross income from the cultivated rice.

Table 4.8 ANOVA for gross benefit of rice cultivation (‘000 Taka/ha)

Source	2015-16				2016-17			
	df	MSS	F-value	P-value	df	MSS	F-value	P-value
Location	5	3,105	27.5	< 0.01	4	22,403	113.7	<0.01
Pump type	1	413	3.7	> 0.05	1	2,367	12.0	<0.01
Variety	3	328	2.9	< 0.05	3	1,804	9.2	<0.01
Transplanting Date	2	40	0.4	>0.05	2	195	1.0	> 0.05
Residual	223	113			174	197		

Table 4.9 ANOVA for gross income of rice cultivation (‘000 Taka/ha)

Source	2015-16				2016-17			
	df	MSS	F-value	P-value	df	MSS	F-value	P-value
Location	5	642	5.4	< 0.01	4	10,402	52.4	<0.01
Pump type	1	885	7.5	< 0.01	1	28	0.1	>0.05
Variety	3	441	3.7	< 0.05	3	1,193	6.0	<0.01
Transplanting Date	2	60	0.5	>0.05	2	102	0.6	> 0.05
Residual	223	118			174	199		

Tukey's HSD post-hoc multiple comparison test was utilised to compare total gross income between the pairs of locations and pump types, and the results are presented in Tables 4.10 and 4.11, respectively for the years 2015-16 and 2016-17. Table 4.10 indicates that, in 2015-16 crop year, there were significant ($p<0.05$) variations in total gross benefit between the pairs of locations, Mithapukur-Kaharol, Tanore-Kaharol, and Thakurgaon-Kaharol. Compared to Kaharol, the gross income is significantly higher in Mithapukur, Tanore and Thakurgaon. While considering the data from 2016-17 crop year, the gross income for Sherpur was significantly lower than that in Ishurdi, Mithapukur, Thakurgaon and Badargonj. However, the gross income in Mithapukurwas was significantly lower than in Ishurdi and Thakurgaon. The differences were not significant for other pairs of locations.

Table 4.10 Differences in gross benefit of rice across locations in 2015-16 crop year

	Difference	95% confidence interval		P-value (adjusted)
		Lower	Upper	
Kaharol-Ishurdi	-6.45	-14.08	1.17	0.15
Mithapukur-Ishurdi	3.40	-2.30	9.10	0.52
Sherpur-Ishurdi	0.35	-5.73	6.43	1.00
Tanore-Ishurdi	6.84	-1.01	14.70	0.13
Thakurgaon-Ishurdi	7.44	-1.026	15.91	0.12
Mithapukur-Kaharol	9.85	2.55	17.16	0.00
Sherpur-Kaharol	6.80	-0.80	14.41	0.11
Tanore-Kaharol	13.30	4.20	22.39	0.00
Thakurgaon-Kaharol	13.90	4.30	23.51	0.00
Sherpur-Mithapukur	-3.05	-8.71	2.61	0.63
Tanore-Mithapukur	3.44	-4.10	10.99	0.78
Thakurgaon-Mithapukur	4.04	-4.11	12.20	0.71
Tanore-Sherpur	6.49	-1.35	14.33	0.17
Thakurgaon-Sherpur	7.09	-1.33	15.52	0.15
Thakurgaon-Tanore	0.60	-9.19	10.40	1.00

Table 4.11 Differences in gross benefit of rice across locations in 2016-17 crop year

	Difference	95% confidence Interval		P value (adjusted)
		Lower	Upper	
Mithapukur-Ishurdi	-12.72	-20.66	-4.77	0.00
Sherpur-Ishurdi	-38.73	-47.19	-30.27	0.00
Thakurgaon-Ishurdi	2.28	-8.80	13.35	0.98
Badarganj-Ishurdi	-6.94	-17.63	3.74	0.38
Sherpur-Mithapukur	-26.01	-33.57	-18.45	0.00
Thakurgaon-Mithapukur	14.99	4.59	25.39	0.00
Badarganj-Mithapukur	5.77	-4.22	15.76	0.50
Thakurgaon-Sherpur	41.00	30.20	51.81	0.00
Badarganj-Sherpur	31.79	21.38	42.19	0.00
Badarganj-Thakurgaon	-9.22	-21.84	3.41	0.26

For the crop year 2015-16, the results of post-hoc multiple comparison tests for gross income across the pump types is presented in Table 4.12. The result indicates that gross income from rice production was higher for the STW-driven by electric motor compared to STW with diesel engine; the difference is significant at $p = 0.06$. For the crop year 2016-17, the difference was insignificant. Alternatively, ANOVA analysis for gross income for the crop varieties was done for the crop year 2016-17. Significantly higher gross income was observed for hybrid rice compared to the BRRI varieties (BRRI dhan28 and BRRI dhan29, Table 4.13).

Table 4.12 Differences in gross income of rice among the pump-types used for irrigation in 2015-16 crop season

	Difference	Lower CL	Upper CL	P-value (adjusted)
DTW- STW (diesel)	1.48	-3.16	6.12	0.73
STW (electric)- STW (diesel)	3.61	-0.08	7.29	0.06
STW (electric)-DTW	2.13	-2.77	7.02	0.56

Table 4.13 Differences in gross income across the rice varieties cultivated in 2016-17 crop season

	difference	LCL	UCL	p-value (adjusted)
BRRI dhan29-BRRI dhan28	4.27	-3041	11.94	0.47
Hybrid-BRRI dhan28	13.11	4042	21.81	0.00
Minikit-BRRI dhan28	5.90	-1.04	12.84	0.13
Hybrid-BRRI dhan29	8.85	-0.03	17.73	0.05
Minikit-BRRI dhan29	1.63	-5.53	8.80	0.93
Minikit-Hybrid	-7.21	-15.46	1.03	0.11

The variations of total paid-out cost, gross benefit, gross income, and benefit-cost-ratio for the plots within the command area of the tubewells at Ishurdi are shown in Figures 4.8 and 4.9. Compared to 2015-16 crop year, the total paid-out cost increased significantly in 2016-17. However, because of higher price of the products, both the gross benefit and gross income were higher in 2016-17. Considering data for the same year, total paid-out cost was consistent across and within the pumps (STWs). However, relatively higher variations in gross income and gross benefit were observed for the plots within the command area of the STWs. In general, there were large variations from plot to plot in the total paid-out cost, gross benefit, and gross income within a STW.

Figure 4.8 Variations in total paid-out cost, gross benefit, and gross income of rice plots in Ishurdi

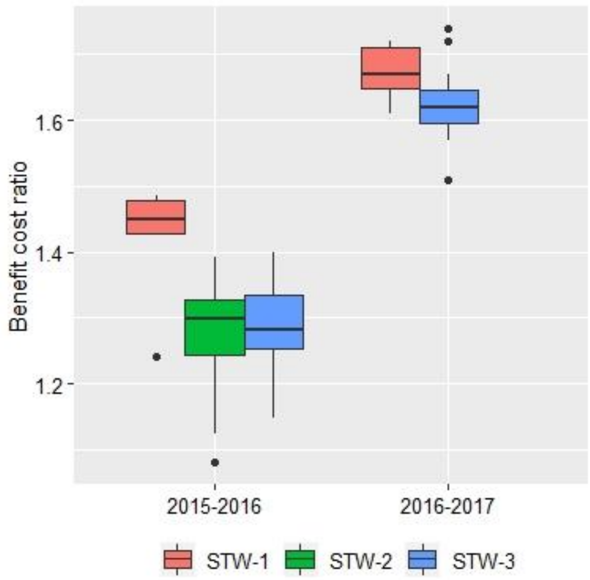

Figure 4.9 Variations in benefit over cost-ratio and yield of rice in Ishurdi

The average total paid-out cost of BRRI dhan29 under STW-1 (77,709 Taka/ha) was lower than that for Hybrid rice (84,441 Taka/ha) in 2015-16. It was mainly because of lower cost of seeds for BRRI dhan29 (3,040 Taka/ha) compared to the Hybrid rice (6,088 Taka/ha). Despite slightly higher average yield of Hybrid rice under STW-3 than STW-1, gross income (27,013 Taka/ha) of Hybrid rice was 18% lower than the average gross income (32,777 Taka/ha) of BRRI dhan29 for the area under STW-1 (Figure 4.10). This is the reflection of higher cost of seeds of the Hybrid rice than inbred varieties as well as higher price of BRRI dhan29 (Figure 4.4). On the other hand, total paid-out costs of rice under STW-2 (76,485 Taka/ha) was lower compared to that under STW-3 (81,605 Taka/ha) for the same variety (BRRI dhan29) because of lower doses of inputs (fertilizer, pesticides, etc.) application. Consequently, the average per hectare yield and gross income (76,485 Taka) were the lowest for the area under STW-2. It was also the case that the benefit over cost-ratio was equal (1.27) to the plots cultivated with the same variety (BRRI dhan29) under STW-2 despite lower average yield of rice. This was because of lower paid-out cost (Figure 4.11).

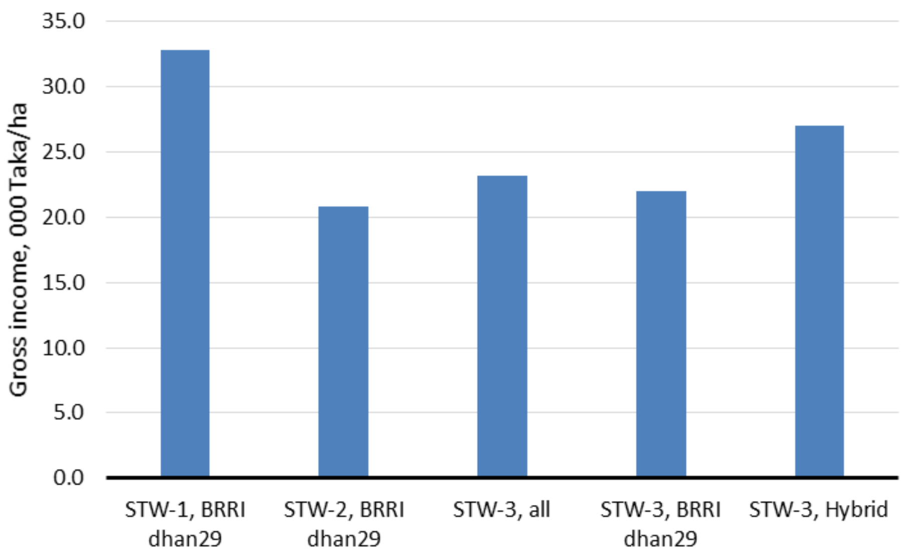

Figure 4.10 Gross income (Gross benefit minus total paid-out cost) of rice cultivation at Ishurdi in 2015-16

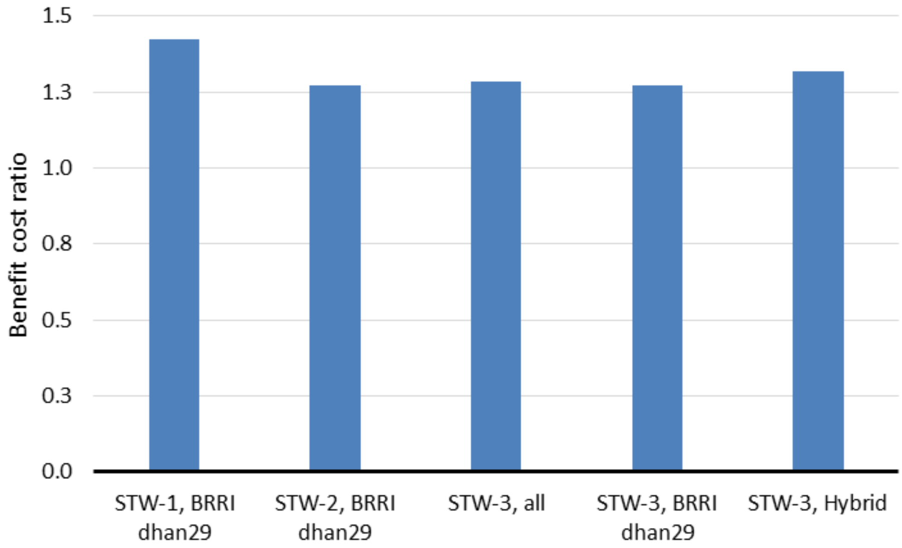

Figure 4.11 Benefit over cost ratio of rice cultivation at Ishurdi in 2015-16

The average paid-out cost of BRRI dhan29 in 2016-17 was 104,410 Taka/ha, which was 35% higher than that in 2015-16. The main reason for this was the higher cost of irrigation. Due to higher price of rice in 2016-17, the estimated cost of irrigation was also higher. Yet, the gross income and benefit-cost-ratio were significantly higher in 2016-17 compared to those in 2015-16 (Figures 4.8 and 4.9). The average paid-out cost of Minikit was slightly higher (106,315 Taka/ha) than BRRI dhan29. The gross income (71,961 Taka/ha) and benefit-cost-ratio (1.68) of Minikit were also higher compared to BRRI dhan29 (64,800 Taka/ha and 1.62) though the average yield of Minikit is lower (6.83 tonne/ha) compared to BRRI dhan29 (7.18 tonne/ha). This is due to higher price of Minikit (23.80 Taka/kg) compared to BRRI dhan29 (21.50 Taka/kg).

4.6 Yield of rice

There are significant variations in the average yield of rice due to location, type of pump and rice varieties as compared in Table 4.6. This variation is mainly due to the variation in cultivation of different varieties at different locations. The potential yield of rice is different for different varieties. Hybrid rice has the highest potential yield, followed by BRRI dhan29, BRRI dhan28, and other varieties (Minikit, Kajallata, and Jirashail). In 2015-16, the average yield was the highest in Thakurgaon and the lowest in Sherpur. Most of the plots in Thakurgaon were under BRRI dhan29, the yield of which was the highest among the High Yielding Varieties (HYV) of Boro released by BRRI with long growth duration (about 165 days). The average yield in Tanore was among the lowest but the net beenfit was among the highest. Among the varieties, in 2015-16, the average yield was the highest (7.39 tonne/ha) for hybrid rice, followed by BRRI dhan29 (6.72 tonne/ha), and BRRI dhan28 (6.14 tonne/ha). According to BRRI (2018), the average expected yield of BRRI dhan29 and BRRI dhan28 are 7.5 and 6.0 tonne/ha, respectvely. So, the average yields achieved in these plots are very close to the expected yields; in case of BRRI dhan28, this is even slightly higher. The reason for this could be the variable moisture content in rice. It was not possible to check the moisture content properly while recording the yield. So, it is likely that the moisture content was not always at the standard level (14%). The yields of the other 3 varieties (Jirashail, Kajallata, and Minikit) were similar, ranging from 4.87 tonne/ha to 5.09 tonne/ha. In 2016-17, the average yield of Hybrid rice (6.05 tonne/ha) was lower than the BRRI dhan29 (6.81 tonne/ha). The average yield of BRRI dhan28 was lower in 2016-17 than in 2015-16 whereas the yield of Minikit was slightly higher in 2016-17. There are variations in yield due to time of transplanting (Table 4.6). But, these variations are embedded with varieties and locations. The mean and median of the yields considering all plots were estimated as 6.16 and 6.13 tonne/ha, respectively. The estimated value of coefficient of skewness for yield is 0.83, which indicates highly skewed nature of the variables.

The ANOVA results for average yield of rice are presented in Table 4.14. For the results of 2015-16 crop year, smaller p-values (<0.05) for the study locations and rice varieties indicate significant variations in the average yield among the levels of these variables. No significant variation in the average yield was observed among various types of pumps or planting dates. While analysing the data for the crop year 2016-17, all the variables except the planting dates appeared to cause significant variation.

Table 4.14 ANOVA for yield (tonne/ha) of rice

	2014-15				2016-17			
Source	df	MSS	F-value	P-value	df	MSS	F-value	P-value
Location	5	33.4	78.6	< 0.01	4	41.6	120.7	<0.01
Pump type	1	1.3	3.0	> 0.05	1	11.5	33.3	<0.01
Variety	3	9.8	23.1	< 0.01	3	6.5	18.8	<0.01
Transplanting Date	2	0.1	0.1	>0.05	2	0.5	1.5	> 0.05
Residual	223	0.4			174	0.4		

Results from Tukey's HSD post-hoc multiple comparison test to compare average yield between pairs of locations and rice varieties are presented in Table 4.15 through Tables 4.18. With exceptions for Thakurgaon–Mithapukur and Tanore–Sherpur, all other combinations of locations have significant difference in the yield for the crop year 2015-16. Among these pairs, Thakurgaon–Mithapukur provided the highest yields and Tanore–Sherpur provided the lowest yields. In the crop year 2016-17, the highest yielding location was Ishurdi; however, no significant difference in yield for this location was observed with Thakurgaon. The insignificant difference for the pair Badargonj-Thakurgaon indicates that the second and third highest yielding sites do not revealed any significant difference. All the other pairs of locations showed significant differences in the yield. Like the previous crop year, yield was the lowest for Sherpur (Table 4.6).

In 2015-16, yield of Hybrid rice was significantly higher than all other varieties (Table 4.17). BRRI dhan29 was the second highest yielding rich variety and the production of this variety was significantly higher than BRRI dhan28, Jirashail, Kajallata and Minikit. Yield of BRRI dhan29 was significantly higher than the three other rice varieties. Significant difference in the yield was observed among the rice categories, Jirashail, Kajallata and Minikit. For the crop year 2016-17, the yield of BRRI dhan29 was significantly higher than all other varieties. The yield of Hybrid rice, the second highest yielding variety in the cultivated lands, was significantly higher than other two varieties, BRRI dhan28 and Minikit. The mean difference in the yield of BRRI dhan28 and Minikit was not statistically significant (Table 4.18).

Table 4.15 Differences in rice yield across locations in 2015-16

	difference	LCL	UCL	p-value (adjusted)
Kaharol-Ishurdi	-0.62	-1.08	-0.15	0.003
Mithapukur-Ishurdi	0.37	0.02	0.72	0.031
Sherpur-Ishurdi	-1.55	-1.92	-1.18	0.000
Tanore-Ishurdi	-1.51	-1.99	-1.03	0.000
Thakurgaon-Ishurdi	0.69	0.18	1.21	0.002
Mithapukur-Kaharol	0.98	0.54	1.43	0.000
Sherpur-Kaharol	-0.93	-1.40	-0.47	0.000
Tanore-Kaharol	-0.89	-1.45	-0.34	0.000
Thakurgaon-Kaharol	1.31	0.72	1.89	0.000
Sherpur-Mithapukur	-1.92	-2.26	-1.57	0.000
Tanore-Mithapukur	-1.88	-2.33	-1.42	0.000
Thakurgaon-Mithapukur	0.33	-0.17	0.82	0.411
Tanore-Sherpur	0.04	-0.44	0.52	1.000
Thakurgaon-Sherpur	2.24	1.73	2.75	0.000
Thakurgaon-Tanore	2.20	1.61	2.80	0.000

Table 4.16 Differences in rice yield across locations in 2016-17

	difference	LCL	UCL	p-value (adjusted)
Mithapukur-Ishurdi	-1.49	-1.83	-1.16	0.000
Sherpur-Ishurdi	-2.56	-2.92	-2.21	0.000
Thakurgaon-Ishurdi	-0.29	-0.76	0.17	0.403
Badarganj-Ishurdi	-0.70	-1.15	-0.26	0.000
Sherpur-Mithapukur	-1.07	-1.38	-0.75	0.000
Thakurgaon-Mithapukur	1.20	0.77	1.63	0.000
Badarganj-Mithapukur	0.79	0.37	1.21	0.000
Thakurgaon-Sherpur	2.27	1.82	2.72	0.000
Badarganj-Sherpur	1.86	1.43	2.29	0.000
Badarganj-Thakurgaon	-0.41	-0.94	0.12	0.204

Table 4.17 Differences in yield across varieties of rice in 2015-16

	difference	LCL	UCL	p-value (adjusted)
BRRI dhan29-BRRI dhan28	0.581	0.215	0.948	0.000
Hybrid-BRRI dhan28	1.255	0.853	1.657	0.000
Jirashail-BRRI dhan28	-1.096	-1.595	-0.596	0.000
Kajallata-BRRI dhan28	-1.263	-1.772	-0.755	0.000
Minikit-BRRI dhan28	-1.050	-1.494	-0.606	0.000
Hybrid-BRRI dhan29	0.674	0.278	1.070	0.000
Jirashail-BRRI dhan29	-1.677	-2.172	-1.182	0.000
Kajallata-BRRI dhan29	-1.845	-2.348	-1.341	0.000
Minikit-BRRI dhan29	-1.631	-2.070	-1.192	0.000
Jirashail-Hybrid	-2.351	-2.873	-1.829	0.000
Kajallata-Hybrid	-2.519	-3.049	-1.989	0.000
Minikit-Hybrid	-2.305	-2.774	-1.836	0.000
Kajallata-Jirashail	-0.168	-0.775	0.439	0.968
Minikit-Jirashail	0.046	-0.509	0.601	1.000
Minikit-Kajallata	0.214	-0.349	0.776	0.884

Table 4.18 Differences in yield across varieties of rice in 2016-17

	difference	LCL	UCL	p-value (adjusted)
BRRI dhan29-BRRI dhan28	1.441	0.889	1.994	0.000
Hybrid-BRRI dhan28	0.678	0.055	1.302	0.027
Minikit-BRRI dhan28	-0.163	-0.660	0.333	0.830
Hybrid-BRRI dhan29	-0.763	-1.392	-0.134	0.010
Minikit-BRRI dhan29	-1.604	-2.108	-1.101	0.000
Minikit-Hybrid	-0.841	-1.422	-0.261	0.001

Within a location, among the STWs of Ishurdi, the average yield (7.0 tonne/ha) of rice in the plots under STW-1 (Figure 4.12) was higher than that (6.2 tonne/ha) in the plots under STW-2 in 2015-16. STW-1 had only 6 plots, all with BRRI dhan29. Of the six plots, all provided over 7.0 tonne/ha (maximum of 7.34

tonne/ha) with only one plot with 6.2 tonne/ha. All the plots under STW-2 were also under BRRI dhan29. However, none of the plots produced yield of 7.0 tonne/ha. The maximum yield was 6.75 tonne/ha. In general, there were large variations in yield from plot to plot within the command area of a STW. In 2015-16, the coefficient of variations (CVs) of yield for STW-1 (6 plots), STW-2 (19 plots), and STW-3 (25 plots) were 6.2, 8.0 and 6.2%, respectively. Considering all plots (50 plots), the CV is 8.2%. In 2016-17, CV of the yield was 4.6% for STW-1 (20 plots) and 4.1% for STW-3 (19 plots).

Figure 4.12 Average yield of Boro rice/irrigated dry season rice in Ishurdi in 2015-16

Of the 25 plots under STW-3 in 2015-16, 6 were planted with Hybrid rice (variety: Tej Gold), the rest 19 were with BRRI dhan29. The average yield of Hybrid rice (7.12 tonne/ha) within the command area of the STW-3 was slightly higher (8.2%) than the average yield (6.58 tonne/ha) of BRRI dhan29 (Figure 4.12). It is noted that the average yield of Hybrid rice was the average of 6 plots and the average yield of BRRI dhan29 was the average of 19 plots. The maximum yield of BRRI dhan29 was 7.22 tonne/ha, which was very close to the maximum yield of 7.37 tonne/ha achieved for the Hybrid rice. For the 6 plots under STW-1, the maximum and average yields of BRRI dhan29 were 7.34 and 7.03 tonne/ha, respectively that were almost equal to that of the Hybrid rice under STW-3 with the same number of plots. So, the difference in yield between the BRRI dhan29 and Hybrid rice was not statistically significant.

In 2016-17, we monitored only STW-1 and STW-3. None of the plots were under Hybrid rice. All plots except one under STW-1 were with Minikit, with an average yield of 6.8 tonne/ha. The maximum yield was 7.25 tonne/ha. In STW-3, 17 out of 19 plots were with BRRI dhan29 and the rests were with Minikit. The maximum and average yields of BRRI Dhan29 were 7.51 and 7.17 tonne/ha, respectively. So, the yield of rice in this site is fairly consistent over the years.

STW-1 and STW-3 are operated by electric motor and STW-2 is operated by diesel engine. As shown in Figure 4.12, the average yield is higher in STW-1 and STW-3 compared to STW-2 for 2015-16. The average yield of 19 plots (all with BRRI dhan29) under STW-2 (diesel engine-operated) was 6.18 tonne/ha, whereas the average yield of 19 plots with BRRI dhan29 under STW-3 was 6.58 tonne/ha. This difference in average yield under electric and diesel operated STWs was found to be statistically significant ($p<0.05$). All three sites have similar soil (silt loam soil), transplanted almost at the same time (Last week of January to 2nd week of February), and had almost similar input costs (Figure 4.4). So, the difference in yield could be related to the timely application of water. For the diesel engine, farmers might not be able to apply irrigation water to the field at the right time due to lack of knowledge or capital to purchase fuels for the pumps, and other issues with the pump.

4.6.1 Effect of transplanting date on rice yield

Figures 4.13 and 4.14 show the scatter plots of yield of different rice varieties against their transplanting dates for 2015-16 and 2016-17 crop season, respectively. In general, there is a decreasing trend in yield with the delay in transplanting for BRRI dhan28 and BRRI dhan29. For BRRI dhan29 in 2015-16, 3 plots, planted in December 2015, had the highest yield (7.48 tonne/ha, Figure 4.13). All other plots were planted during 2nd half of January and 1st half of February and there is almost no variation in the average yield (Table 4.19). Higher yield of BRRI dhan28 was also achieved when transplanting was done in early December and 1st half of January though only 3 plots were planted at that time. Eighty-eight percent of the plots were trasplanted during February and the variation in average yield is insignificant. In most cases, delayed transplanting occurred due to harvesting of potato in the same plots. Both growth duration and grain yield of rice are affected by the time of transplanting (Biswas et al., 2001). However, the Hybrid rice seems not affected by the transplanting time. For this rice, the highest yield (7.73 tonne/ha) was achieved when tranplanting was done during 1st half of February followed by 2nd half of January (7.40 tonne/ha). For Jirashail, 21 of 22 plots were planted during 16 January to 15 February and there is no variation in average yield. However, there is a general trend of increasing yield with late transplanting.

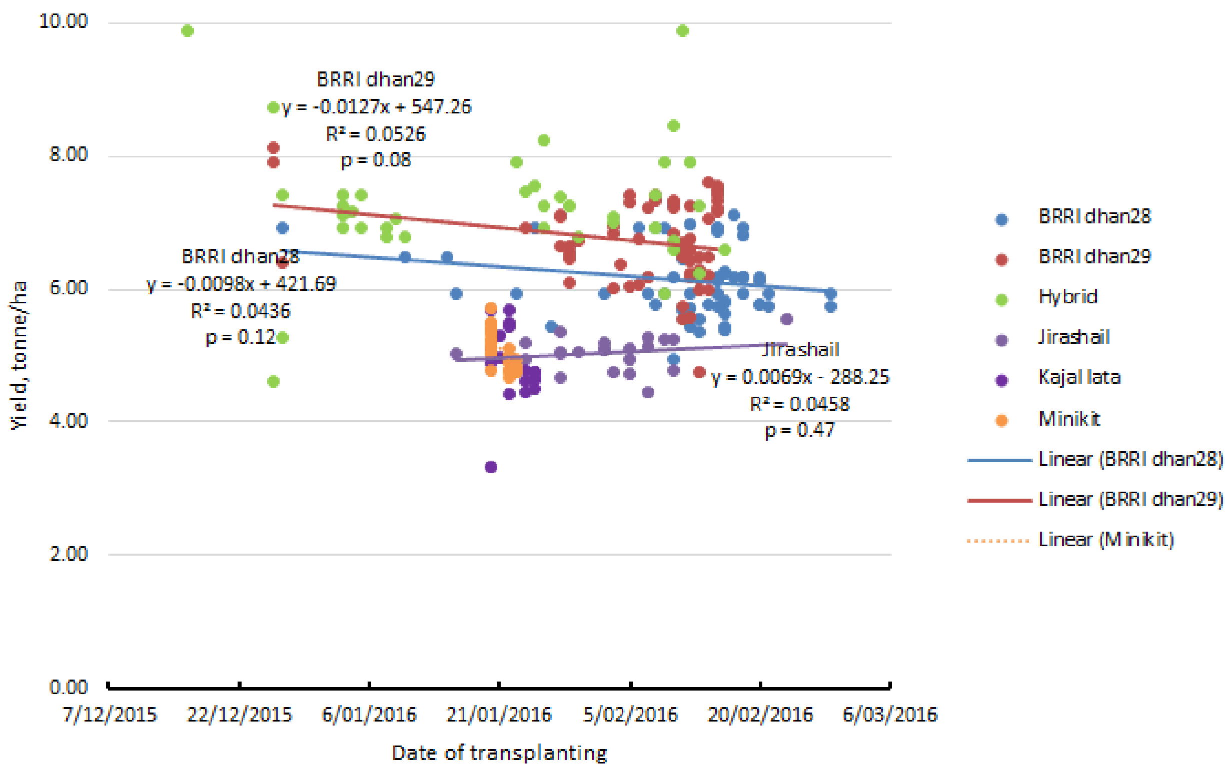

Figure 4.13 Scatter plots of yields of different rice varieties against their transplanting dates for 2015-16

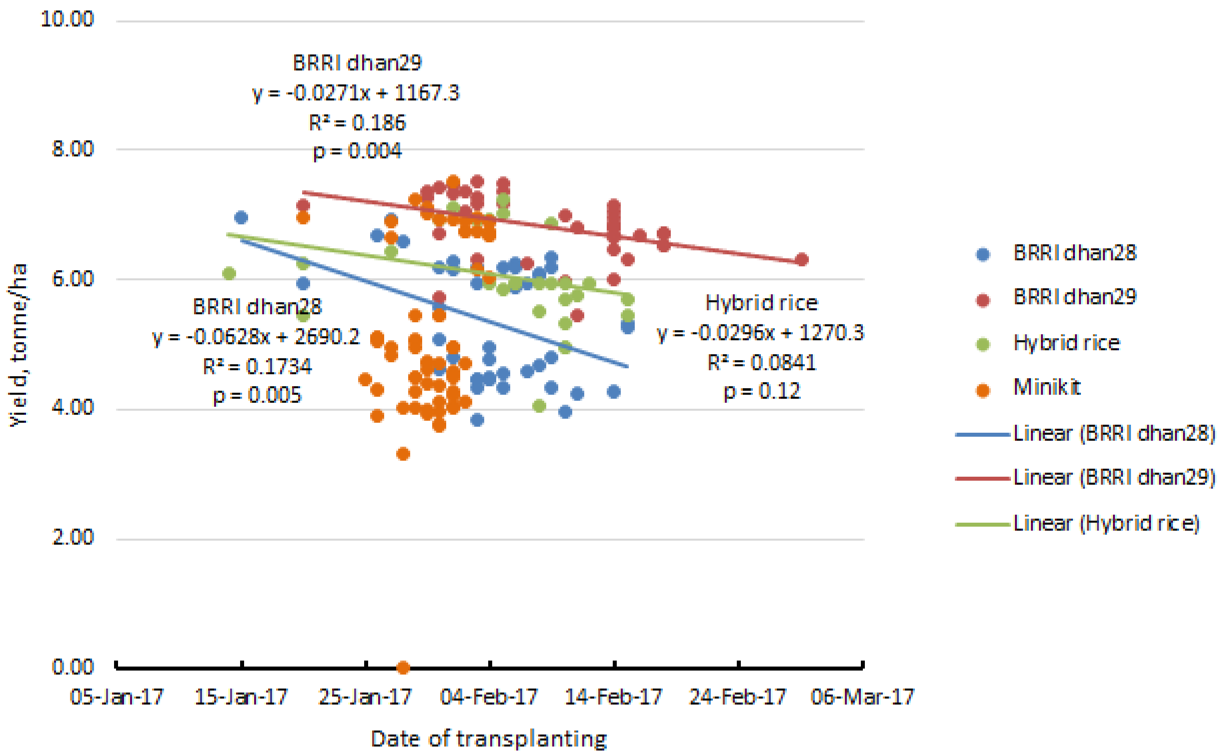

Figure 4.14 Scatter plots of yields of different rice varieties against their transplanting dates for 2016-17

Table 4.19 Average yields of different rice varieties with different transplanting times

Variety	Transplanting Date	Yield, tonne/ha (no. of plot) 2015-16	2016-17
BRRI 28	January	6.30 (07)	6.08 (11)
	01-15 February	6.17 (28)	5.19 (35)
	16-28 February	6.05 (22)	5.29 (02)
BRRI 29	January	6.86 (14)	6.94 (06)
	01-15 February	6.68 (47)	6.86 (29)
	16-28 February		6.56 (08)
Hybrid	January	7.21 (26)	6.26 (03)
	01-15 February	7.73 (16)	6.07(23)
	16-28 February	6.59 (01)	5.56 (02)
Jirashail	January	5.04 (08)	
	01-15 February	5.00 (13)	
	16-28 February	5.54 (01)	
Kajallata	January	4.87 (21)	
Minikit	January	5.09 (31)	4.84 (40)
	01-15 February		5.71 (26)
	16-28 February		

4.6.2 Effect of seedlings' age on rice yield

The age of seedlings is an important factor in the yield of rice (Figures 4.15 and 4.16). The higher the age of seedlings lower was the yield for BRRI dhan28 and BRRI dhan29. The recommended age of seedlings for these two rice varities is 40 days (BRRI, 2018). However, the average age of seedlings was 64 days and 58 days for BRRI dhan28 and BRRI dhan29, respectively in 2015-16. For the Hybrid rice, Jirashail, Kajallata and

Minikit, the average age of seedlings was 48, 43, 44, and 41 days, respectively. In 2016-17, the average age of seedlings was 59, 66, 60, and 54 days, respectively for BRRI dhan 28, BRRI dhan 29, Hybrid rice and Minikit. Although there is no strong linear relationship, there is a clear trend of decreasing yield with increasing age of seedlings for BRRI dhan28 and BRRI dhan29. This result is also supported by Mobasser et al. (2007), who reported that older seedlings significantly reduced the yield of rice. There is, however, no trend of yield with the age of seedlings for the Hybrid rice, Kajallata and Minikit. For Jirashail in 2015-16, the age of seedlings varied from 37 to 60 days with avearge age of 43 days. The yield increases slightly with the age of seedlings. It is noted that the yield of every plot is affeced by a number of factors such as date of transplanting, age of seedlings, fertilizer and pesticide applications, water application, agronomic management of the crops, soil properties, and climatic factors. So, the impact on rice yield is the combined impact of all these factors. However, the observed trends in yield provide the likely impact of date of transplanting and age of seedlings on the yield of rice.

The age of seedlings although reduces the yield of rice, it is also likely to reduce the application of irrigation water. If 40-days old seedlings were transplanted in the field, the field would have required additional 20 days of irrigation water in the field. That would have increased the cost of irrigation in some locations where the payment is based on fixed charge and fuel. One of the main reasons of transplanting older seedlings could be that the land was not free in time. In this region, farmers grow three crops in a year. After harvesting Aman rice (monsoon season rice), farmers cultivate a non-rice crops such as potato, tomato, pulses, vegetables and oilseeds. Boro rice is cultivated as the 3rd crop after harvesting of the other crops. So, the land does not become ready for preparation and transplanting with seedlings of recommended age. Consequently, transplanting is delayed. So, farmers transplant older seedlings to harvest rice on time. Otherwise, harvesting will be late and will be affected by early monsoon rainfall often with hailstorms. Late harvest may also delay transplanting of monsoon Aman rice. Though there is slight loss of yield due to transplanting of older seedlings, the overall benefit would be higher because of growing an additional crop and the reduced level of input required.

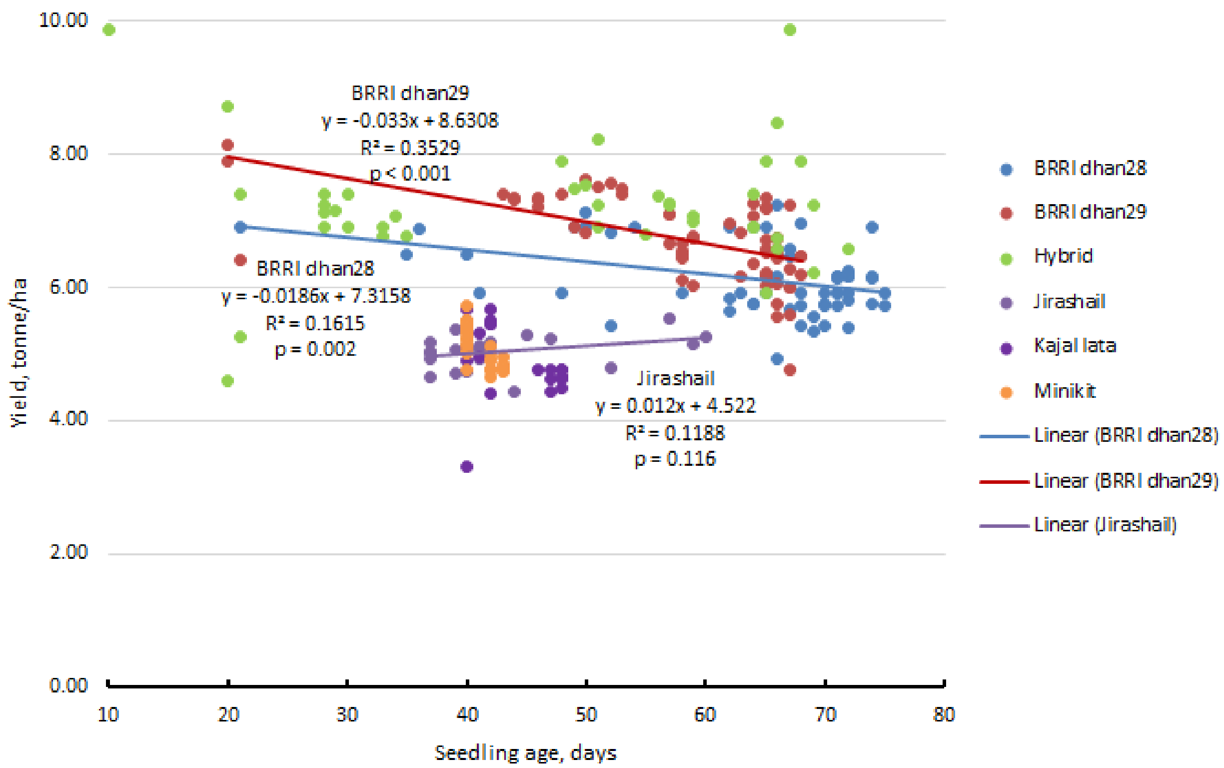

Figure 4.15 Scatter plots of yield of different rice varieties against age of seedlings for 2015-16

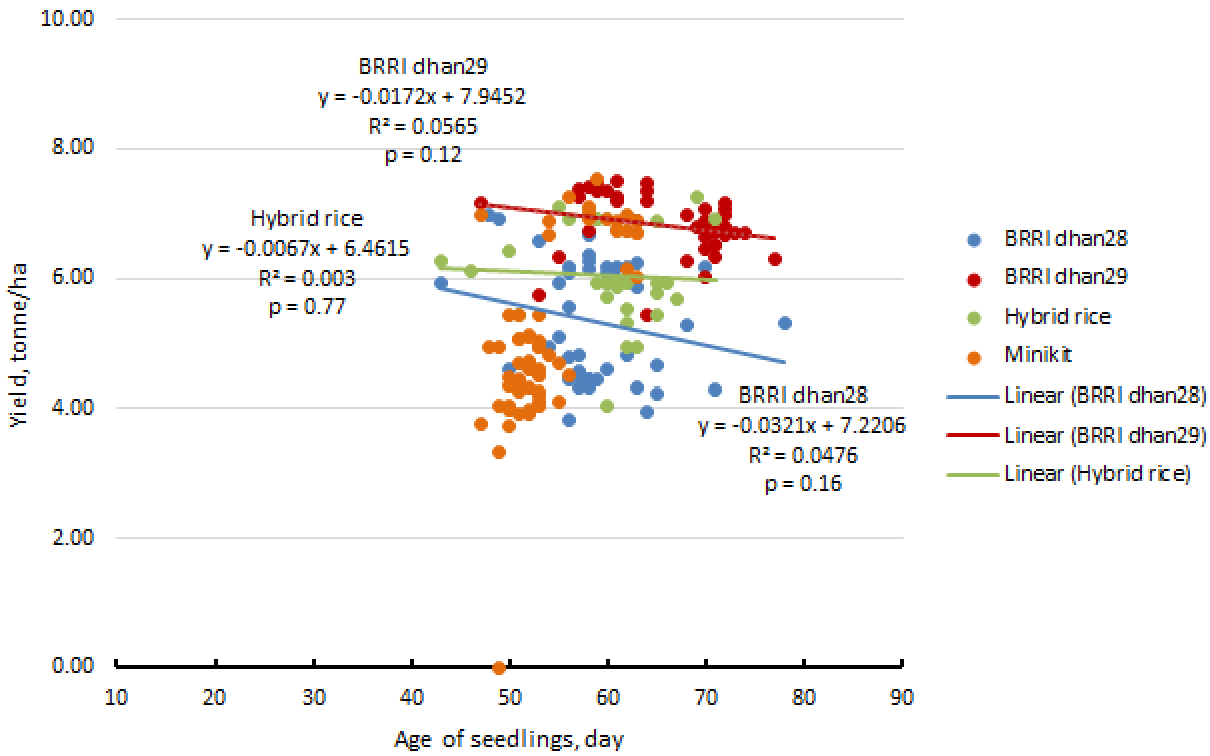

Figure 4.16 Scatter plots of yield of different rice varieties against age of seedlings for 2016-17

4.6.3 Yield probability and gross income in growing rice

There are significant differences in the average yield of rice between Hybrid rice, BRRI dhan29 and BRRI dhan28 as compared in Tables 4.17 and 4.18 for 2015-16 crop season. The yield of other 3 rice varieties (Jirashail, Kajallata and Minikit) are almost similar but significantly ($p<0.05$) lower than the Hybrid rice, BRRI dhan29 and BRRI dhan28. Although the yield was higher for Hybrid rice than the other varieties, the variability in yield was also higher as depicted in the probability of exceedance of the observed yield (Figures 4.17 and 4.18). In 2015-16, the coefficient of variation, CV, of yield for Hybrid rice was 14.0% compared to 8.7 and 9.4% respectively for BRRI dhan28 and BRRI dhan29. The CV of yield for the other 3 varieties were 5.0, 11.1 and 5.8% for Jirashail, Kajallata and Minikit, respectively. The probability of achieving yield of 8.0 tonne/ha for Hybrid rice in 2015-16 was only 20% although it has the higher potential than the other rice varieties.

In 2016-17, the yield was significantly higher for BRRI dhan29 (Figure 4.18) than the Hybrid rice contrary to the results of the 2015-16 crop year. The variation in yield was also higher for Hybrid rice (CV = 12.5%) compared to that of BRRI dhan29 (CV = 7.1%). The variations in yield of BRRI dhan28 and Minikit was much higher in 2016-17 compared to that in 2015-16. The CVs were 17.0% and 25.8% for BRRI dhan28 and Minikit, respectively. These results clearly indicate that the yield of BRRI dhan29 is much more stable than the other varieties across the locations and from year to year. The potential yield of Hybrid rice is higher (as achieved in 2015-16) than that of BRRI dhan29 but the risk is also higher. The yield of Hybrid rice was lower with higher variability in the 2nd year (2016-17).

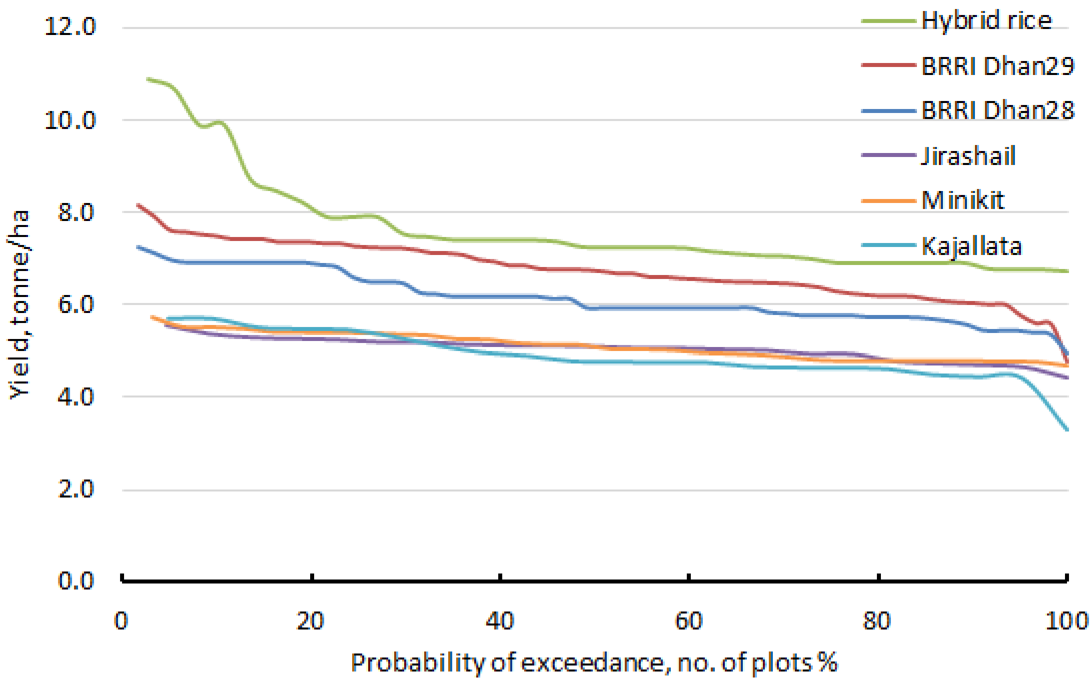

Figure 4.17 Probability of yields of different rice varieties grown at different sites in 2015-16

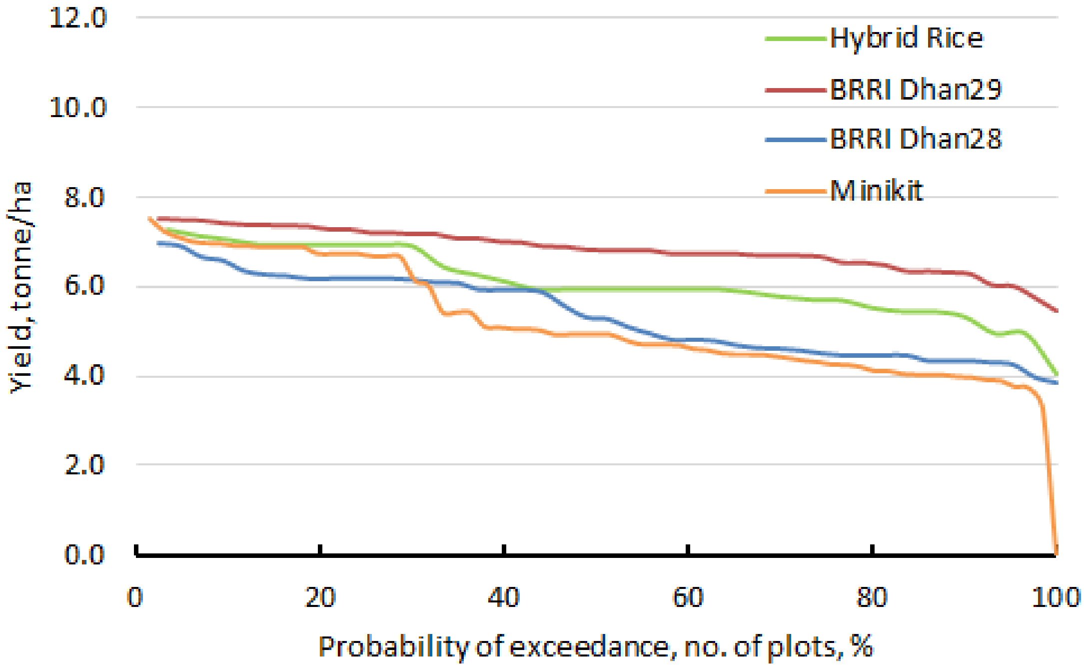

Figure 4.18 Probability of yields of different rice varieties grown at different sites in 2016-17

The probability distribution of gross income is different from the yield (Figures 4.19 and 4.20). In 2015-16, the average gross income was the highest for Jirashail and lowest for Kajallata; BRRI dhan28 was just above Kajallata. The average gross incomes of Kajallata and BRRI dhan28 were significantly lower than that of Jirashail, Hybrid rice, BRRI dhan29 and Minikit. The average gross incomes of Hybrid rice, BRRI dhan29 and Minikit were almost similar. However, the results were quite different in 2016-17. The average gross income was significantly higher for BRRI dhan29 and Hybrid rice compared to BRRI dhan28 and Minikit. The variability in gross income was lower in 2016-17 than in 2015-16 for both BRRI dhan29 and Hybrid rice. The CVs were 10.0 and 27.1% respectively for BRRI dhan29 and Hybrid rice in 2016-17 compared to 34.7 and 47.6%, respectively in 2015-16. The CVs of gross incomes for BRRI dhan28 and Minikit were 25.2 and 27.7%, respectively in 2016-17 compared to 51.6 and 23.6%, respectively in 2015-16. Comparison of the results of two years clearly indicates that BRRI dhan29 is much more stable with lower risk compared to the other rice varieties both in terms of yield and gross income. The Hybrid rice may produce higher yield and gross income in one year but could be different in the other years. Jirashail and Minikit have the potential to give more gross income (Figure 4.17), but they are also susceptible to higher risks (Figure 4.19).

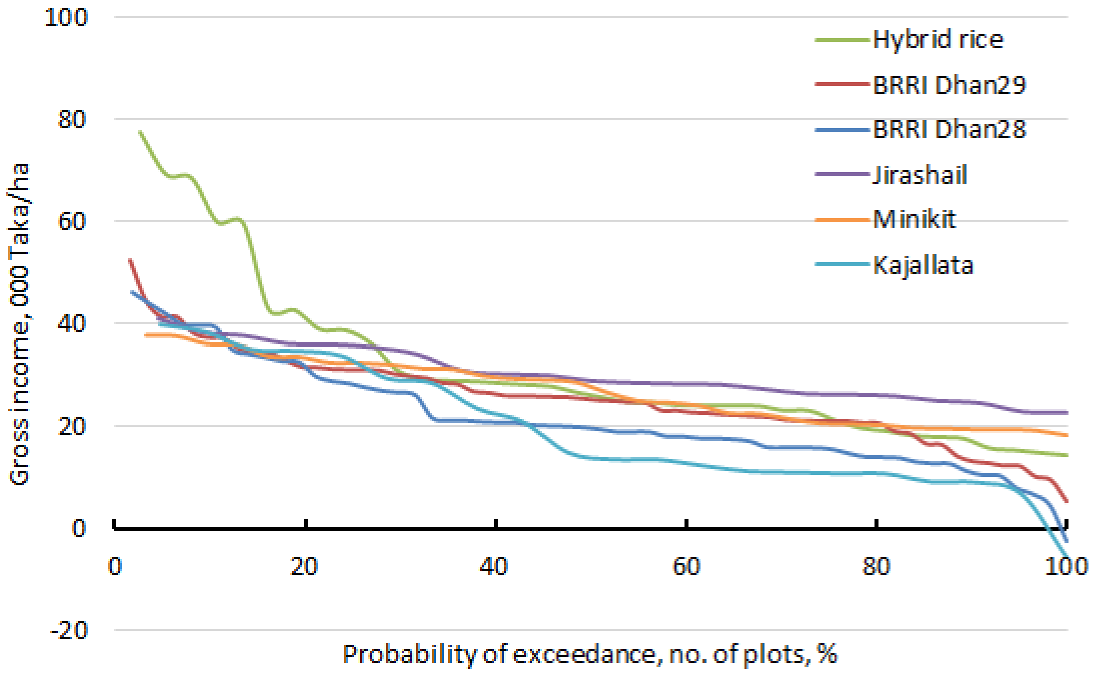

Figure 4.19 Probability of gross income of different rice varieties grown at different sites in 2015-16

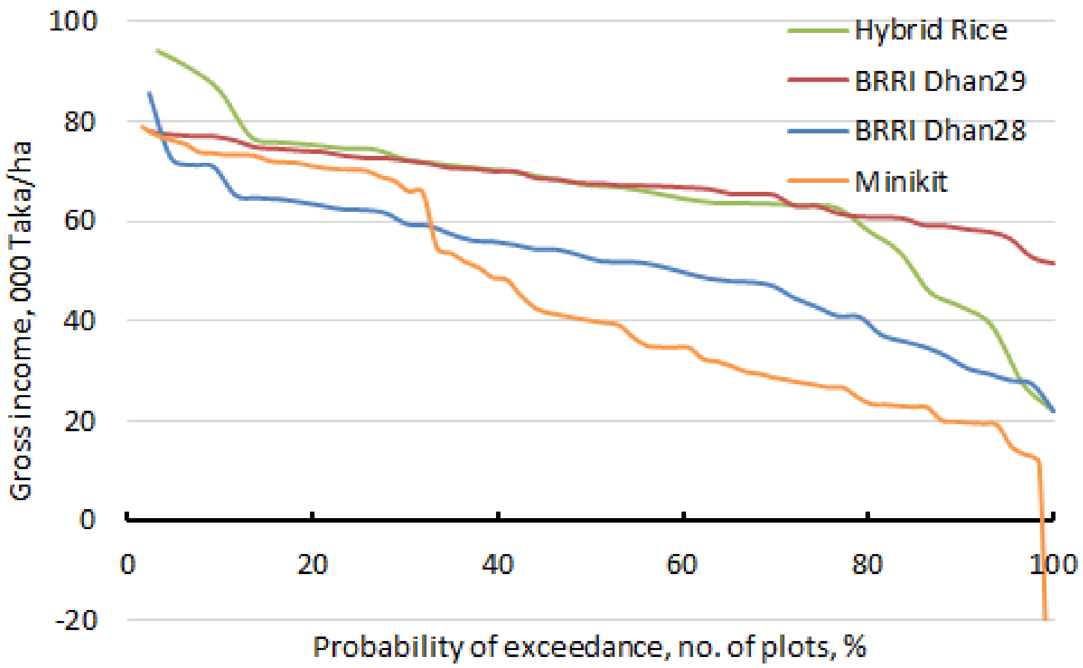

Figure 4.20 Probability of gross income of different rice varieties grown at different sites in 2016-17

Farmers prefer to grow BRRI dhan28 and Minikit for own consumption due to good production with medium growth duration, grain quality, taste and slow digesting character of this rice. The growing period of BRRI dhan29 is 15-20 days longer that BRRI dhan28. So, in places where 3 or more crops are grown in a year, if it is not possible to fit BRRI dhan29 there. Therefore, for subsistence, it could be better to cultivate BRRI dhan28 although the gross income from this rice could be lower. Also, farmers who are growing rice for selling to the market, it could be better for them to grow Jirashail, Minikit, Hybrid rice, and BRRI dhan29. The gross income of BRRI dhan29 and Hybrid rice are also at par with Minikit. However, Minikit may be easier to sell because of its high demand in the market. The decision to cultivate a certain variety of rice is however complex and depends on several other factors such as availability of seeds, time of transplanting, local conditions, local traditions, etc.

4.7 Cost, benefit, income and yield of other crops

Rice was the dominant crops in all sites under investigation. However, in the 2015-16 crop season, non-rice crops such as maize, wheat, potato, mustard, lentil, and few vegetables covered 27% of the total monitored area (13.05 ha) and 30% of the total number of plots (Figure 4.21). Of the non-rice crops, maize, wheat and potato were the dominant crops in the sites. Some of the crops were cultivated only in very few plots in some locations. But, in 2016-17 crop season, the selected sites, especially Mithapukur and Thakurgaon, had very few non-rice crops. One of the reasons of growing more rice is the sudden increase of the price of rice. Of the total 195 plots (24.6 ha) monitored, only 10 plots (1.53 ha) were under non-rice crops (4 in Mithapukur, 5 in Thakurgaon and 1 in Ishurdi). Seven of these 10 plots were under maize (0.955 ha), 2 under potato (0.445 ha) and the other under Okra (0.134 ha) in Ishurdi. For the analysis we did not consider the plot with Okra in Ishurdi.

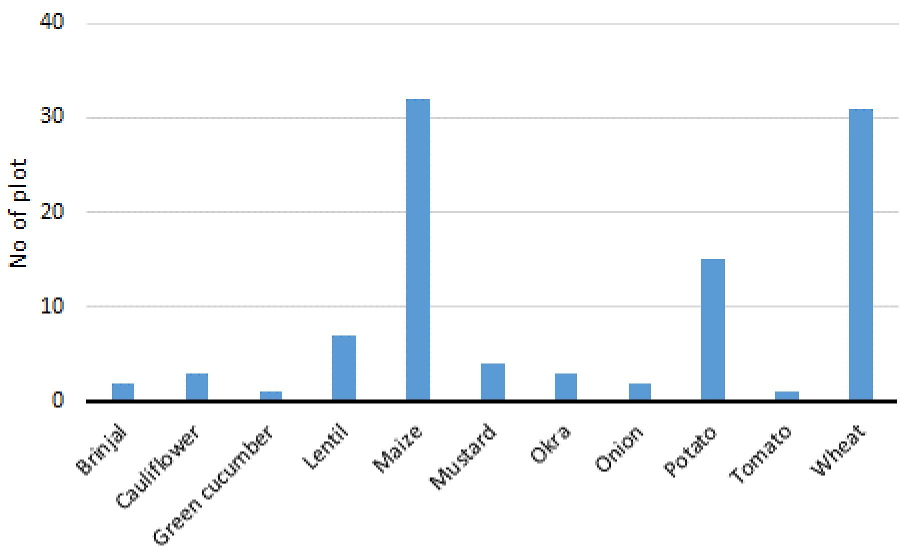

Figure 4.21 No of plots for non-rice crops across the sites in 2015-16

The average total paid-out costs (TPC) of production, gross benefit (GB) and gross income (GI) gained from cultivation of these crops are compared in Figure 4.22 for 2015-16. Figure 4.23 compares TPC, GB, and GI for rice, maize and potato for both 2015-16 and 2016-17. Of the four major crops (rice, maize, wheat, and potato), TPC, GB and GI were the highest for potato. Compared to rice, TPC, GB, and GI for potato were 59%, 128%, and 326% higher, respectively in 2015-16 and 6%, 46%, and 106% higher, respectively in 2016-17. Potato is the most profitable crop (106,837 Taka/ha in 2015-16 and 111,976 Taka/ha in 2016-17) with higher investment (much higher in 2015-16 compared to rice) followed by maize (57,957 Taka/ha in 2015-16 and 86,859 Taka/ha in 2016-17), rice (25,076 Taka/ha in 2015-16 and 54,254 Taka/ha in 2016-17) and wheat (1,511 Taka/ha). Growing potato was also reported more profitable than other crops during Rabi season by other investigators (Ahmed et al., 2009; Haque et al., 2012; Mukul et al., 2013). Uddin et al. (2010), Ferdausi et al. (2014), and Rahman et al. (2016) reported that maize crop is also profitable compared to other crops in the same season. The gross income was much higher for rice (216%) and maize (114%) in 2016-17 compared to that in 2015-16. The main reason for this is the higher price of rice. Wheat was affected by the severe blast disease in 2015-16. The average yield loss was 25-30 percent, but in severely infected fields, it reached up to 100 percent (Pandit et al., 2018; Malaker et al., 2016). So, the average yield (2.13 tonne/ha) was much below the yield generally achieved in this region (3.15 tonne/ha in 2014-15). The yield loss thus reduced the gross income.

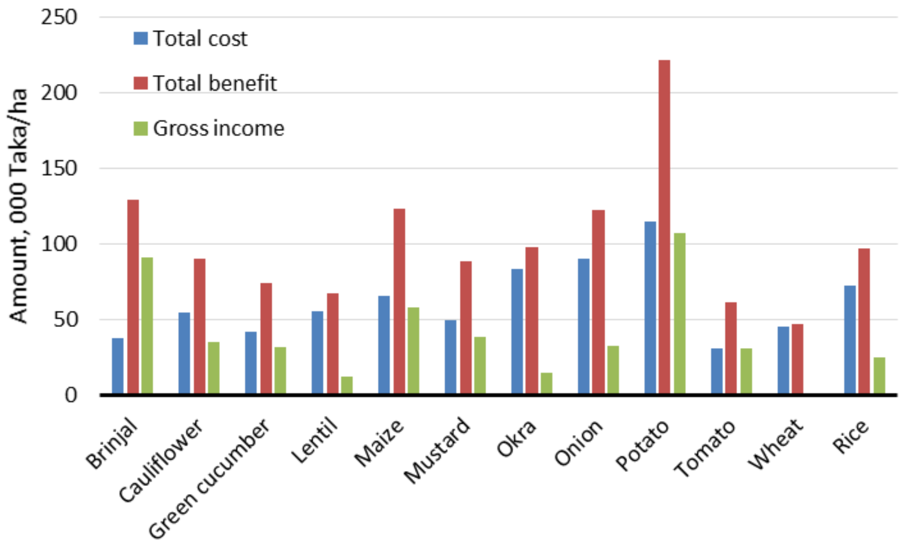

Figure 4.22 Comparison of total paid-out cost, gross benefit, gross income and yield of rice with other crops for 2015-16

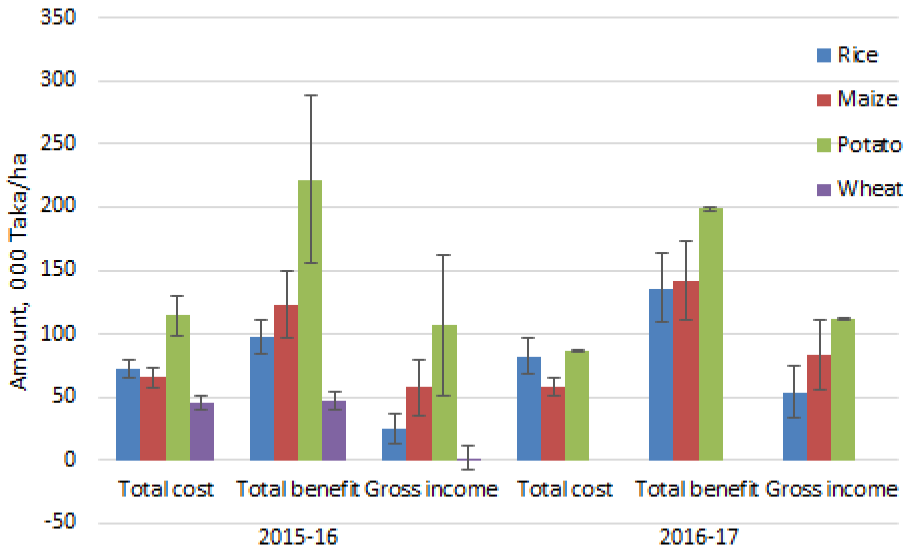

Figure 4.23 Total paid-out cost, total benefit and gross income of rice, maize, potato and wheat for 2015-16 and 2016-17

Potato is grown in Mithapukur, Sherpur and Tanore due to suitability of soil conditions at these locations. Apart from suitability of the soils, cultivation of potato also needs high initial investment, which could be beyond the reach of many farmers. For maize, the investment (cost of production) is lower than rice, but the gross income of maize is higher (2.31 times in 2015-16 and 1.54 times in 2016-17) than that of rice. This explains the phenomenal growth of maize cultivation in the region over the last decade (Figure 2.13).

Although potato has much higher gross income than rice and maize, the risk of growing potato may be higher. Figure 4.24 shows the probability distribution of gross income of rice, maize, wheat and potato for 2015-16. The slope of the curve indicates risk; the higher the slope the higher is the risk. There is a sharp fall in the gross income after about 50% probability of exceedance (i.e., for the 50% of the plots). There is high variation in the gross income of potato with a coefficient of variation, CV, of 52.2%. For rice and maize, CV was 46.6% and 37.8%, respectively.

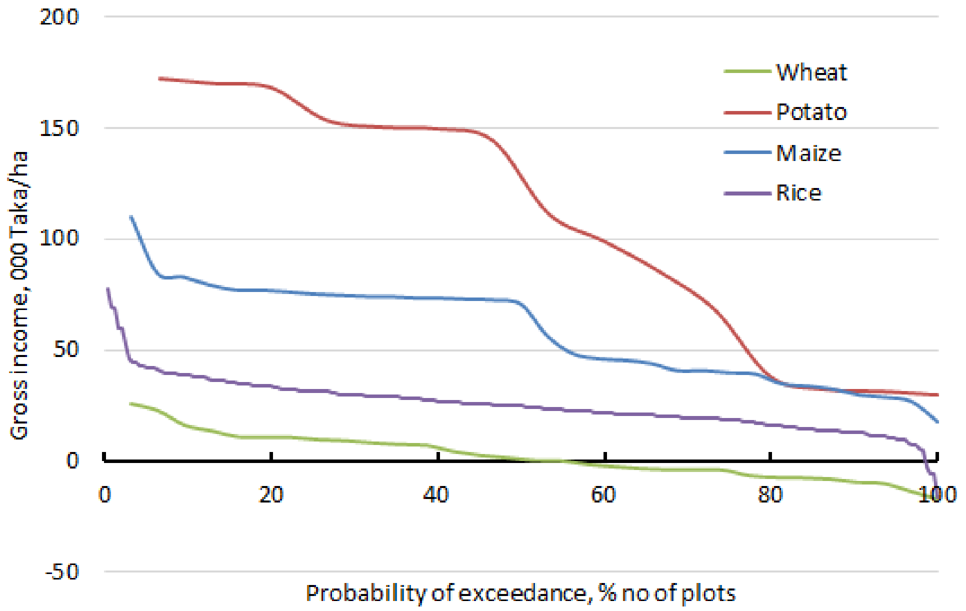

Figure 4.24 Probability distribution of the gross income of rice, maize, wheat, and potato for 2015-16

While there is a sharp decline in gross benefit of potato, the variation in yield is more gradual (Figure 4.25). The CV of yield for rice, maize, and potato was 18.1, 19.1 and 32.9%, respectively. So, considering the risk and gross income that can be obtained, cultivation of maize may be better (low risk and higher benefit). It should be noted here that the number of observations varied widely for the crops. Potato had the lowest number of plots (15 only), which also might have some impacts on the higher variation in yield and gross income. Wheat is the riskiest crop among the four major crops due to the severe disease infestation. In general, potato is a risky crop due to disease and rainfall damage in some years. But that was different in 2015-16 season. Of the 31 plots of wheat, only 17 plots (55%) managed to recover the cost of production. Although the variation in yield is low (CV = 18.8%), the variation in gross benefit is extremely high (CV = 454%).

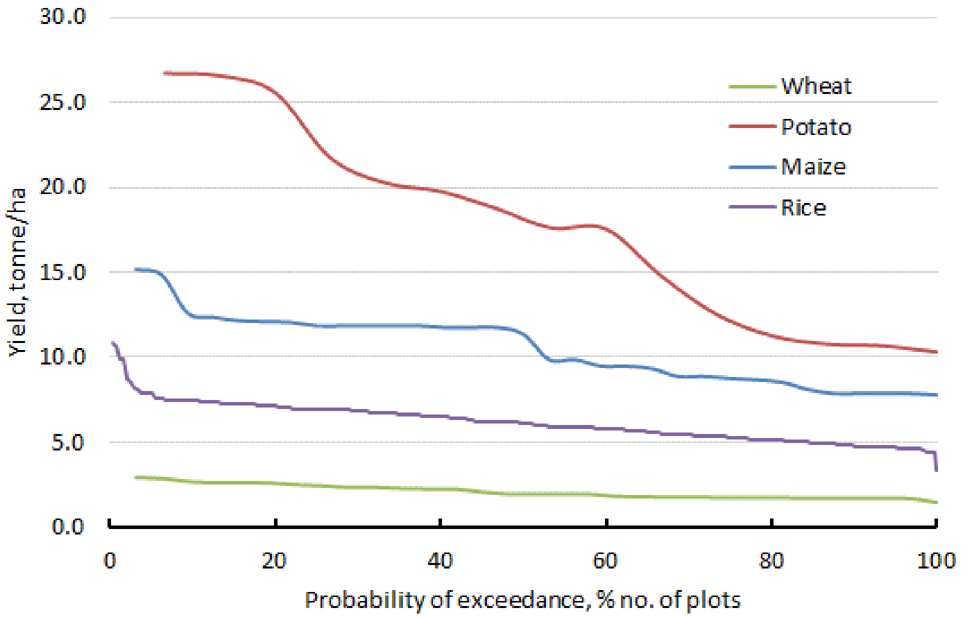

Figure 4.25 Probability distribution of the yield of rice, maize, wheat, and potato for 2015-16

In Ishurdi, only wheat, lentil, and okra were cultivated within the command area of STW-3 and STW-4 in 2015-16. Table 4.21 compares the statistics of total paid-out cost, gross benefit, gross-income, yield, water use and productivity of these crops with rice.

Table 4.20 Plot size and per hectare costs, returns, yield, water use, and productivity of wheat, lentil, and Okra cultivated at Ishurdi in 2015-16

Crop (no. of plots)	Statistical parameter	Plot size, ha	Total paid-out cost, Taka	Gross benefit, Taka	Gross income, Taka	BCR	Yield, tonne/ ha	Irrigation water use, mm	Economic water productivity Taka/m^3
Rice (50)	Maximum	0.668	86,254	114,825	37,516	1.49	7.,37	539	7.1
	Mean	0.188	79,532	102,981	23,449	1.30	6.55	502	4.7
	Minimum	0.049	68,653	74,100	5,447	1.08	4.76	472	1.1
	CV (%)	68	4	8	31	7	8	3	30
Lentil (7)	Maximum	0.267	60,603	79,040	24,322	1.44	0.79	0	
	Mean	0.135	55,048	67,185	12,137	1.22	0.67	0	
	Minimum	0.069	50,977	58,118	-582	0.99	0.58	0	
	CV (%)	55	6	15	89	16.0	15	0	
Wheat (18)	Maximum	0.202	56,483	63,034	13,794	1.28	2.96	207	18.6
	Mean	0.137	48,342	44,090	-4,252	0.92	1.91	110	-3.6
	Minimum	0.053	40,792	37,424	-16,813	0.70	1.50	67	-21.4
	CV (%)	43	8	14	-160	14	17	41	-219.6
Okra (3)	Maximum	0.150	91,280	102,614	33,927	1.49	16.42	173	22.2
	Mean	0.117	83,017	97,820	14,803	1.20	15.65	161	9.5
	Minimum	0.069	68,687	93,543	4,459	1.05	14.97	153	2.6
	CV (%)	36	15	5	112	21	5	7	115

Note: BCR = Benefit-Cost-Ratio, 'total paid out cost' is the actual cost of purchasing inputs, 'Gross benefit' is the market value of grain and straw yield at current price, and 'gross income' is the 'gross benefit' minus 'total paid-out cost'.

The average gross income per hectare for rice (23,449 Taka/ha) was almost double for that of okra (14,803 Taka/ha) and lentil (12,137 Taka/ha). The average gross income of wheat was negative (-4,252 Taka/ha), implying that the farmers lost money by cultivating wheat since the yield of wheat was low (<2.0 tonne/ha in 15 plots), mainly, because of sowing delay and blast injury. Out of 18 plots, only 4 plots produced positive gross income. It is noted that the attainable yield of the wheat varieties (BARI Gom -23 and BARI Gom - 24) ranges between 4.0 tonne/ha and 4.5 tonne/ha in the region (BARI, 2015). Besides, national average yield of wheat is 3.0 tonne/ha in 2015-2016 (BBS, 2016).

Like the gross income, irrigation water usage is also the highest for rice cultivation. The average irrigation water use for rice was 502 mm compared to 110 mm for wheat, and 161 mm for okra. Irrigation was not required for lentil. So, in spite of the highest gross income of rice the economic water productivity is the lowest. Average economic water productivity is much higher for okra (9.5 Taka/m^3) due to very low irrigation water use compared to rice (4.7 Taka/m^3).

Groundwater is the only source of irrigation in this region. In Chapter 2, we have discussed in detail about the declining groundwater level in the region. The government is now vigorously promoting growing non-rice crops to reduce pressure on groundwater. Growing non-rice crops such as wheat, lentil and okra will save groundwater in the aquifer. However, this will be at the expense of gross income for the farmers in this location. The risk of growing non-rice crops is also very high as evident in the coefficients of variation of the yields of these crops. The average CV of the yield of rice is only 8% compared to 15% for lentil and 17% for wheat.

4.8 Potential evapotranspiration of different crops

We estimated potential crop evapotranspiration (ETcrop) at 10-15 days interval after sowing/transplanting the crops in the field. Figure 4.26 shows the potential crop evapotranspiration of the different varieties of rice and other major crops transplanted (for rice) and sown (for other crops) at different periods for 2015-16 crop season. Figure 4.27 shows ETcrop of rice at different locations for 2016-17 season for the transplanting period of 20 December 2016 to 10 March 2017. As shown in Figures 4.26 and 4.27, ETcrop increases with delaying transplanting or sowing dates. This is mainly because of the increase in temperature with the progress of time. Boro rice and other Rabi crops start its journey in cooler and drier conditions and continue to grow up to their vegetative stages. Their flowering, ripening and harvesting stages are exposed to hot summer weather. ETcrop is the highest for BRRI dhan29 and Hybrid rice, which for 2015-16 crop season, varies from 359 to 545 mm across the locations and transplanting dates, with an average evapotranspiration of 448 mm due to their longer growth duration. The growth period of BRRI dhan29 and Hybrid rice was about 15 days longer than BRRI dhan28 and 20 days longer than other varieties of rice in the field. The average ETcrop for BRRI dhan28 and other rice varieties were estimated as 385 and 379 mm, respectively in 2015-16 (Figure 4.26). In 2016-17, ETcrop of BRRI dhan29 and Hybrid rice was 254 mm for transplanting on 20 December 2016 and 497 mm for transplanting on 10 March 2017. For BRRI dhan28 and Minikit, ETcrop was 208 and 424 mm, respectively. ETcrop was the highest in Ishurdi and lowest in Mithapukur. Of the non-rice crops, maize has the highest ETcrop, which varied from 276 to 528 mm across the locations and different sowing dates for 2015-16 crop season. The average ETcrop (393 mm) was almost equal to that of BRRI dhan28. The average ETcrop was estimated to be 241 and 222 mm for potato and wheat, respectively.

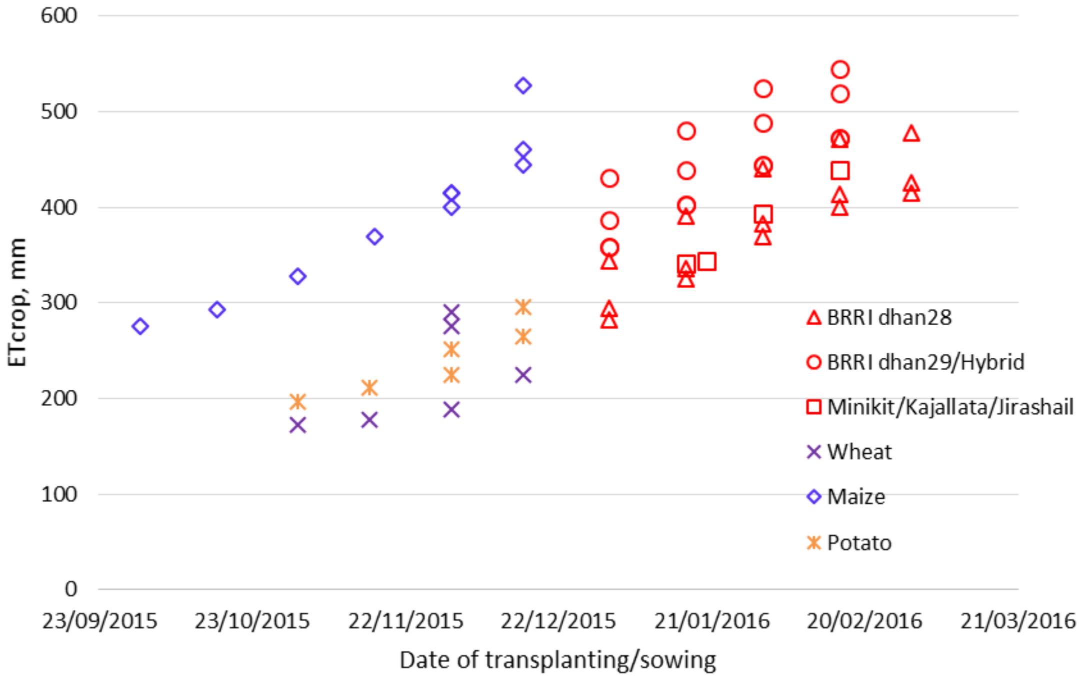

Figure 4.26 Potential crop evapotranspiration (ETcrop) of different crops for 2015-16 (same marker at vertical position shows the ETcrop for different locations)

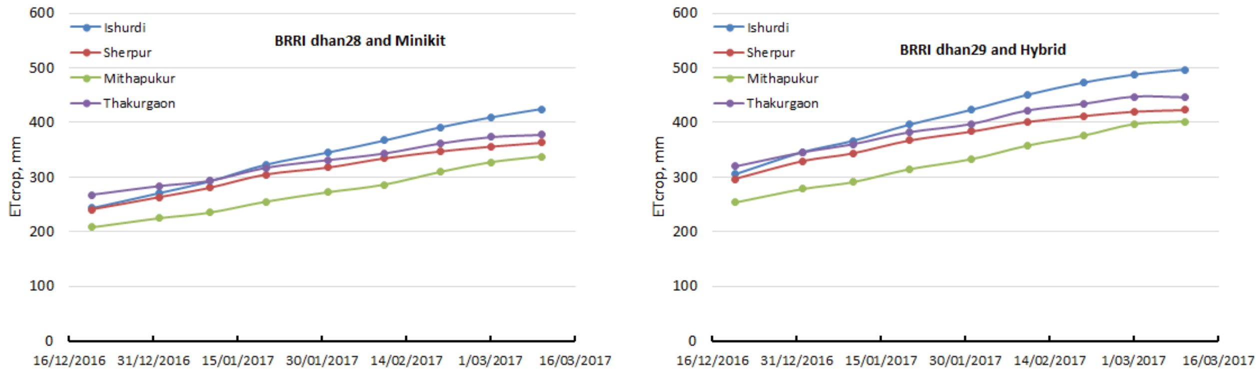

Figure 4.27 Potential crop evapotranspiration (ETcrop) of different rice varieties at different locations for 2016-17

4.9 Supplied versus estimated irrigation water requirements for rice

Irrigation water supplied to each plot was estimated by multiplying the pump capacity with the duration of pump operation. Farmers decide to irrigate their fields based on the field condition; usually they irrigate when there is no standing water in the field. Within the command area of a STW or DTW, there are many plots. So, sometimes the irrigation application is delayed. Sometimes farmers also take the opportunity to irrigate early if they find that the pump is free, anticipating that they may have to wait for irrigating later. Figure 4.28 shows the scatter plot of irrigation water supplied to the rice fields at different locations. Among the sites, water supply was higher in Mithapukur (890 to 1,601 mm) and lower in Ishurdi (472 to 539 mm) in 2015-16. For the Kaharol, Sherpur, Tanore and Thakurgaon sites, water supply varied from 563 to 871 mm, 615 to 802 mm, 768 to 958 mm, and 889 to 1052 mm, respectively. In 2016-17, water supply was higher in the plots in Ishurdi (565 to 965 mm) and lower in Sherpur (460 to 625 mm) (Figure 4.28). The variation in water supply to the plots for different sites was much less in 2016-17 (395 to 965 mm, CV = 16.6%) compared to 2015-16 (472 to 1601 mm, CV = 33.2%).

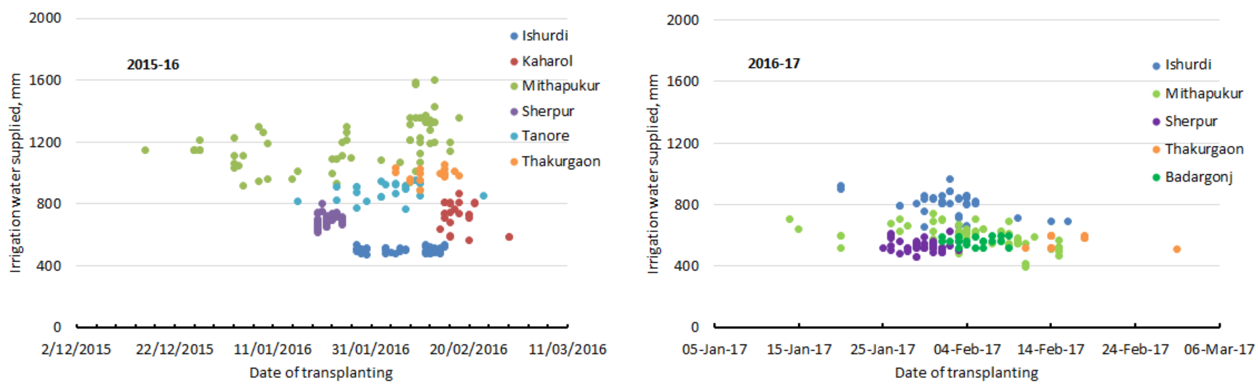

Figure 4.28 Scatter plot of irrigation water supplied to the plots at different sites in 2015-16 and 2016-17 crop seasons

Irrigation water requirement of rice varies due to its geographical locations, climate variations, soil properties, rice varieties, and time of transplanting. To compare the irrigation water supply with the requirements for full yield potential, we estimated irrigation water requirements for rice at different planting dates for all sites using the Soil Water Balance, SWB, model described in Section 3.4. In estimating the irrigation requirements, we considered the transplanting date at regular interval within the transplanting period for the sites. Figures 4.29 and 4.30 show the scatter plots of actual water supplied to the plots with the estimated requirements for different locations for 2015-16 and 2016-17, respectively. Figure 4.31 compares the average (average of the plots) water supplied and the requirements, and Figure 4.32 shows the percentage of undersupply or oversupply compared to the estimated requirements.

In 2015-16 season, actual water supply was less in all plots compared to the estimated requirements in Ishurdi (-23%). In Sherpur and Kaharol, actual supply was very close (-2%) to the estimated requirements; in some plots water supply was slightly higher and, in the others, actual supply was slightly lower. In the other three sites (Mithapukur, Thakurgaon, and Tanore), the actual water supply was considerably higher (60%, 37%, and 36%, respectively) in all plots compared to the estimated requirements (Figure 4.29). In 2016-17 season, the actual water supply was fairly close to the estimated requirements in Mithapukur (7%), Sherpur (4%) and Badarganj (3%) (Figures 4.30-4.32). The water supply was higher in Ishurdi (36%) and Thakurgaon (57%) than in the other sites.

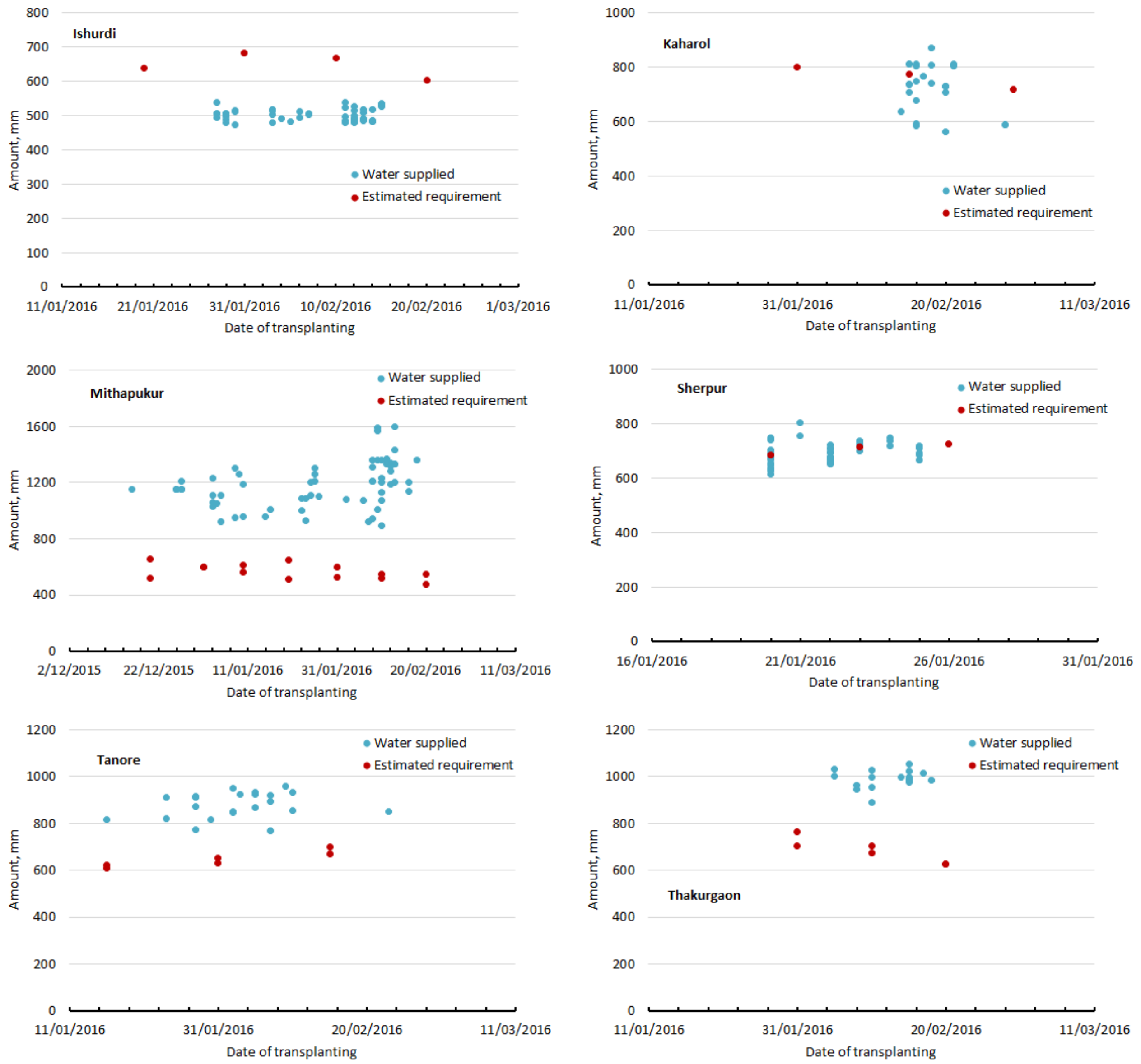

Figure 4.29 Comparison of irrigation water requirements with actual water supplied to the plots for rice at different locations for 2015-16

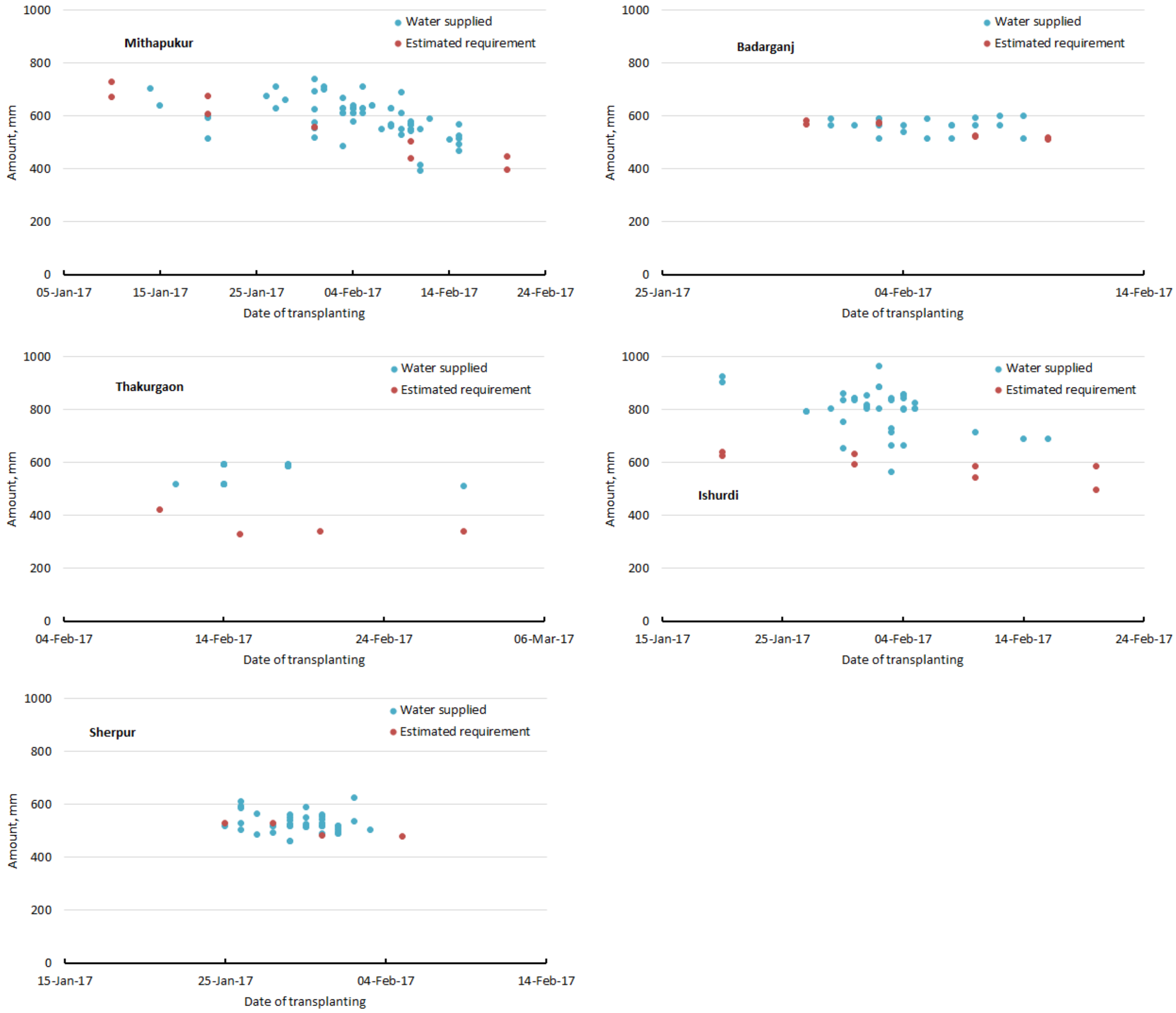

Figure 4.30 Comparison of irrigation water requirements with actual water supplied to the plots for rice at different locations for 2016-17

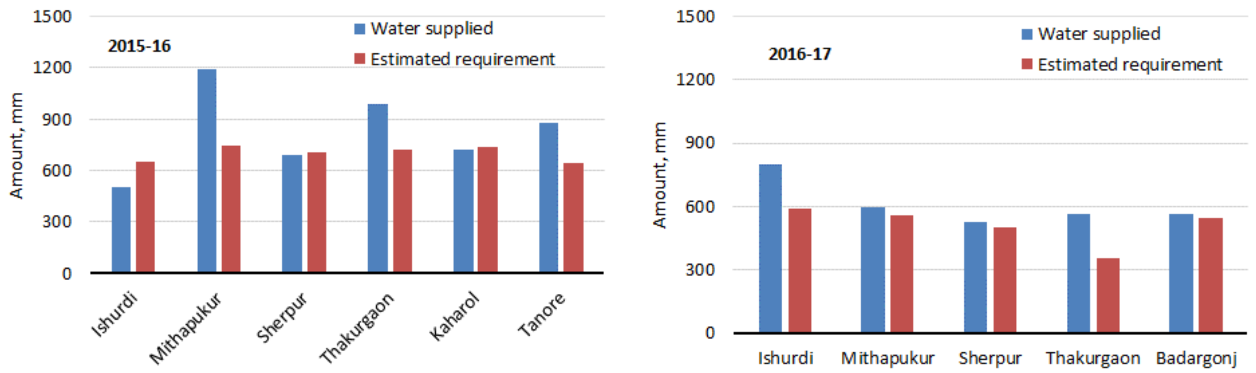

Figure 4.31 Comparison of the average irrigation water supplied and requirements for rice at different locations for 2015-16 and 2016-17

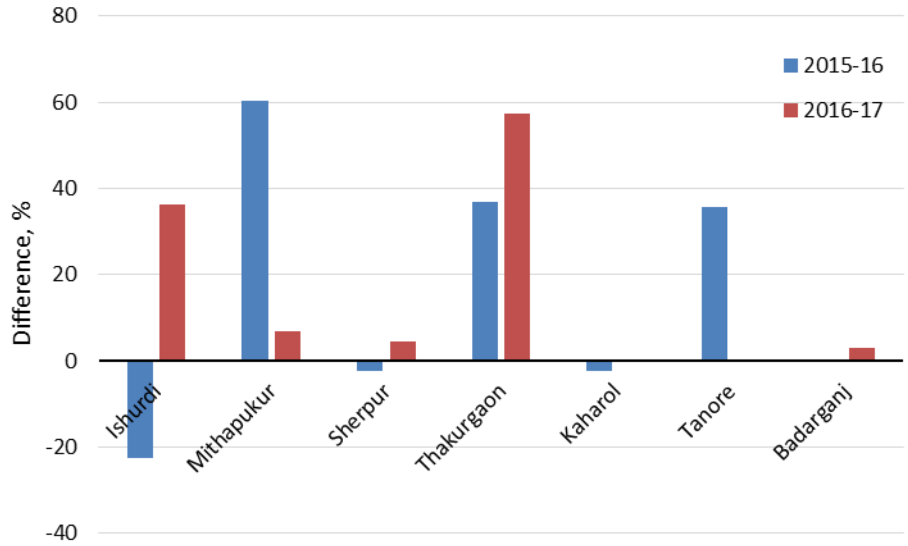

Figure 4.32 Difference between water supply and estimated requirements as percentage of the requirements

In Ishurdi, one of the STWs (STW-1) used a centrifugal pump operated by electric motor in 2015-16. Due to decline in groundwater level (Figure 4.33), it was difficult to pump water with full capacity of the pump. There was a long idle period for the pump as well. So, the pumping of water was constrained that could be one of the reasons of lower than required water supply in this area in 2015-16. In 2016-17 crop season, the owner of the pump replaced the centrifugal pump with a submersible pump, installed deeper into the ground. So, there was no constraint of pumping water, and the pump might have contributed to the higher supply of water in the field in 2016-17.

In all locations, we promoted alternative wetting and drying (AWD) method of irrigation in the field and distributed the AWD kit to some farmers in all sites in 2016-17 crop season (see the companion report of Maniruzzaman et al., 2019). Due to higher supply of water in the fields of Thakurgaon and Mithapukur in 2015-16, we actively promoted to the farmers the AWD method of irrigation or to supply less water in the field. We conducted three demonstrations of AWD method in Thakurgaon and 5 in Mithapukur where we have actively monitored the water supply (Maniruzzaman et al., 2019). Apart from that, there were three farmers in Thakurgaon, five farmers in Mithapukur, and four farmers in each of Ishurdi and Sherpur, who used the AWD method for irrigation in their plots. This awareness might have helped, to some extent, for significant reduction in water use in 2016-17 (11% oversupply) compared to water use in 2015-16 (67% oversupply). However, this was not the case in Thakurgaon. Water supply was 37% higher over the estimated requirements in 20156-16 and 57% higher 2016-17. Thakurgaon is dominated with DTWs and there is no problem of pumping water. The farmers can independently operate the pump using pre-paid card. The cost of irrigation is significantly lower for the DTW compared to that for the STW. So, there is a tendency of the farmers to supply more water in the fields. As we found in the two crop seasons, farmers oversupplied water in the field in Thakurgaon (DTW site). This is also true (36% oversupply) for another DTW site at Tanore for the 2015-16 season.

In both seasons, water supply was very close to the estimated requirements (within -2 to 4% of the requirements, Figure 4.32) at Sherpur. Among the STW sites, the highest decline in groundwater level was in Sherpur (Figure 4.33). The water level declined to 8.2 meter in 2015-16 and 8.7 meter in 2016-17 at the beginning of April; these groundwater levels were very close but out of the range of the suction limit (Maniruzzaman et al., 2019). To capture the suction limit of the STWs, all tubewell owners lowered their pumps about 1 meter below the ground surface. However, the capacity of the pumps in pumping water decreased. The farmers are aware of this condition, and they very wisely apply water. That could be the main reason of highly efficient water supply to the plots of Sherpur in both seasons. In Badarganj, water is supplied by commercial provider using solar energy. Qualified agriculture and irrigation management professionals oversee the management of the solar scheme and water distribution, which may be a significant contributing factor for very small difference (3%) in actual water supply and the requirements.

In estimating the irrigation requirements, we considered the average conveyance losses for different sites based on the information available from the literature. Syed et al. (2014) studied the conveyance losses in STW irrigation schemes during Boro season of 2010-11 at Mithapukur. They found the average conveyance losses of 45% in the existing earthen canals and 24% in the improved earthen canals. We considered 24% as losses instead of 45%. For all sites, we used conservative values of conveyance losses. The actual losses could be higher that is likely to have some impact in the difference between the estimated requirements and the actual water supplied. We have also used single value of seepage and percolation for all plots within a site. In reality, there is likely to have some difference due to the variation in soil condition, condition of the bund, and location of the plots. Nonetheless, in general, following inference can be made from the comparison of water supply with the estimated requirements for the sites in two seasons.

- DTW-irrigated area has significant oversupply due to low cost of water.
- The supply of water is very reasonable in STW-irrigated area due to higher cost of water than DTW and declining groundwater level.
- In STW area, farmers are prudent in supplying water in the field.

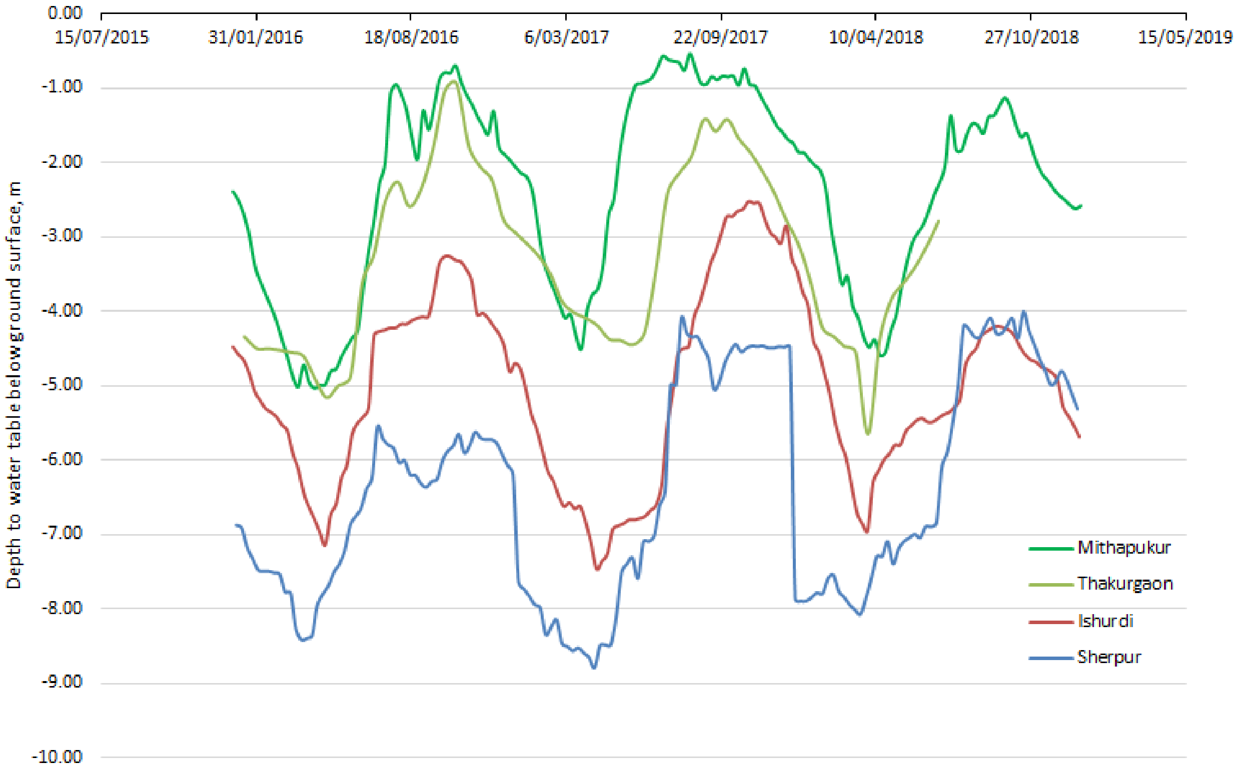

Figure 4.33 Observed groundwater levels in the selected sties

There is a general perception with the researchers and policy makers that farmers waste water by applying too much water (Rahman, 2018; Hoque, 2018) in the field than is required. The results of this study do not support that perception, at least for the STW areas. For the STW-irrigated areas, the results suggest that farmers are very careful and wise in applying water in their fields. There is some over-application of water in the DTW areas. However, the scale of this over application is not as big as the general perception.

Reverse water productivity (amount of water needed to produce 1 kg of paddy) is a popular term to indicate water consumption for rice production. This is just reciprocal of the water productivity expressed in litres instead of m^3. Figure 4.34 shows the reverse water productivity or irrigation water supplied to the plot to produce one kilogram of rice for all the plots for the crop season of 2015-16 and 2016-17. Irrigation water supplied varied from 670 to 2,683 lit/kg in 2015-16 and from 701 to 1,593 lit/kg in 2016-17. The average for all the plots was 1,086 lit/kg and 1,402 lit/kg for 2015-16 and 2016-17 season, respectively. In 2015-16, water supply was higher (29%) than in 2016-17. Out of 235 plots of 2015-16, only 2 plots used water more than 2,500 lit/kg (0.85%) and 17 plots (7.23%) used water more than 2,000 lit/kg. In 2016-17, only one plot used water more than 1,500 lit/kg. In the closely monitored plot with AWD and farmers' practice (Maniruzzaman et al., 2019), the maximum water needed to produce one kilogram of rice under farmers' practice and AWD was 1,836 lit and 1,689 lit, respectively. The minimum was 911 and 780 litres/kg under farmers' practice and AWD, respectively. The average amount of water needed to produce one kilogram of rice under farmers' practice and AWD was 1,475 and 1,293 litres, respectively. So, the general perception of overuse of water to the extent of 3,000 to 5,000 lit to produce one kilogram of rice (Reddy et al., 2014; Tuong, 2008) is nowhere near the reality in the field. As discussed earlier, due to high price of water, reduced availability of water, and experience of the farmers, farmers are very wise in supplying water to the fields. Over the years, yield of rice has increased linearly (Figure 2.15, also see Mainuddin et al. 2014) while the actual water supply may have been reduced; this is also a contributing factor in the lower water use for producing unit weight of rice.

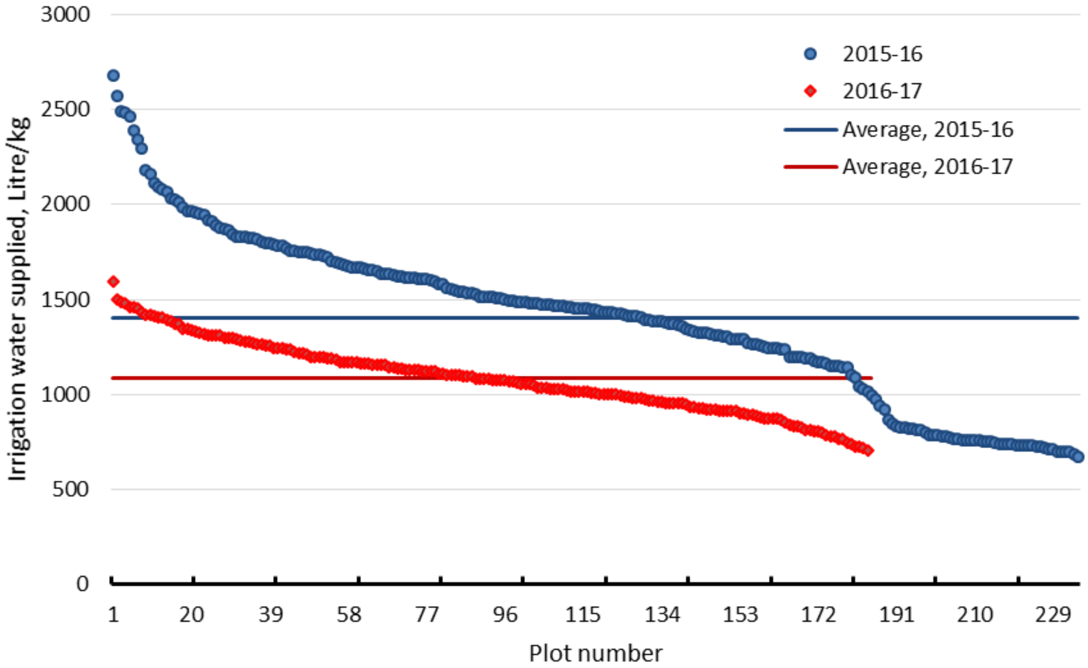

Figure 4.34 Irrigation water supplied to grow one kilogram of rice

Not all water supplied to the rice field is consumed by the plants. Evapotranspiration is the real loss from the field. Seepage from one field goes to the others and used by the plants. Rice fields are contiguous, separated by narrow and low-height bund, to each other in a huge area. So, at the single plot level, seepage in and out of the field balances each other. Only the plots at the edges of the whole area (usually the area is bounded by roads, there are also some ditches along the roads) may lose some water to the adjacent ditches (where sometimes they are reused) or used by the plants and trees along the roads.

Percolation from the rice field is not really consumed by the plants and is not lost from this system. This goes back to the aquifer as recharge. Irrigation water is extracted from the aquifer below the field in the northwest region in the dry season. Consequently, groundwater level goes down, creates space for recharge during the monsoon months. Percolation from the rice field recharges the aquifer in the dry season. The withdrawal of water is more than the recharge to the aquifer by percolation. So, percolation is not visible in the water level hydrographs. Without that recharge, water level would have dropped further below than is observed now. Percolation could be loss from the system if water is pumped from the other sources (such as rivers) for irrigation in an area where groundwater is not used due to some limitations (such as unsuitable water, saline aquifer, extraction of water not economically viable). This is not the case in the groundwater irrigation system of the northwest region or in the whole Eastern Gangetic Plain.

Actual water used to produce rice is the actual evapotranspiration during the cropping period. Figure 4.35 shows the actual water (ET) used to produce one kilogram of rice for all the plots. This was done by dividing the yield with the actual evapotranspiration estimated using the SWB model. The average actual water (ET) used was 661 lit/kg and 584 lit/kg, respectively for 2015-16 and 2016-17 crop seasons. These results clearly indicate that the perception of actual water use (actual crop evapotranspiration) or water supplied to the field to grow one kilogram of rice is far larger from the reality in the field.

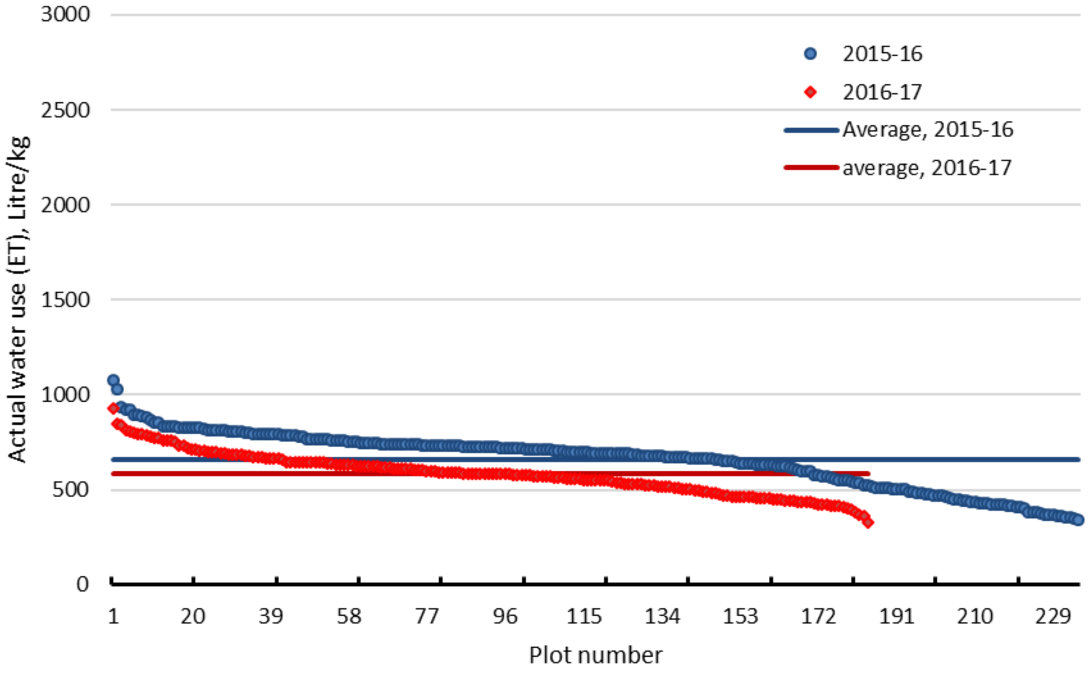

Figure 4.35 Actual water used to grow one kilogram of rice

4.10 Irrigation water requirements and usage for other crops

For the crops other than rice grown in the areas under investigation, the estimated irrigation water requirements, in general, were higher than actual irrigation water supplied to the fields (Figure 4.36). In estimating the irrigation requirements, the capillary rise of groundwater was not considered that usually contributes to plant-water uptake by the non-rice crops. Some of the monitored plots were adjacent to the rice fields from which water seeped to the non-rice fields (as there was no standing water in those fields), requiring less water for irrigation. Pricing of water for non-rice crops is different from the rice crop. Unlike rice where pricing is mainly based on area and supply of irrigation water for the whole growing season, the pricing for non-rice crops is usually based on per irrigation or time of pump operation. It is likely that due to these factors, actual supply of irrigation water in the field was less than the estimated requirements.

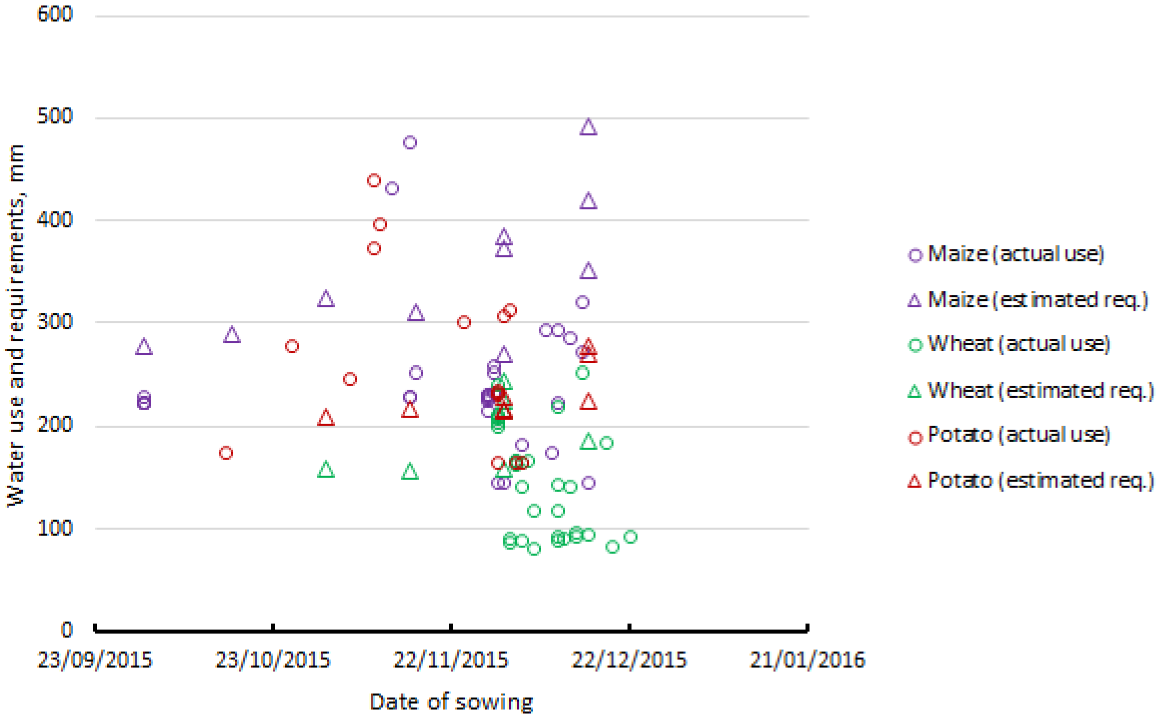

Figure 4.36 Comparison of irrigation water requirements with actual water used for non-rice crops

4.11 Real price of irrigation water

Different water pricing methods, currently being used in the monitored area, were discussed in section 3.3. None of these pricing methods are based on actual volume of water. Using the amount of irrigation water supplied to the plots under investigation, we estimated the real cost of irrigation water based on its volume. Figure 4.37 shows the estimated average cost of irrigation water for different locations, varieties, and pump types. Among the locations, the cost of irrigation water was the highest (>4.00 Taka/m^3) in Ishurdi in both 2015-16 and 2016-17 crop seasons. The lowest cost was at Thakurgaon (1.00 Taka/m^3). As discussed earlier, water pricing is based on crop-sharing in Ishurdi that makes the water costliest in this location. Thakurgaon is a DTW-irrigated site where water price is fixed at 110 Taka/hour operation of the DTW. The water from DTWs is the cheapest among the different pump types.

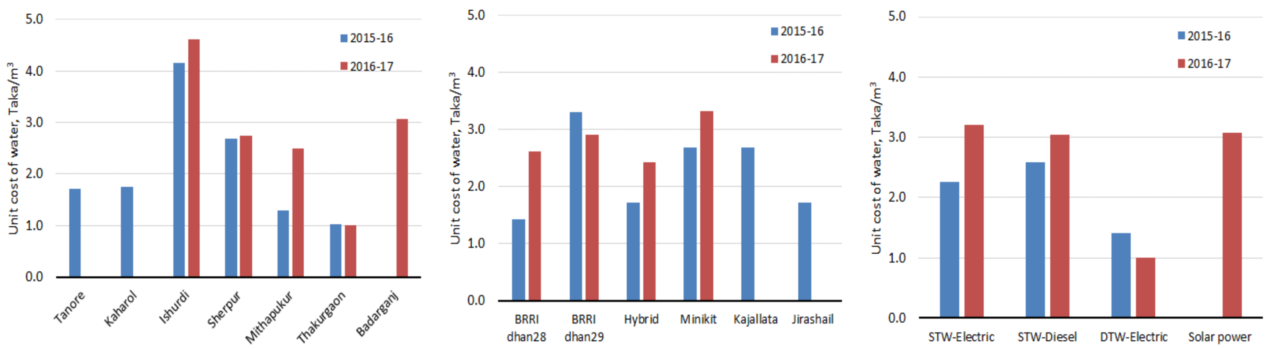

Figure 4.37 Real cost of irrigation water for rice by location, varieties, and type of tubewells

4.12 Water productivity

Water productivity analysis combines physical accounting of water with crop yield or economic output to give an indication of how much value is being obtained from the use of water (Molden, 1997). Cook et al. (2006) discussed methods of estimating water productivity at a range of scales, and for different agricultural systems. In general, three different types of crop-water productivity that can be distinguished (Cook et al., 2006; Immerzeel et al., 2008; Abdullaev and Molden, 2004) are:

(i) physical water productivity (PWP, kg/m^3) defined as the mass of product per unit of consumed water,

(ii) economic water productivity (EWP, value in currency/m^3) defined as standardized gross or net value of product, or net benefit per unit of water consumed, and

(iii) non-economic (e.g., social or environmental) water productivity (value in currency/m^3) defined as the net social benefits per unit of water consumed, which are difficult to valuate.

In this study, we estimated physical water productivity, PWP, as the crop yield per unit of water supplied to the field and as the crop yield per unit of water consumed (ET). Economic water productivity was calculated by dividing the gross income ('gross benefit' minus 'total paid-out cost') by the water supplied to the field. The physical water productivity depends on rice yield, water used and ET. The yield and water usage varied from variety to variety, climatic conditions, and soil properties. The physical water productivity of rice based on irrigation water supplied to the fields varied from 0.37 kg/m^3 to 1.47 kg/m^3 for all the plots during 2015-16 season (Figure 4.38). In 2016-17 crop season, this water productivity varied from 0 to 1.43 kg/m^3. One plot of Sherpur was completely damaged and there was no yield. So, the productivity of this plot was nil (0).

The average (average of all plots) physical water productivity based on actual ET (denoted as WP_{ET}) was 1.60 kg/m^3 and 1.77 kg/m^3 in 2015-16 and 2016-17, respectively (Figure 4.38). The highest WP_{ET} was 2.92 kg/m^3 and 3.03 kg/m^3 in 2015-16 and 2016-17, respectively. Zwart and Bastiaanssen (2004) provided a range of globally-measured WP_{ET} values based on the review of 84 literature sources, with results not older than 25 years. They reported average WP_{ET} values for rice as 0.60–1.6 kg/m^3. Tuong and Bouman (2003) provided a very similar range of 0.4–1.6 kg/m^3 for lowland rice conditions. In this study, the average WP_{ET} is higher than that reported by Zwart and Bastiaanssen (2004) and Tuong and Bouman (2003). The observed maximum WP_{ET} was much higher than that reported by Zwart and Bastiaanssen (2004) and Tuong and Bouman (2003). The main reason of this difference is the higher yield or Boro rice in Bangladesh.

The economic water productivity, EWP, varied from -1.40 to 7.14 Taka/m^3 in 2015-16 and -15.07 to 14.84 Taka/m^3 in 2016-17 (Figure 4.39). Due to higher price of rice in 2015-16 and lower use of irrigation water, the economic productivity was significantly higher in 2016-17.

Figures 4.40 to 4.43 show the physical and economic water productivities of rice by locations, varieties, and type of tubewells. In 2015-16, the highest water productivity based on irrigation water was in Ishurdi due to higher rice yield, and lower water use, and the lowest water productivity was in Mithapukur due to lower yield and high amount of irrigation water used. In 2016-17, the highest water productivity was in Thakurgaon and the lowest was in Sherpur. Among the rice varieties, the physical water productivity, based on irrigation water, was the highest for BRRI dhan29 in 2015-16. In 2016-17, the highest water productivity was surprisingly for Minikit. The reason for this is relatively higher yield and lower irrigation water use. There are significant variations in water productivity among the locations, varieties and type of tubewells. These variations are due to the variations in yield and irrigation water supplied to the fields. Unlike productivity of irrigation water, the ET-based water productivity, WP_{ET}, was the highest in Mithapukur in 2015-16 and in Badarganj in 2016-17. BRRI dhan28 and Hybrid rice had the highest WP_{ET} in 2015-16 and 2016-17, respectively.

Among the type of tubewells, there were significant differences in economic water productivity for DTWs for 2015-16 and 2016-17 crop seasons. For the STWs, there was no significant variation in this water productivity from year to year. The economic water productivity, in general, follows the pattern of physical water productivity for the locations, varieties and type of tubewells (Figure 4.41). This water productivity was significantly higher in 2016-17 than in 2015-16 crop seasons.

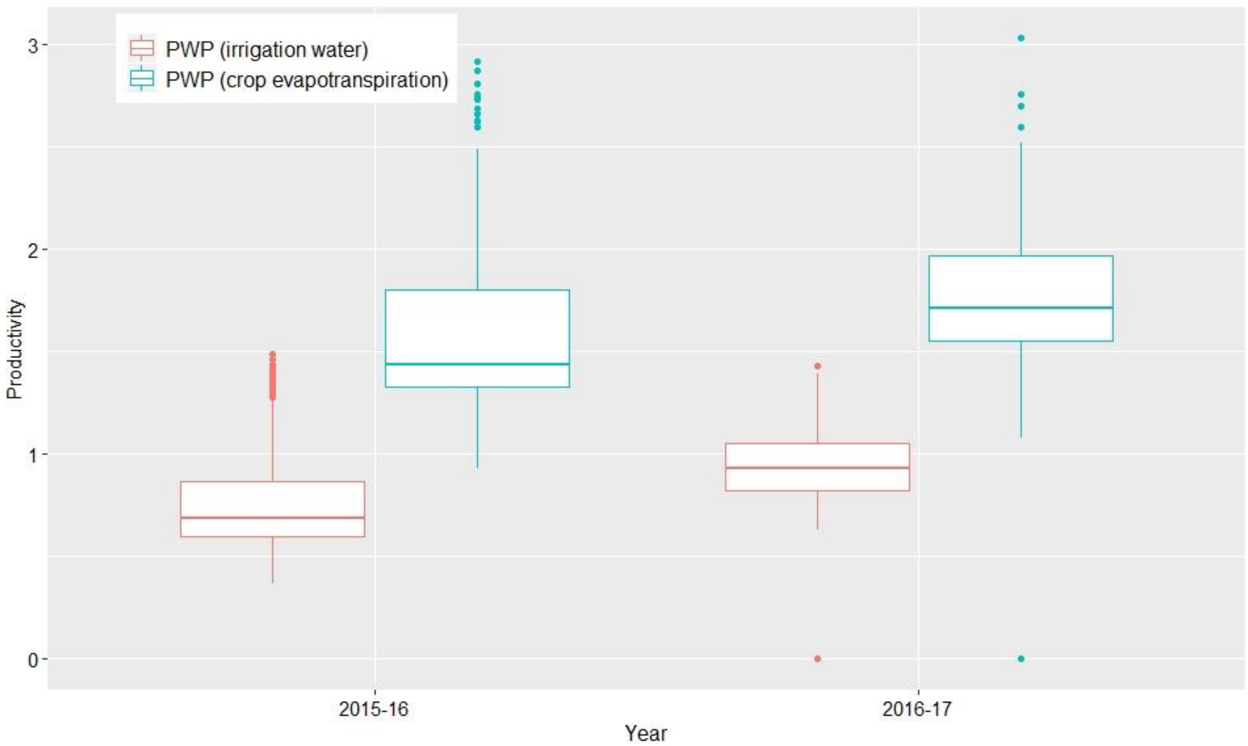

Figure 4.38 Physical water productivity (PWP) of rice

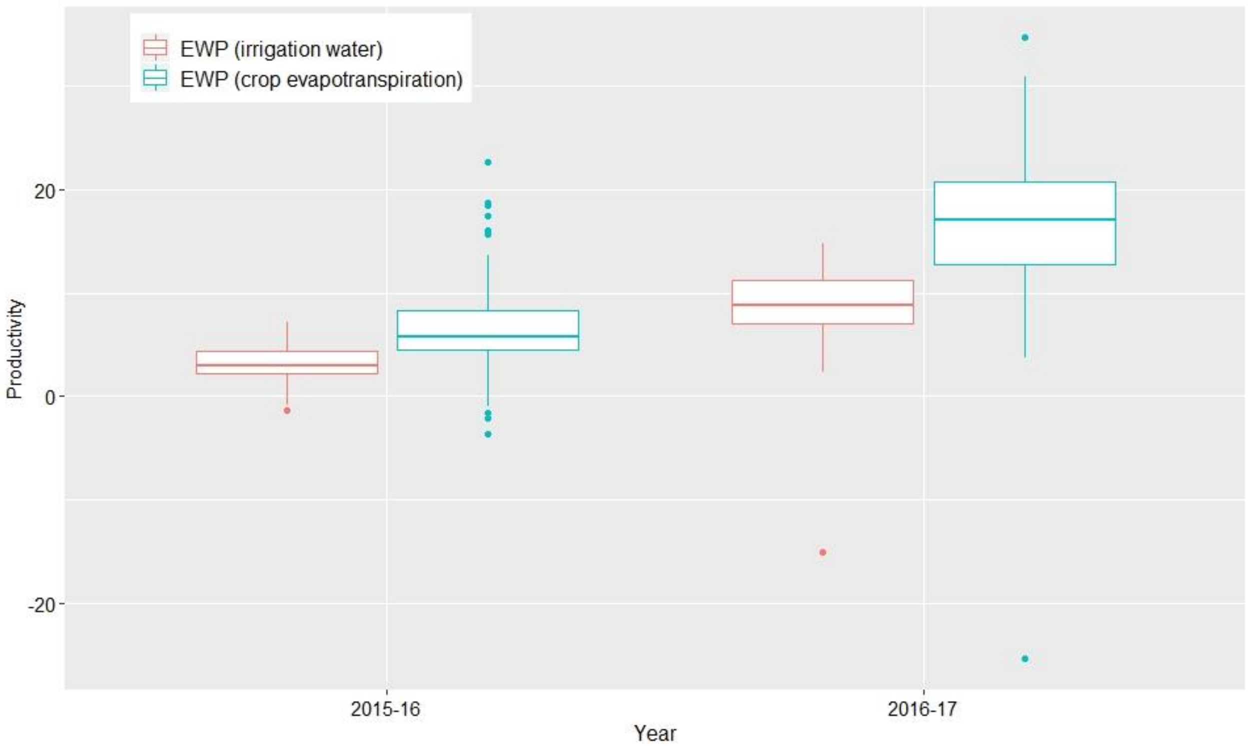

Figure 4.39 Economic water productivity (EWP) of rice

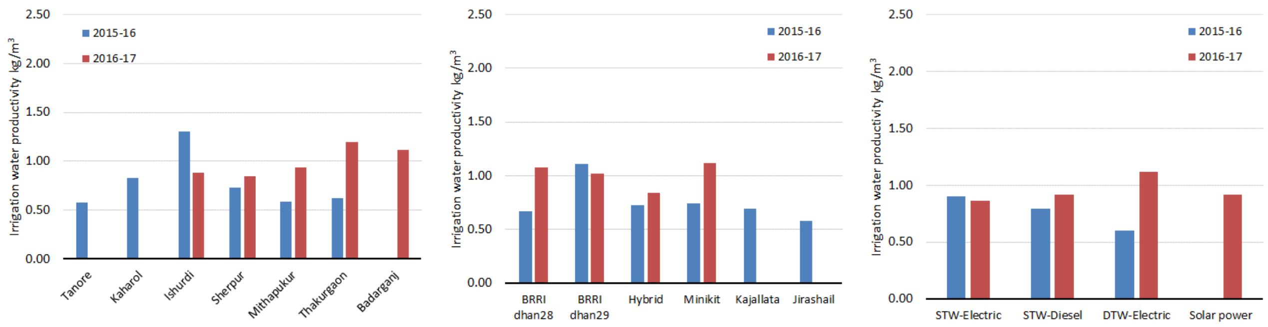

Figure 4.40 Physical water productivity of rice in terms of irrigation water supplied by location, rice varieties, and type of tubewells

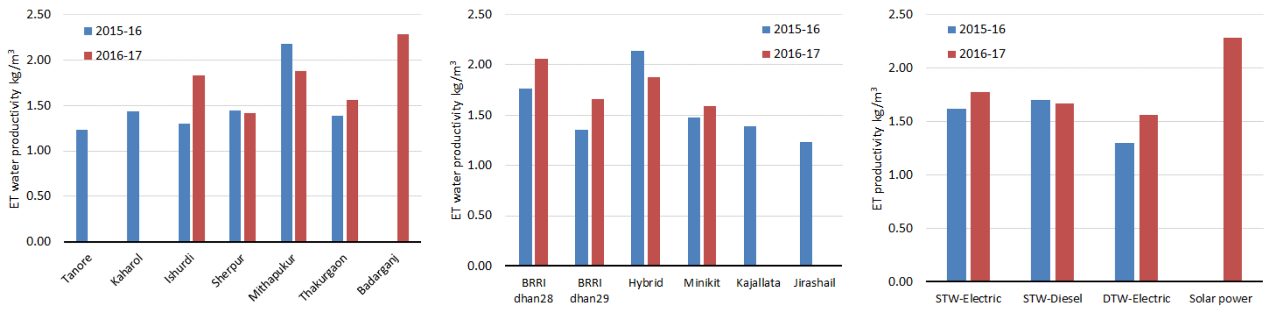

Figure 4.41 Physical water productivity of rice based on ET (WP_{ET}) by location, rice varieties, and type of tubewells

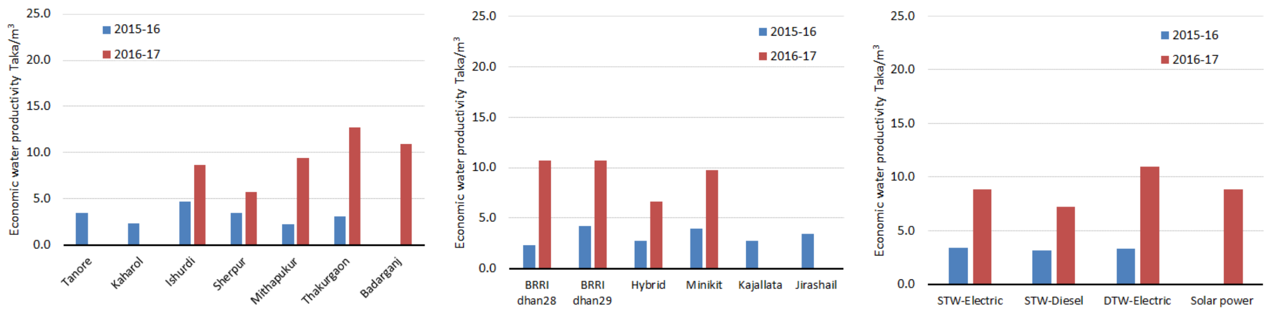

Figure 4.42 Economic water productivity of rice in terms of irrigation water supplied by location, rice varieties, and type of tubewells

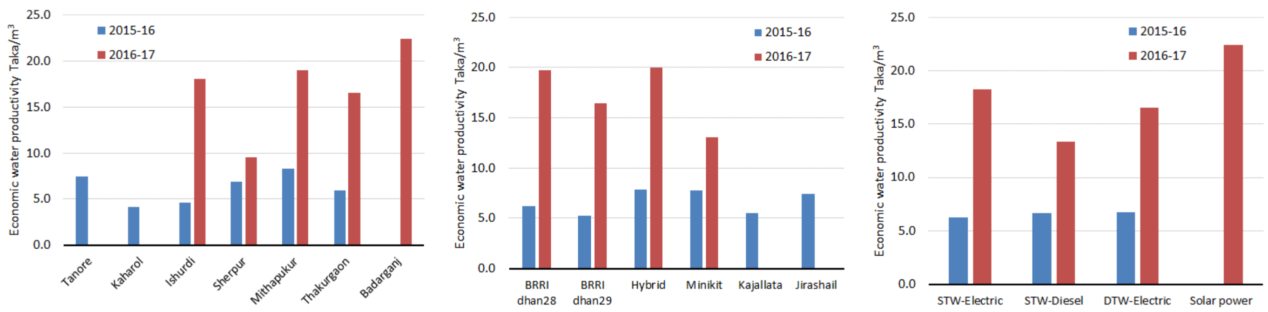

Figure 4.43 Economic water productivity of rice based on ET by location, rice varieties, and type of tubewells

Within the command area of the tubewells in Ishurdi, the physical water productivity based on irrigation water in 2015-16 varied from 0.88 kg/m^3 for the area under STW-2 to 1.00 kg/m^3 for the plots with Hybrid rice under STW-3 (Figure 4.44). The difference in water productivity between the Hybrid rice under STW-3 (1.00 kg/m^3) and BRRI dhan29 under STW-1 (0.97 kg/m^3, with same number of plots) is insignificant. The variation in physical productivity was mainly due to the variation in yield. The variation in irrigation water use is very small, ranging from 472 mm to 539 mm. So, the variation in economic water productivity (Figure

4.44) is like that of gross income (Figure 4.10). Although the physical water productivity was that highest for the plots with Hybrid rice under STW-3, the economic water productivity was the highest for the plots with BRRI dhan29 under STW-1 (4.52 Taka/m^3), which is 20% higher than that of Hybrid rice under STW-3. The reason for this is the higher cost of cultivation of Hybrid rice.

In 2016-17, BRRI dhan29 and Minikit were grown in this location. The average physical water productivity of BRRI dhan29 was 0.93 kg/m^3, with a range of 0.79 to 1.286 kg/m^3. For Minikit, the average productivity was 0.84 kg/m^3, with a range of 0.699 to 1.086 kg/m^3. The average economic water productivity was 8.37 and 8.87 Taka/m^3 for BRRI dhan29 and Minikit, respectively.

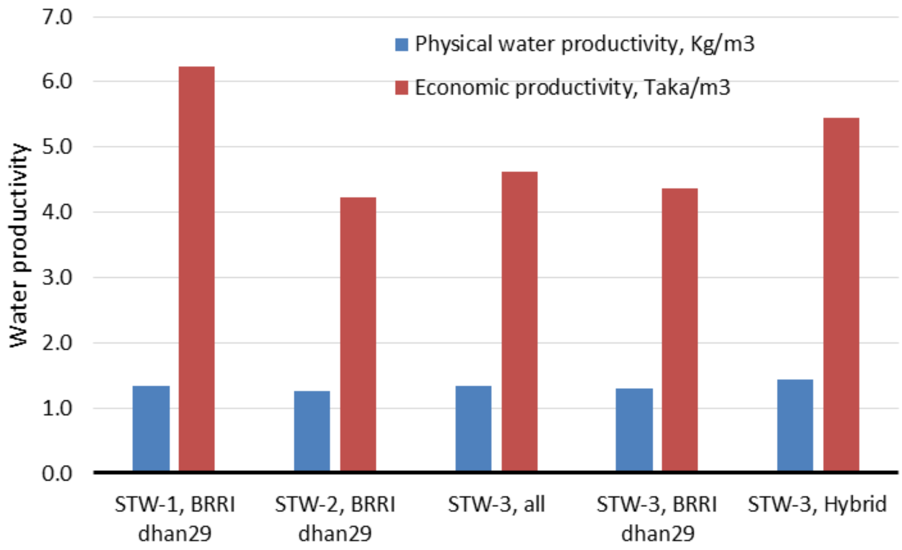

Figure 4.44 Physical water productivity of rice under STWs at Ishurdi

Figure 4.45 compares the economic water productivity of rice, maize, potato and wheat (4 major crops grown in the northwest region) for 2015-16 and 2016-17 crop seasons. The economic water productivity of rice (3 and 9 Taka/m^3, respectively for 2015-16 and 2016-17) was significantly lower than that of maize (41 and 39 Taka/m^3) and potato (40 and 102 Taka/m^3). In 2016-17, the economic water productivity of potato was several folds higher than that in 2015-16 due to higher production, higher price and less amount of water used. Wheat had the lowest economic water productivity.

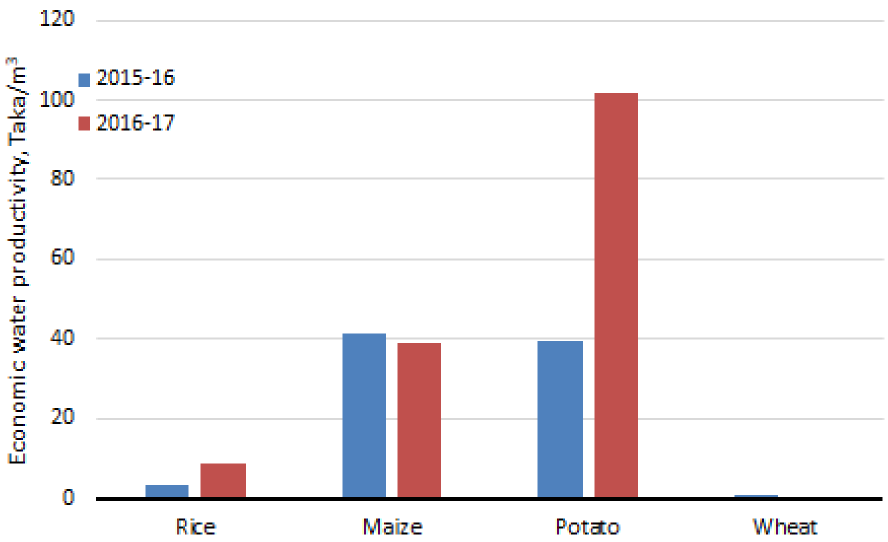

Figure 4.45 Comparison of economic water productivity of rice, maize, potato and wheat for the northwest region

4.13 Farmers’ perceptions about technologies and management

Farmers’ group discussion (FGD) was conducted with key informant farmers (KIF) to delineate their perceptions about potential and existing technologies, management and purpose of adopting different rice cultivars. An FGD was conducted with 12-15 KIF in each trial village of Mithapukur and Badargonj Sub-Districts in Rangpur District and Sadar Sub-District in Thakurgaon Distract.

4.13.1 Drivers of adoption of rice cultivars

Mithapukur: Farmers in group discussion told that BRRI dhan28 being a medium slender grain with higher amylase and tested good to eat is the main driver of its adoption. They told that over the last 2-3 years, adoption of this variety decreased to only 15% of the total areas of dry season rice from 50-55% of the total area about 4-5 years ago. This reduction in adoption of the variety was mainly due to severe infestation of blast in the variety as well as availability of higher yield potential hybrid cultivars. Despite severe susceptibility to blast, they have been continuing cultivation of BRRI dhan28 since the grain is the most preferred one for family consumption. One average, 70-80% of the total production of this rice variety is used for household consumption. This rice is slowly digested so that people do not have appetite for food for longer hours than that of other rice varieties. Besides, cooked rice of its medium slender grain is tested good to eat and remains fresh for eating even in the following morning. Other drivers of adoption of the variety included good yield potential (5.0 - 5.8 t/ha), 10-12 days and 15-20 days shorter growth duration than the Hybrid rice and BRRI dhan29, respectively. Therefore, BRRI dhan28 not only needs less irrigation, fertilizers, and pesticides but also matured for harvesting before commencing early monsoon rain. As a result, cost of production of this rice is also low. Due to early harvest, farmers can dry up the grains and straw of the rice easily before commencement of the rainy season. Moreover, cattle like the straw of this variety very much as their feed since the quality of straw remains good as the harvesting ended almost before the rainy season.

Similarly, the adoption rate of BRRI dhan29 decreased to only 10% of the total area of dry season rice from 30-35% of the total area of the trail village in Mithapukur mainly. This was due to the availability of hybrid cultivars, which are potential to give similar/or higher yield. The life cycle of the Hybrid rice is 5-10 days shorter than BRRI dhan29. Therefore, only a limited area is allocated for BRRI dhan29, mainly for family consumption (only 20-30% of total production is marketable surplus) since the cooked rice of the medium slender grain is tested good to eat. Market demand of medium slender BRRI dhan29 is lower than coarse grain Hybrid varieties since the demand Hybrid rice is higher at mill gate because of higher demand of bold grain rice at procurement center. Besides, less infestation of neck blast and other pests, and no shattering and lodging problems are the major reasons of continuing cultivation of BRRI dhan29. Due to longer growth duration its performance and post-harvest activities (e.g., harvesting, threshing and drying) are frequently affected by extreme weather events (heavy rain and storm). Consequently, post-harvest losses increase. These are the main concerns about BRRI dhan29.

The Hybrid cultivars are mainly cultivated in the trial village in Mithapukur, mainly for commercial purpose as it gives higher yield (6.5-7.5 t/ha) and it has 5-10 days shorter life cycle than BRRI dhan29. Additionally, demand for paddy rice at local market is ensured because of higher demand of coarse grain husked rice at procurement center.

Badargonj: The adoption rate of BRRI dhan28 is 20% of the total area of dry season rice in the studied village. Farmers mainly cultivate this rice variety for family subsistence as about 80% of the total produce is used for family consumption. The key drivers for adoption of BRRI dhan28 are shorter growth duration and good taste of cooked rice. Due to shorter growth duration, this variety not only needs less irrigations and fertilizers but also is free from damage by extreme weather events such as heavy rainfall and storm in the early monsoon months. This rice matures for harvesting before commencing early wet season rain so that farmers can dry the grains and straw without any hazard. In addition to the good taste, the left-over cooked rice remains fresh for consumption in the following morning. The adoption rate of BRRI dhan29 is 40% of the total area of dry season rice. The farmers mainly cultivate this rice for commercial purpose as over 70% of the total produce is marketable surplus and only 20% of the total produce is used for family consumption. The key drivers of adoption of the variety include higher yield potential, medium slender grain rice with higher amylase as well as large supply so that its demand in the local markets is ensured. Furthermore, the variety is tolerant to lodging despite rain and storm at maturity stage. Adoption rate of hybrid rice cultivars is 15% of the total area of dry season rice. This rice is mainly cultivated for commercial purpose. The adoption rate of Minikit is 10% of the total area of dry season rice. This variety is adopted both for family consumption and sale irrespective of the farm types. `

Thakurgaon Sadar: BRRI dhan28 is cultivated in high land as it is less irrigation-intensive due to shorter lifecycle. Additionally, cooked rice is of good taste. Although BRRI dhan28 gives lower yield (5.7-6.3 t/ha) than BRRI dhan29 (6.8-7.3 t/ha), it is more profitable due to higher price (BDT 20,000 – 25,000/ton). Both the BRRI dhan28 and 29 are cultivated for commercial purpose as their marketable surplus is about 75% of the total production of the respective cultivars. It indicates that about 25% of the total production of the respective cultivar is used for household consumption. On the other hand, the Hybrid rice is cultivated entirely for commercial purpose due to its slightly shorter lifecycle than BRRI dhan29. Medium and large farmers cultivate both the BRRI dhan28 and BRRI dhan29 along with some Hybrid rice and BRRI dhan58 (6.3-6.8 t/ha). However, small farm household types mostly cultivate BRRI dhan29 due to higher yield (6.8 – 7.3 t/ha). Some large and medium farmers cultivate Minikit in some areas mainly for family subsistence since the demand of this rice at local market is low due to small lot of supply although price is still high.

4.13.2 Variations in seedlings' age between cultivars

Farmers' started transplanting Boro rice after mid-January since the growth of rice crop during mid-December to first half of January is very poor because of cold. Farmers usually sowed seed of BRRI dhan29 in nursery about two weeks earlier than BRRI dhan28 and Hybrid rice. However, the BRRI dhan28 and Hybrid rice are transplanted 2-3 weeks earlier than BRRI dhan29 as yield of the BRRI dhan28 gradually decreases with increasing seedling age over 45 days. In the contrary, the performance of BRRI dhan29 increasingly decreases with decreasing seedling age lower than 45 days. These findings indicate that BRRI dhan28 performs better for younger seedlings, while BRRI dhan29 performs better for older seeding.

BRRI dhan28: Farmers in the group discussion mentioned that they usually transplanted about 30-40 days old seedlings of the BRRI dhan28, a short duration cultivar. However, this cultivar performs best for the seedling age of about a month (25-30 days) and its yield decreases at an increasing rate with seedling age over 45 days. This is because the flowering stage of the rice plants appears after short period of time if older seedlings are transplanted. Also, the number of effective tillers decreased with increasing seedling age.

BRRI dhan29: Farmers in group discussion informed that they usually transplanted 60-65 days old seedlings for BRRI dhan29. Firstly, because of tenderly aged-seedlings, the rice plants are wilted or stunted during cold period as well as they give low yield due to higher vegetative growth, which causes more infestation of pest and higher sterility. Secondly, older seedings are transplanted for shortening field duration to apply less irrigations (at least two irrigations), fertilizer and pesticides. Thirdly, despite transplanting older seedlings, the cultivar is potential to produce plenty of tillers (most of which are effective) with more filed grains (less or no sterility) and eventually to give better harvest. Finally, the farmers usually sow seeds of BRRI dhan29 in nursey before commencing winter (within November) since the seedlings are wilted and/or stunted if sowed during winter. Therefore, the farmers transplanted older seedlings. It was also the case that farmers are forced to transplant older seedlings as the pump operators intentionally delayed supplying water for applying less irrigations. Additionally, some farmers delayed land preparations so that pump owners wait to supply irrigation until the total command area is ready for transplanting. It was informed that the tenderly-aged seedlings get longer period in the fields and produce profuse tillers, but proportion of the effective tillers is low. Additionally, infestation of pests, including stem borer and sheath blight, and rot become severe as micro climate is created in the rice fields with more vegetative growth because air and light cannot to pass through the fields adequately.

Sometimes farmers transplanted even three-month-old seedings for BRRI dhan29 under extremely delayed planting date after harvesting of potatoes. Yet the cultivar is potential to give better harvest (5.9-6.9 t/ha). Farmers' adaptation option for over three-months old seedlings is that they transplanted 4-5 seedlings per hill. Farmers also transplanted Hybrid rice for extremely delayed transplanting date as well, but they transplanted about 25-35 days old seedlings since this cultivar is potential to produce sufficient number of tillers, and despite transplanting younger seedlings, the Hybrid rice matured for harvesting before BRRI dhan29.

Hybrid rice: Farmers informed that they transplanted only 20-25 days old seedlings for Hybrid rice as the cultivar gives better harvest for tenderly-aged seedlings.

4.13.3 Pump rental charge and its criteria and constraints

Diesel-operated pump: For diesel engine-operated pump, the pump owner charges 2,400 Taka/acre as charge for the pump in most cases. The farmers then can use diesel as much as needed to irrigate his/her fields. The pump owner only provides required lubricant as needed. The basic idea behind this type of arrangement is that the number of irrigation differs based on land topography and soil types, and therefore the pump owner does not agree to provide fuel.

Electricity-operated pump: The pump owner decides the cost for irrigation depending on soil types and topography of the lands. For instance, demand for irrigation is higher (two irrigations per week) for sandy soil followed by sandy loam (one irrigation per week) and loam (one irrigation per fortnight) soil. On average, the lowest cost for irrigation is 4,000 Taka/ha for soil with less irrigation interval and increased to 6,000 Taka/ha depending on the demand of soils for irrigations. Although the pump owner gets 20% subsidy on the electricity bill, it is not subtracted from the rent charged from land owner. On the other hand, rising fuel price has not much impacts on amount of irrigation applications. Also, demand for irrigation water has been increasing due to rising temperature and decreasing rainfall in the post winter months.

Usually there is no notable variation in yields between the diesel- and electricity-operated pumps. However, sometimes the diesel-operated pumps give higher yield than that of the electricity-operated pumps because of timely application of adequate irrigations since the land owners can apply required amount of irrigation in time as they pay fuel cost. In the contrary, electricity-operated pumps sometimes gives lower yield. It is due to, firstly, the pump owners often intentionally apply inadequate irrigations to save electricity cost as they pay for it. Most importantly, they sometimes are unable to apply irrigation timely, in particular, at maturity stage. This is (i) partly because of disruption of power supply, and (ii) partly because of increased demand for irrigations at the maturity stage; the pump owners often commit to apply irrigations in areas higher than that of the capacity of their pumps. Therefore, turns of plots sometimes come after exceeding the threshold level of soil-moisture stress. This adversely affects performance of the irrigation system.

4.13.4 Market price of paddy

The market price of paddy rice is mostly influenced by the traders. However, level of tariff on imports of husked rice and time of import, in particular large import prior to harvesting season, have considerable influences on the price of paddy rice. Additionally, although contradicts with the supply and price theory (increasing supply decreases demand, and consequently decreases price), farmers in group discussion informed that large supply of the same variety of paddy rice, irrespective of grain quality, increases demand. This, consequently, rises price of the paddy rice. This happens due to the millers' willing to pay higher price for higher market demand since they need to collect adequate amount of paddy rice from the market to run their automatic rice mills. For instance, the coarse grain Hybrid rice is cultivated in about 75% of the total dry season rice areas in studied village in Mithapukur. So, the price of the Hybrid rice is sometimes higher than that of even medium slender grain because of higher supply of coarse grain rice in the market as the traders would not like to purchase medium slender grain due of inadequate supply of the rice for running the mills. For instance, the prices of BRRI dhan28 and BRRI dhan29 are same (19.5 Taka/kg) but slightly higher than Hybrid (17.5 Taka/kg) at harvesting season in the selected village in Mithapukur. However, after 1-2 months of harvest, the price of Hybrid rice (20 Taka/kg) exceed the price of BRRI dhan28 and BRRI dhan29 (19.5 Taka/kg). It is mainly because of dominance of supply of Hybrid rice at the local markets as traders are willing to pay higher price when supply of a paddy rice is adequate to run their mills.

4.13.5 Farmers' perception on solar pump

According to the farmers, there are several drawbacks of the solar pumps. These are:

(1) Sometimes, the owners of the solar pumps commit to supply irrigation in areas higher than that of the pumps' capacity to supply irrigations. Consequently, they become unable to supply water to the fields in time, with a negative effect on yield. One of the key informants told that he harvested higher yield from the areas under diesel-operated pump than from the areas under solar pump. He could apply adequate irrigations with STW in time since he paid the cost for fuel.

(2) Sometimes, transplanting dry season rice is delayed as solar pumps become unable to operate at full-swing during transplanting date (mid-December to mid-February) because of low temperature and shorter sunshine hours. The delayed transplanting not only reduces yield but also increases likelihood of being affected by extreme weather events at the maturity stage. Similarly, when the sky is cloudy, the capacity of solar pump decreases to irrigate 1.5-1.8 acres per day from 2.0-2.5 acres per day. As a result, the pump fails to apply irrigation in time. However, sometimes the solar pump manager makes alternate arrangement for a generator and electricity-operated pump to reduce delay of transplanting date.

(3) The command area of the pump mainly depends on types of soils. For instance, command area in sandy soil is much lower than that in areas with sandy loam, loam and clay soils. It is due to water holding capacity of the soils. Therefore, turns of applying irrigations in some fields came even after exceeding threshold level of soil moisture at the studied village (Dhalua), that consequently affected the yield. Nevertheless, there are some solar pumps in a nearby village that are able to supply irrigations adequately since the soil in that village is sandy loam to loam. As a result, there is not much variation in yields between the solar pump and diesel- or electricity-operated pumps. However, the performance of the irrigation system under solar pumps was largely lower (0.6 – 1.0 t/ha) than that under diesel-operated pumps in areas with clay soil.

The main benefit of the solar pump, reported by the key farmers, is that the pump operator can apply irrigations independently in absence of the land owners, ultimately saving labor-hours for the land owners. However, sometimes the operator applies inadequate amount of water to complete the cycle of applying irrigation in all fields during high demand.

Overall, the farmers in group discussion anticipated that the solar irrigation system might be popular in areas with sandy loam to loam soil and even in the areas with clay soil if the areas are not connected with national grid of electricity supply. However, the farmers may stop receiving irrigations from solar pump if electricity-operated pump is available in the areas because of lower cost of irrigation under that system.

5 Conclusions, key messages, and recommendations

The northwest region is considered as the food bowl of Bangladesh. The region produces 35% of rice, 64% of wheat, 62% of maize, and 67% of total potato production of the country. It is a most diversified agricultural region of the country and the average yields of major crops are higher than their country-average values. The northwest region is the most intensively irrigated region of the country. Groundwater is the predominant source of irrigation, covering 97% of the total irrigated area. In recent years, there are serious concerns about the sustainability of groundwater use in this region. Many studies show that groundwater levels are falling and that the use of shallow aquifers for irrigation in the region has become unsustainable. Yet, the availability of water for irrigation remains crucial for maintaining the current and future growth in agricultural production. So, sustaining groundwater irrigation while maintaining the current growth in production, particularly in the northwest region, is of utmost priority of the government. But there is lacking in clear understanding of the current state of irrigated agriculture in the region.

In this study, we provide a comprehensive analysis of the current trend of area, yield, production, water use, and productivity of the major crops grown in the northwest region of Bangladesh based on both the historical data and primary information collected from the field. To the best of our knowledge, we did not come across any literature on the state of irrigated agriculture of the region based on such comprehensive analysis.

5.1 Conclusions

The following conclusions have been drawn from this study.

1. The northwest region of Bangladesh is the most intensively cultivated region of the country. It is the most diversified crop-growing region. The average cropping intensity of the region was 205% in 2012 compared to the country-average value of 190%. The cropping intensity of this region is greater than the national average values of all districts and the intensity is increasing over time.
2. Average yield of rice is higher in the northwest region. Although, in general, the yield is higher and increasing over time, there is spatial variation in the yield.
3. Both the cultivated area and yield of maize is increasing rapidly in the region. This is triggered by the higher price due to market demand. Farmers are using good seeds and a lot of inputs for maize cultivation.
4. Groundwater is the main driver of the remarkable growth in irrigation and crop productivity. Currently, 83% of the net cultivable area (NCA) is irrigated in the northwest region compared to the 61.2% at the country level. In the northwest region, 97% of the total irrigated area is irrigated by groundwater only.
5. There are evidences that groundwater levels are falling in some parts of the northwest region. The water table drops below the suction limit of Hand Tubewell (HTW) and Shallow Tubewell (STW) in some areas. Despite this, the usages of STW and Deep Tubewell (DTW) are increasing over time. The pumps of some STWs were installed below the ground level to pump water in Bogura.
6. Groundwater level is declining in some areas, particularly in the Barind region. STWs are unable to pump water in the driest period (April-May). Consequently, the area irrigated by STWs is decreasing as farmers are installing DTWs to pump water.
7. The cultivated area of Boro rice remains steady over the last few years. The area under maize is increasing rapidly, mostly, at the expense of other crops except rice.

8. The initial drivers for the change in cropping system were the availability of irrigation, research, development, extension and education. The current change (e.g., growth of maize) is mostly driven by market demand, availability of water, risk (e.g., climate, disease, market instability), economic profit and price fluctuation, and conversion of subsistence to more commercial farming.
9. A certain variety of rice is dominant in certain location due to the prevailing cropping system, farmers' requirements and choice, and the nature of farming (subsistence vs profit making).
10. There is a decreasing trend in yield for BRRI dhan28 and BRRI dhan29 due to the delay in transplanting. Most of the plots, investigated in this study, were planted during 2nd half of January and 1st half of February. Hybrid rice seems not affected by the transplanting time.
11. Age of seedlings affects the yield of rice for BRRI dhan28 and BRRI dhan29. It appeared that the higher the age of seedlings the lower is the yield.
12. Total cost of irrigation significantly differs among the locations, types of pumps used for irrigation, varieties of rice, and transplanting dates. There is significant ($p<0.05$) variation in total income from rice cultivation among the locations and variety of rice. Significant variation also exists in gross income for location, pump type and varieties of rice.
13. Cost of irrigation was as high as 35% of the total production cost of rice. The average cost was 25% in 2015-16, and 20% in 2016-17. Different price models (e.g., area based, fixed charge based on area plus diesel by the farmer, crop sharing, etc.) are used in different places. The estimated cost was the highest in Ishurdi because of crop sharing model. Irrigation with DTW was the cheapest (110 Taka/hour, 60 lit/s). Solar irrigation was costlier than irrigation with STW (7,000 Taka/acre vs 4,000 taka/acre in Mithapukur).
14. In 2015-16, the average gross incomes of Hybrid rice, BRRI dhan29 and Minikit were almost similar. But in 2016-17, the gross incomes of Hybrid rice and BRRI dhan29 were higher than the other rice varieties (Minikit and BRRI dhan28), mainly, because of higher yields. The price of rice for all varieties was higher in 2016-17; the price of Minikit was much higher in 2015-16. In general, when the price of rice is high, the difference in price between the fine and coarse rice becomes lower.
15. Cost of irrigation water per unit volume (estimated based on water supplied to plots by the farmer) varies widely, - 45 Taka/ha-mm to 10 Taka/ha-mm. Irrigation with DTW is the cheapest and solar irrigation is costlier (30 Taka/ha-mm) than irrigation with STW operated by diesel engine or electric motor.
16. There is significant variation in yield among the locations and rice varieties. But, the variation in yield is not significant among the types of pumps or planting dates. The Hybrid rice and BRRI dhan29 produced higher yields than the other varieties. The variation in yield is less in BRRI dhan29. For own consumption by the farmers, it is better to grow BRRI dhan28 and Minikit because of relatively good production with medium growth duration, good grain quality, good taste of cooked rice and its slow digest character. For selling to the market, farmers can grow Jirashail, Minikit, Hybrid rice and BRRI dhan29. Although Jirashail, Minikit, and Kajallata are low yielding varieties, they can be more profitable (depending on market price).
17. The probability of achieving the yield of 8.0 tonne/ha for Hybrid rice is only 20%. The average net benefit of Hybrid rice, BRRI dhan29 and Minikit are almost similar.
18. Potato is the most profitable crop, but initial investment is very high. Maize has similar initial investment to rice, but much provides higher profit than rice. However, the risks of growing potato may be higher. There is a high variation in gross income of potato with coefficient of variation of 52.2%.
19. Groundwater is the only source of irrigation in this region. Growing non-rice crops such as wheat, lentil and okra will save groundwater in the aquifer. However, this will be at the expense of gross income for the farmers. The risk of growing non-rice crops is very high.

20. Potential crop evapotranspiration (ETcrop) of rice varies from 283 mm to 545 mm. ETcrop for maize varies from 276 to 528 mm. So, for saving water, maize may not be a good replacement for rice.
21. The yield and gross income of rice vary from plot to plot and location to location but, in general, the rice is a profitable crop contrary to the popular belief (that there is no profit).
22. Contrary to the popular belief, farmers are, in general, very efficient in applying irrigation water to rice. In STW sites, water applied by the farmers was very close to the actual requirements. Plots in DTW sites had some oversupply. Irrigation water use is higher in DTW site; the price of DTW water is much lower compared to STW water. The average irrigation water use was less than 800 mm except in Mithapukur and Thakurgaon in 2015-16. In 2016-17, average water use was less than 800 mm in all locations.
23. The average water applied to the crops other than rice was less than the estimated requirements. The difference in applied and estimated water was very high for maize (the average water applied was 50% of the estimated one).
24. There is a general perception that 3000-5000 litres of water are required to grow one kilogram rice. However, the average irrigation water supplied to grow one-kilogram rice was 1,402 litres in 2015-16 and 1,086 litres in 2016-17. However, not all the water supplied to the plots are consumed by the plants. A part of the applied water returns to the aquifer as return flow through percolation and seepage. The real water use by the plants is the actual crop evapotranspiration. Based on this, the quantity of water required to grow one kilogram rice was 661 litres and 584 litres in 2015-16 and 2016-17 crop seasons, respectively.
25. The physical water productivity depends on production of rice, usage of water, and actual ET. This water productivity, based on irrigation water supplied to the field, varied from 0.37kg/m^3 to 1.47 kg/m^3 for all plots in 2015-16 and from 0 to 1.43 kg/m^3 in 2016-17. The average water productivity was 0.80 kg/m^3 and 0.94 kg/m^3 in 2015-16 and 2016-17, respectively. The average (average of all plots) physical water productivity, based on actual ET, was 1.60 kg/m^3 and 1.77 kg/m^3 in 2015-16 and 2016-17, respectively. The highest water productivity was 2.92 kg/m^3 in 2015-16 and 3.03 kg/m^3 in 2016-17.
26. The economic water productivity, based on irrigation water supplied, varied from -1.40 Taka/m^3 to 7.14 Taka/m^3, respectively in 2015-16 with an average of 3.23 Taka/m^3. This water productivity, based on actual ET, varied from -3.63 Taka/m^3 to 22.68 Taka/m^3 in 2015-16 and 2016-17, respectively with an average of 6.53 Taka/m^3.
27. The water productivity of rice varies from site to site due to the variation in yield, gross income and irrigation water use. The economic water productivity of maize and potato is several times higher than that of rice.

5.2 Key messages

This study is supposed to provide a few key messages for the other parts of the Eastern Gangetic Plain (areas in West Bengal, Bihar and Nepal Terai region), which have similar agro-ecology and natural resources, but irrigation and agriculture are not as developed as in the northwest region of Bangladesh. Following are the key messages that can be drawn based on this study.

1. Irrigation is essential for dry season cropping. In the northwest region, no emphasis was given on the conjunctive use of surface water and groundwater; rather the development of irrigation was solely based on groundwater. This resulted in current decline in groundwater level in some parts of the region. So, while developing irrigation, it is necessary to explore other water sources along with groundwater (not fully dependent on groundwater) for long-term sustainability of the resources.
2. No emphasis was given in the northwest region to understand the sustainable limit of groundwater use. It is imperative to understand the availability of the resources, particularly groundwater resource, so that no concerns arise after some years of use.

3. Use of STWs revolutionized irrigation development in the northwest region, hence this technology can be promoted.
4. Crop diversification could be promoted from the beginning rather than relying mostly on the cultivation of rice. This will need development of market for the non-rice crops.
5. Research and extension services in Bangladesh is well-developed and have great contributions in the current agricultural development. The farmers are well-trained on cropping practices and up-to-date with the current events and market conditions. So, it is necessary for the farmers to get adequate training and access to keep them up to date with any current information.

5.3 Recommendations

The results presented in this report appear to be enough to boost further investment in exploring the ways for sustainable utilization of groundwater resources for irrigation in the northwest region. Accordingly, the following studies are recommended.

1. Examination of all the factors and their relative magnitude that are controlling the decline of groundwater levels in some parts of the region. The current focus by the government and policy makers is on the pumping of water for rice only – which is based on a misconception of 'water savings'.
2. Examination of the impacts of different 'water savings' and 'conservation practices' on the local and regional water balance and groundwater recharge.
3. Examination of different 'effective water saving measures' and ways of enhancing recharge into the aquifers for long-term sustainability of groundwater irrigation.

List of abbreviations

ACIAR	Australian Centre for International Agricultural Research
AWD	Alternate Wetting and Drying
BADC	Bangladesh Agricultural Development Corporation
BARI	Bangladesh Agriculture Research Institute
BBS	Bangladesh Bureau of Statistics
BMD	Bangladesh Meteorological Department
BMDA	Barind Multipurpose Development Authority
BRRI	Bangladesh Rice Research Institute
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAE	Department of Agricultural Extension
DTW	Deep Tubewell
EGP	Eastern Gangetic Plains
EWP	Economic Water Productivity
GB	Gross Benefit
GI	Gross Income
GoB	Government of the People's Republic of Bangladesh
IRRI	International Rice Research Institute
M	Million
Mha	Million ha
MoA	Ministry of Agriculture
NCA	Net Cultivable Area
PWP	Physical Water Productivity
STW	Shallow Tubewell
TPC	Total Paid-out cost

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