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Irrigated agriculture in the northwest region of Bangladesh

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March 2019

ACIAR

Australian Aid

Australian Government
Australian Centre for International Agricultural Research

University of Southern Queensland

Citation

Mainuddin M, Maniruzzaman M, Alam, MM, Islam MT, Kabir MJ, Hasan M, Scobie M, and Schmidt E (2019) Irrigated agriculture in the northwest region of Bangladesh. CSIRO, Australia.

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Executive summary

Bangladesh has made remarkable development in agriculture over the last few decades and gained self-sufficiency in rice production. This development was driven by increased cultivation during the dry season, made possible by the growing availability of irrigation. *Boro* rice is the major crop grown in the dry season which 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. This growth was driven by the growing use of groundwater. Northwest region has the highest percentage of net cultivable area irrigated and has the most intensive use of groundwater; over 97% of the total area is irrigated by groundwater. 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 basket of Bangladesh and groundwater is the main driver of this development. But, there are serious concerns about the sustainability of groundwater use in the northwest region. Many studies showed that groundwater levels are falling and that the use of shallow aquifers for irrigation in the area is unsustainable. Therefore, for sustainable production to feed the huge population this study was undertaken to understand the bio-physical and socio-economic aspects of groundwater irrigation for improving the land and water productivity in the northwest region of Bangladesh. Therefore, this study was conducted by intensive monitoring of the groundwater irrigation by shallow tubewell (STW) and deep tubewell (DTW) in six selected sites in Rajshahi, Pabna, Bogra, Rangpur, Dinajpur and Thakurgaon Districts in north-west regions of Bangladesh. Rice is the major crops (about 73%) grown in the region along with wheat, maize, potato, pulses and oilseeds. A wide range of yield variation in rice was found (4.87 to 7.39 t ha^{-1}) in different locations mainly for the varietal differences, transplanting times, climatic conditions, inputs used and management practices. A huge variation of total cost was found (56,150 to 86,250 Taka ha^{-1}), of which lion shares borne by fertilizer (18%) and irrigation (23%). Harvesting and carrying cost was also alarming for total production cost. The average net benefit was about 24,550 Taka ha^{-1}, which indicated that rice growing during dry season was marginally profitable. Compared to four major crops (rice, wheat, maize and potato), the production cost, income and net benefit were highest for potato. Water requirements of rice varied with the growth duration. Crop evapotranspiration (ETcrop) of long duration (160 days) BRRI dhan29 and hybrid rice varieties varied from 359 to 545 mm across the locations and transplanting dates. For medium duration BRRI dhan28 (140 days) was varied from 385 to 479 mm. The average ETcrop of maize, wheat and potato were 392, 241 and 222 mm, respectively across the study locations. In most cases, irrigation water used were perfectly matched with the irrigation requirement with little deviations in Rangpur, Rajshahi and Thakurgaon regions for rice and non-rice crops. The water productivity of rice varied from 0.56 to 0.92 kg m^{-3}, whereas the economic water productivity varied from 2.2 to 3.4 Taka m^{-3} across the locations. Among the non-rice crops, the economic productivity of potato was the highest (46 Taka m^{-3}) followed by maize (24 Taka m^{-3}). By adopting improved distribution system i.e. buried pipe in DTW and plastic pipe in STW, about 90% of conveyance loss was reduced. Field water loss was reduced by 25% by adopting AWD method in dry season rice, which ultimately improved the water and economic productivity of crop production and reduced the groundwater pumping of those location.

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 the population of 76 million in 1977, total production of rice was 11.6 million tonnes (152 kg/capita). Now in 2012, with the population of 153 million, the total production of rice has increased to 34 million tonnes (222 kg/capita). 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. Agriculture is a leading contributor to poverty reduction in Bangladesh since 2000 (World Bank, 2016).

Production increases have resulted from a substantial intensification of agriculture rather than from increases in land area available for cultivation. The overall cropping intensity for the country has increased from 148.9% in 1977 to 183% in 2010 with an increasing proportion of land being double- or triple-cropped. This growth in intensity was driven by increased cultivation during the dry season, made possible by the growing availability of irrigation. *Boro* rice is the major crop grown in the dry season which currently (2012) 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 phenomenal growth in irrigation development over the last 3 decades. Total irrigated area has increased from 1.52 million ha in 1983 (18% of the net cultivable area) to 5.4 million ha in 2013, (63% of the net cultivable area). This growth was driven by the growing use of groundwater through rapid increase in the adoption of shallow tubewells. Groundwater covers about 80% of the total irrigated area of the country and is growing. 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 35 thousand.

Northwest region (Figure 1) has the highest percentage of net cultivable area irrigated in 2012-13 (around 85%) and has the most intensive use of groundwater; over 97% of the total area is irrigated (2012-13) by groundwater. 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 basket of Bangladesh. Groundwater is the main driver of 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) show that groundwater levels are falling and that the use of shallow aquifers for irrigation in the area is unsustainable.

The current (2010) population of Bangladesh is 151 million and is projected to increase to 194 million by 2050. 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. The availability of water for irrigation is 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.

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, 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. 2014) which raises the question about the nature of social and institutional constraints to rural development holding back smallholders in India and Nepal.

1.2 Objective

The objective of this study in Bangladesh is to understand the bio-physical, socio-economic and institutional aspects of groundwater irrigation in the northwest region of Bangladesh. This will be done through intensive monitoring of the groundwater irrigation by STW and DTW in 6 selected sites in Rajshahi, Pabna, Bogra, Rangpur, Dinajpur and Thakurgaon District. The study is expected to provide the answers to the following questions:

- How water and land productivity varies from plot to plot or from location to location and by different modes of irrigation? What are the reasons? How they can be improved?
- What institutional arrangements are in place? What are their effects on the productivity/performance? How they can be improved?

What lessons can we draw for the sustainable and equitable management of GW resources that may be applicable in Nepal and Bihar?

2 Current state of irrigation and agriculture in the northwest region

2.1 Topography and climate

The total area of the northwest region 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 Division (Rajshahi and Rangpur Division). 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 northwestern 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, Bogra, and Joypurhat districts of Rajshahi Division and some parts of Dinajpur, and Rangpur districts of the current Rangpur Division.

Figure 2.1 Regions as described in this report

Climatically, this region belongs to the dry humid zone with annual rainfall varying from 1,273 to 2,515 mm (average of 1985-2010). The average annual rainfall is 1927 mm. Among the regions, northwest region has lowest average annual rainfall (Figure 2.2). The average reference evapotranspiration (ETo, estimated by Penman-Monteith method) is 1309 mm, which is one of the highest (the highest is in the southwest region, 1334 mm). Thus the region is the driest and have the 2nd greatest reference evapotranspiration.

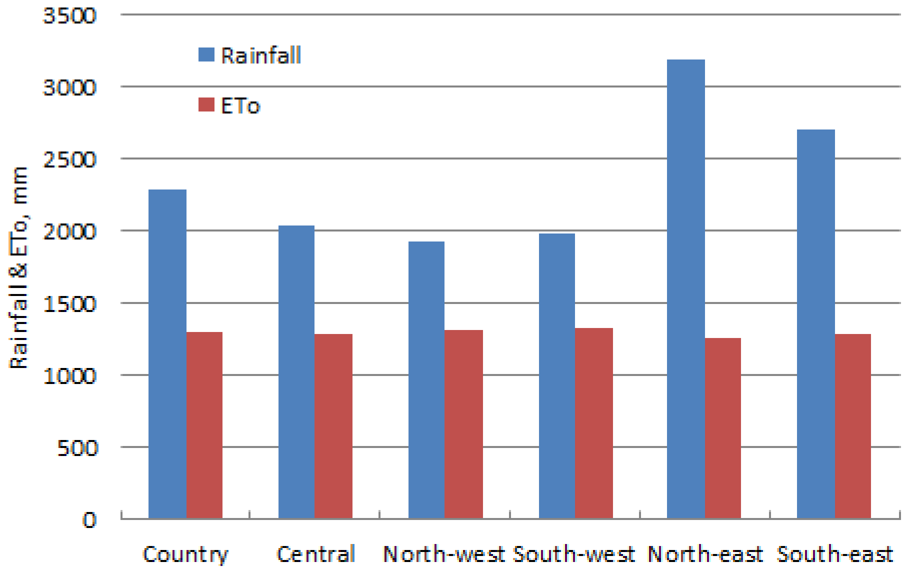

Figure 2.2 Average (1985-2010) annual rainfall and ETo of the different regions of Bangladesh

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 (1428 mm) and Rangpur has the highest (2262 mm). Rainfall varies (CV varies for 20 to24%) widely 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 varies from 6 to 8%) then the variation in rainfall. The highest average ETo is 1366 mm for Ishurdi (within Pabna district) and the lowest is 1251 mm in Rangpur.

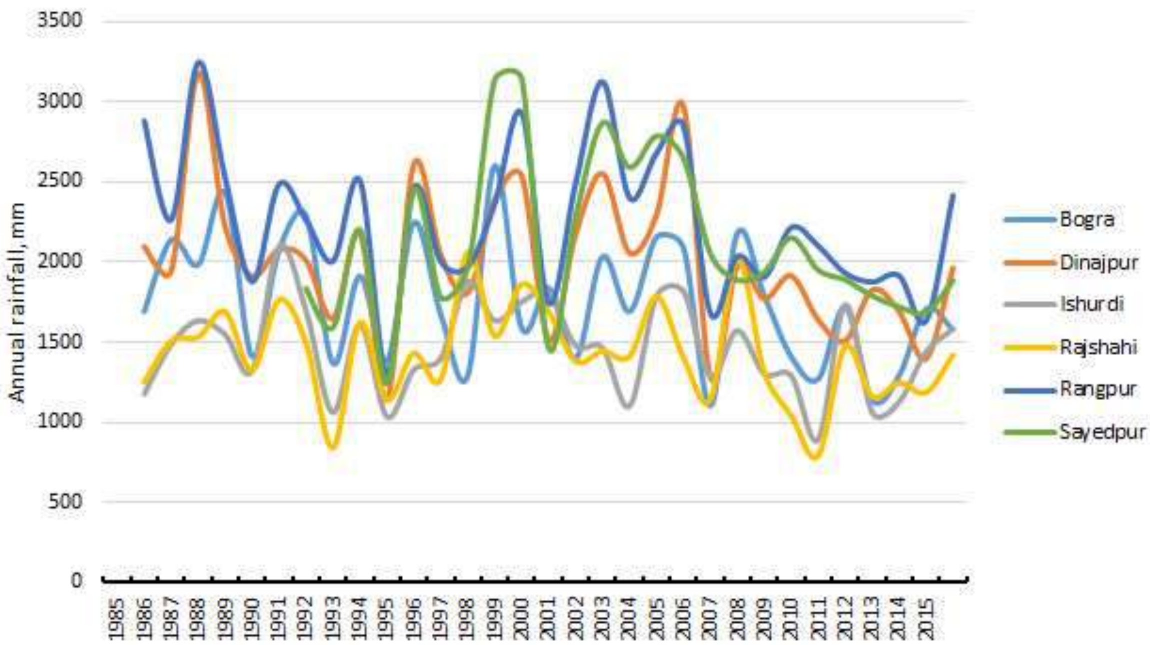

Figure 2.3 Annual variation in rainfall for the 6 rainfall stations in the region

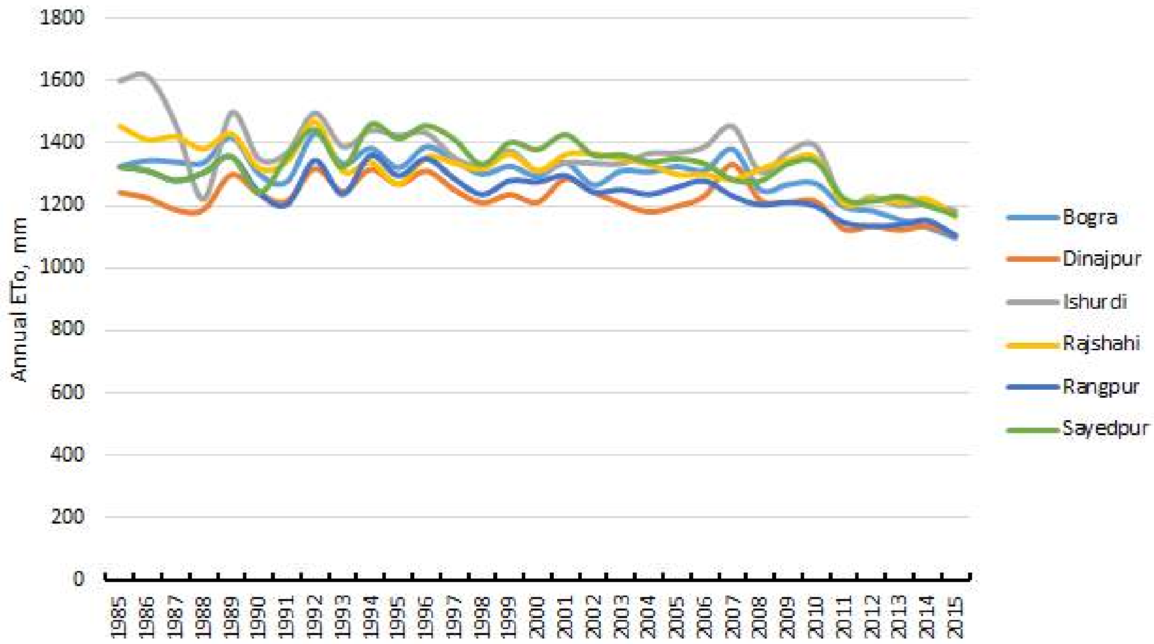

Figure 2.4 Annual variation in ETo for the 6 stations in the region

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).

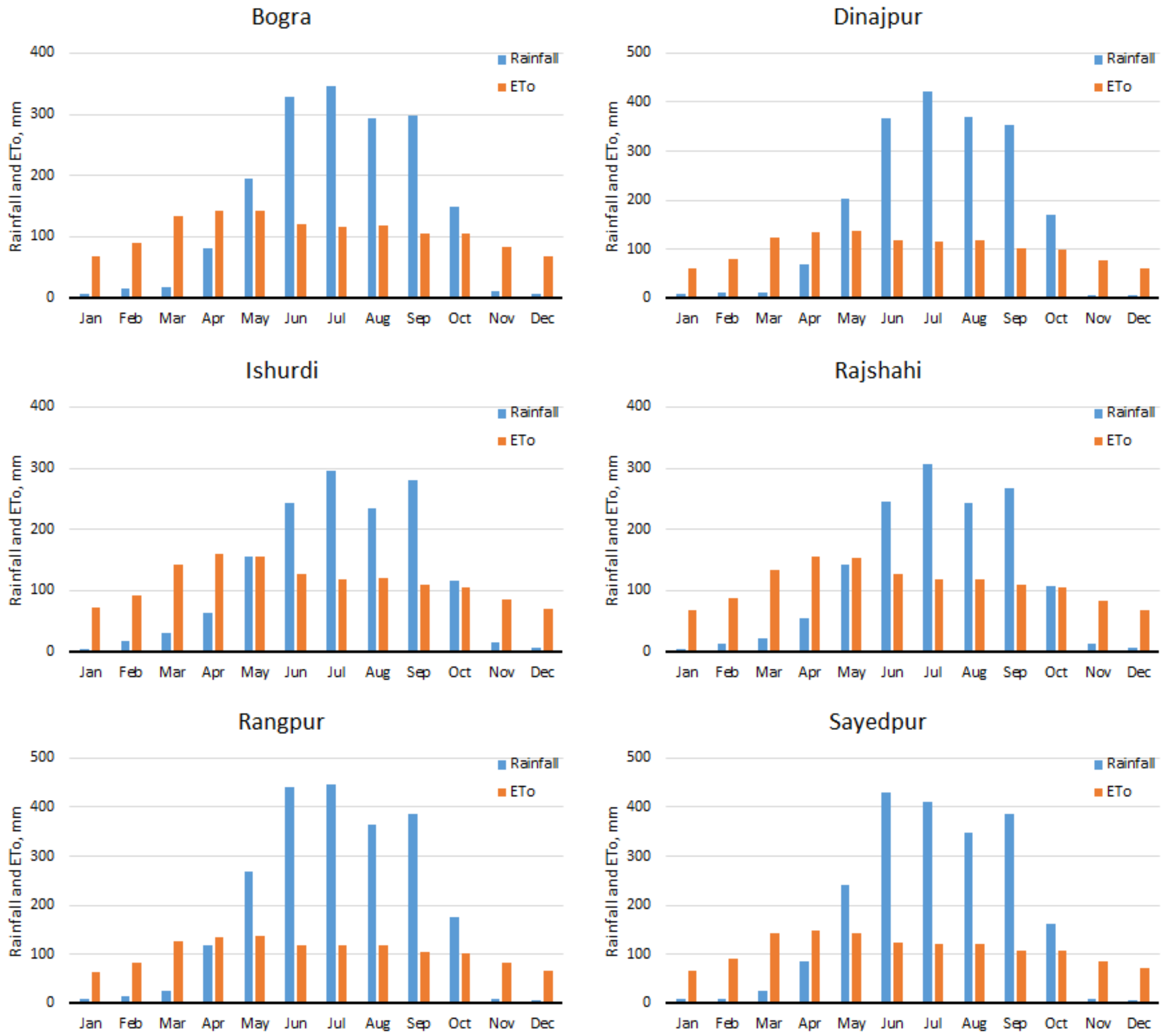

Figure 2.5 Comparison of average monthly rainfall and ETo in the northwest region

In terms of temperature, 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 were 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, according to seasons in which they are grown, into two groups:

(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 season. 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 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 is grown in Kharif-II, and Boro is grown in Rabi season. Aman is the main rainfed rice and Boro is the fully irrigated rice. Aus is grown in very small areas nowadays and are not 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 crop area in the Rabi season.

The region is also 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 area of the crops grown in the region in 2011-12 are given in Figure 2.7.

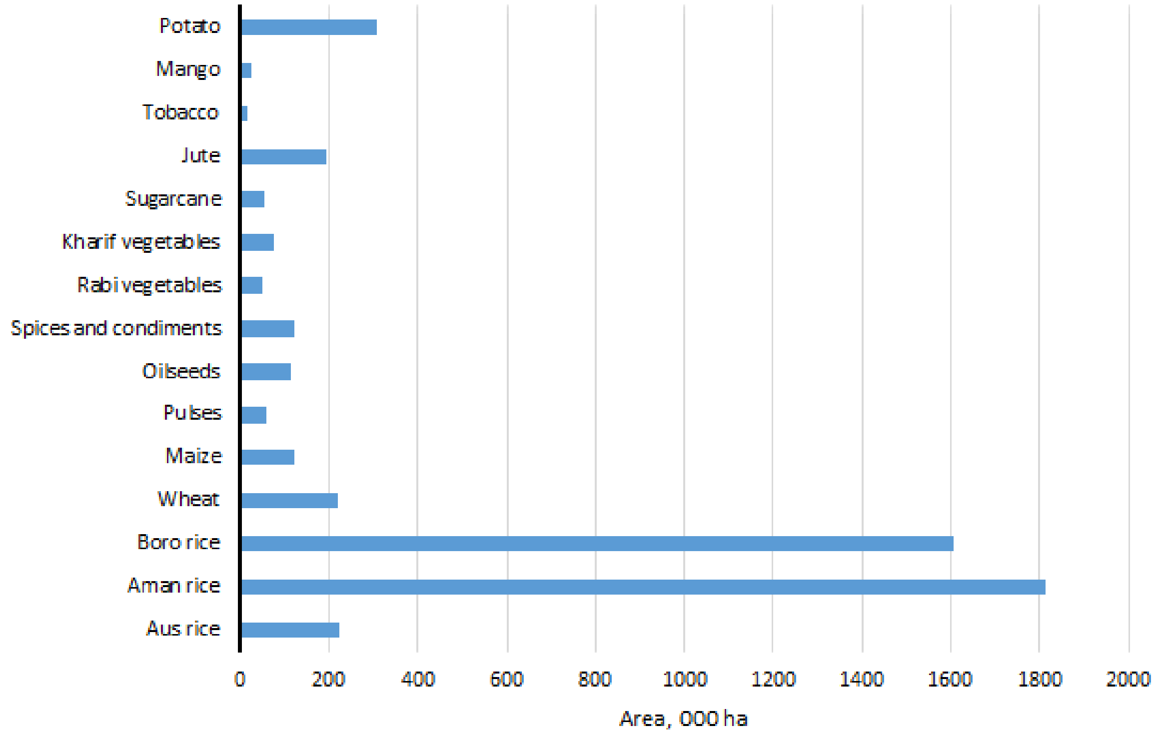

Figure 2.7 Area of crops in the northwest region (mango and sugarcane are perennial crops, Jute is Kharif-1 crop)

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 Bogra (Bogra and Joypurhat Districts) and the lowest is in greater Rajshahi (Rajshahi, Naogaon, Nawabganj, Figure 2.8). All greater districts have cropping intensity higher than the country average. The cropping intensity is gradually increasing.

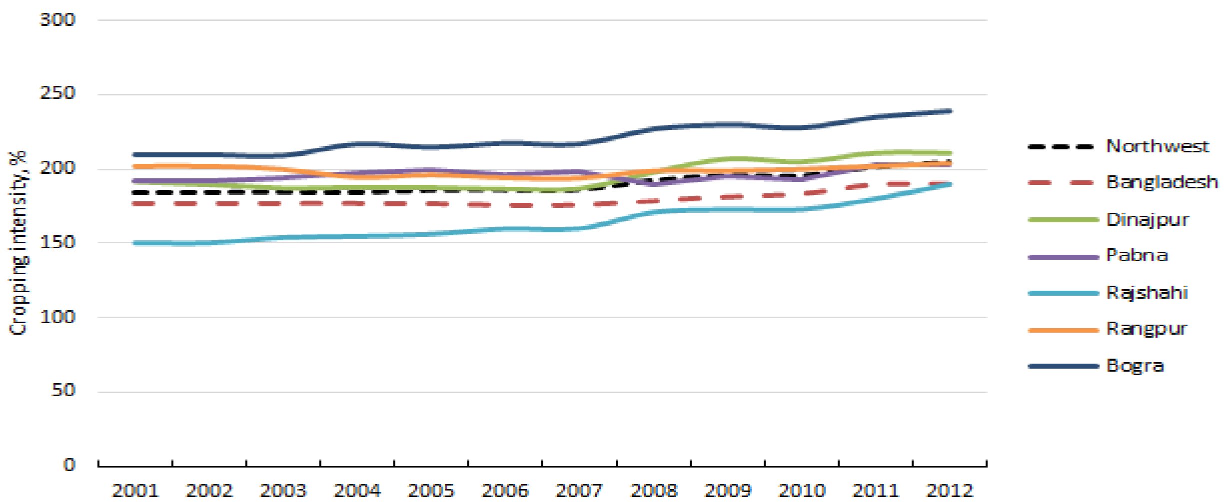

Figure 2.8 Cropping intensity (%) in the major districts of the northwest region with the average of the region (black dotted line) and the country (red dotted line)

2.3 Trend in area of major crops

Over the last decades, there was phenomenal growth in the area of Boro rice (Figure 2.9) in the country. In the northwest region in 1979-80, the area was 116 thousand ha which has risen to 1.62 million ha in 2014-15; an increase of about 14 times. There was linear growth in the area until 2008-09. Since then 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 (a decrease of 3.3%) ha in 2010-11 and then again risen to 379,101 ha in 2014-15 in Rajshahi (the most water stressed area).

The increase in the area of Boro rice was due to decrease in the area 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) as the net cropped area during this period has decreased during this period due to urbanization and industrial development. The area of Aus in the region has declined gradually; from the maximum of 968 thousand has in 1983-84 to minimum of 110 thousand ha in 2004-05 (Figure 2.10). Over the last 5 years the area has increased to over 200 thousand ha. The government policy is to increase the Aus area and reduce the Boro area. But there is no noticeable growth at the regional level over the 7 years. Only in Rajshahi, there is noticeable growth in Aus area which has risen to 162 thousand ha in 2011-12 from 59 thousand ha in 2001-02. In 2014-15 the area was 143 thousand ha.

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 in-seasonal drought 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 ha in the region as shown in Figure 2.11. The area is also steady within the greater districts.

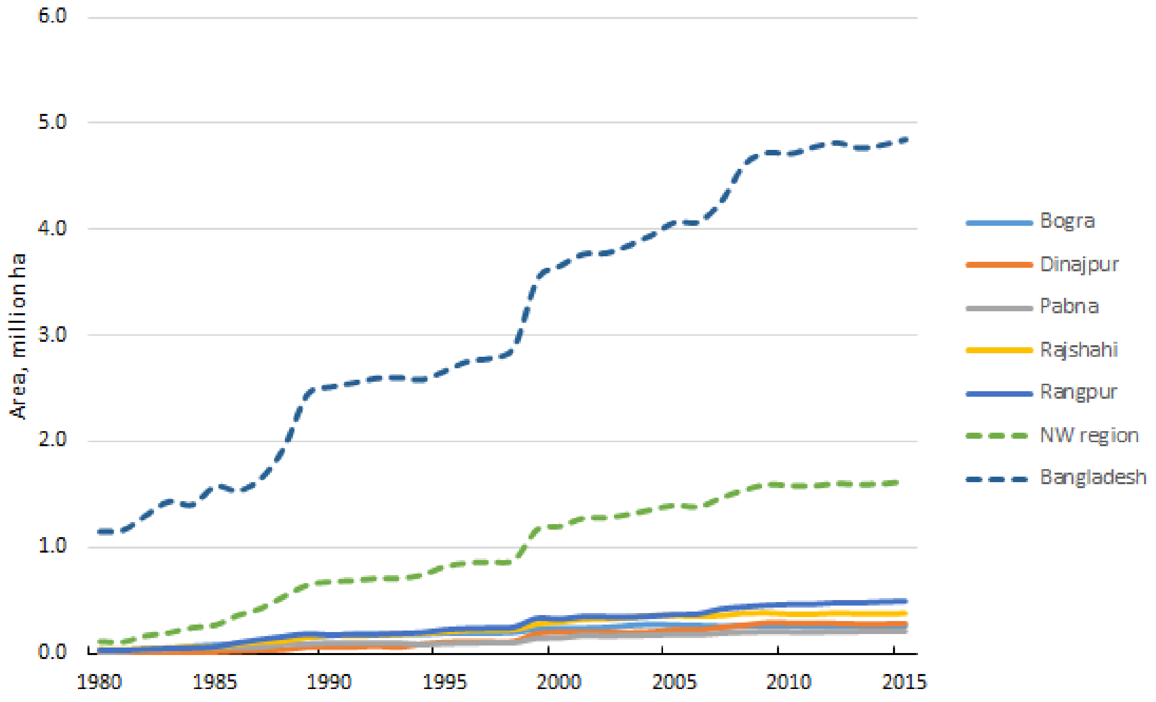

Figure 2.9 Trend in area of Boro rice

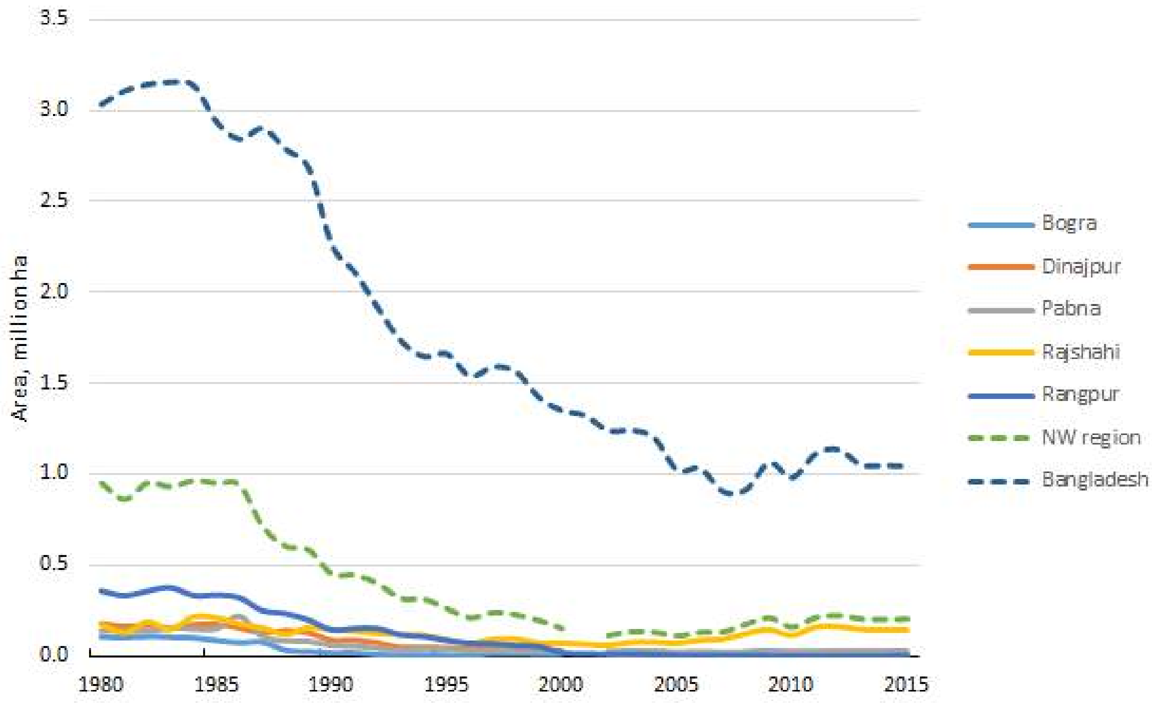

Figure 2.10 Trend in area of Aus rice

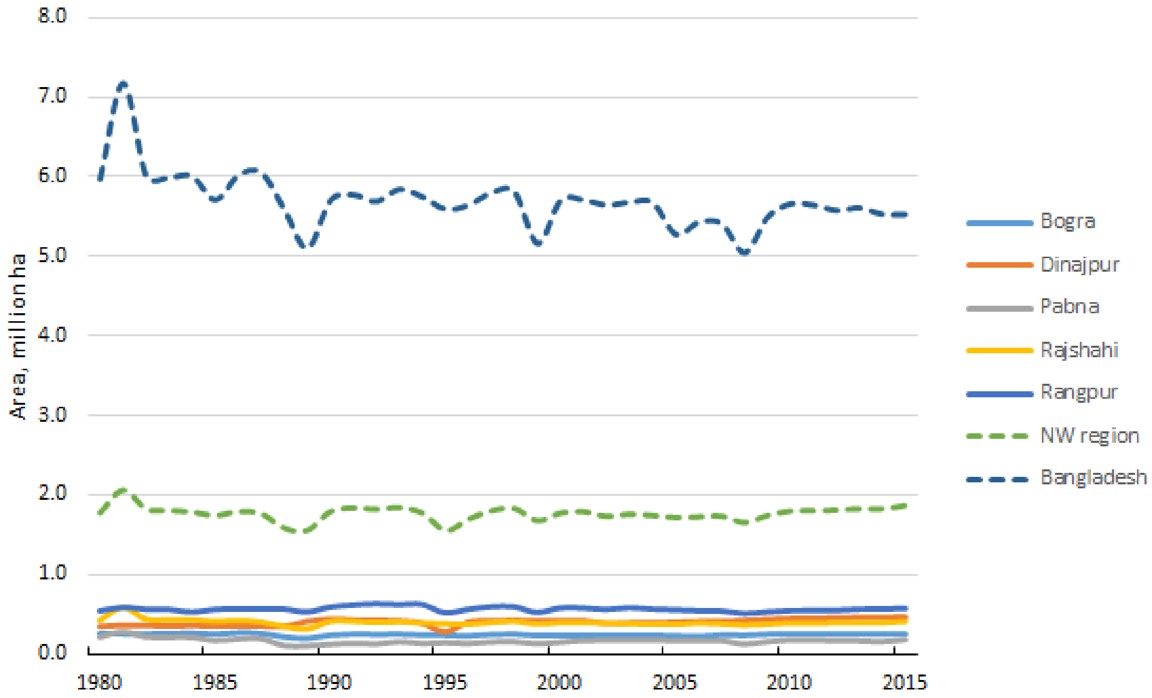

Figure 2.11 Trend in area of Aman rice

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

The decrease in the area of wheat can be partly attributed to the increase in the area of maize. The area of maize has increased exponentially with a dip in 2008-09 and 2009-10. The area has increased from 7 thousand ha in 2001-02 to 148 thousand ha in 2007-08 and reduced to 99 thousand ha in 2009-10. Since then area has increased exponentially again to 211 thousand ha in 2014-15. 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 area 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).

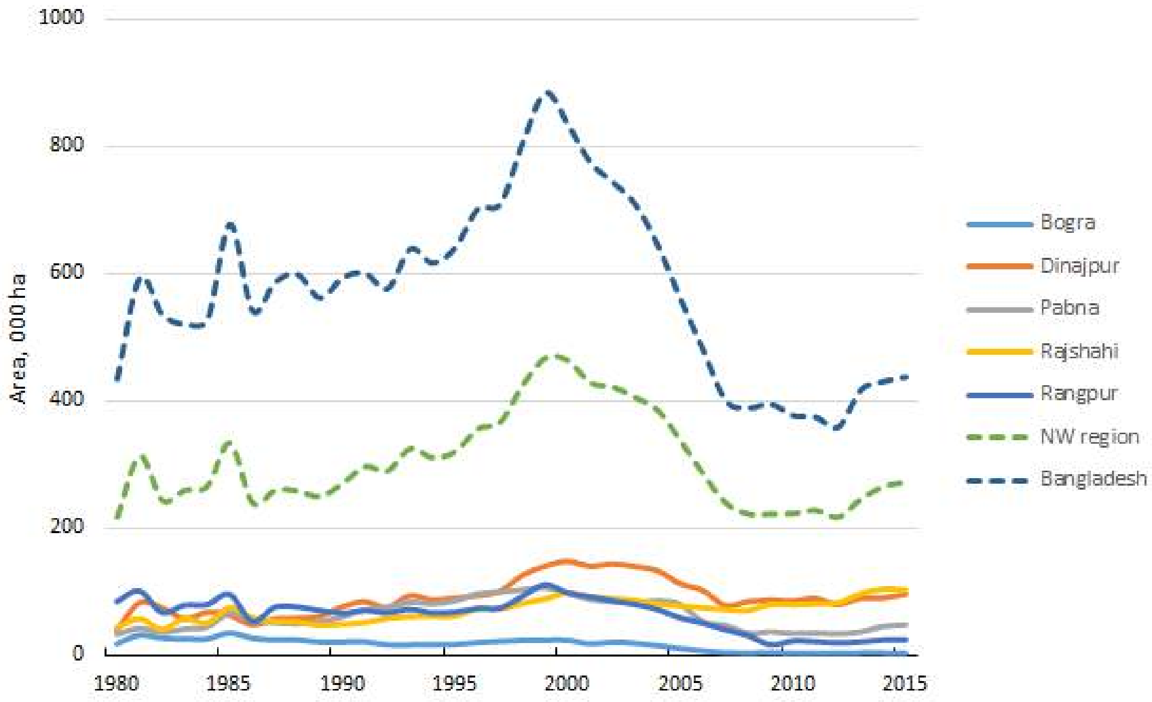

Figure 2.12 Trend in area of wheat

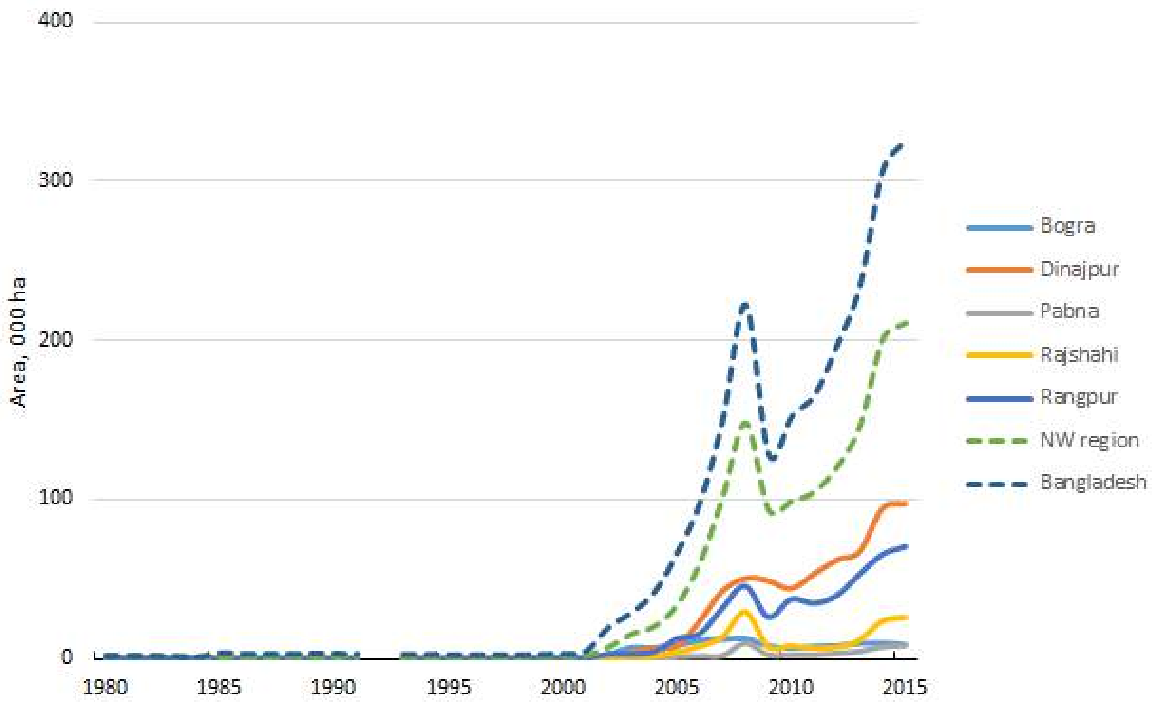

Figure 2.13 Trend in area of maize

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). Number in parenthesis shows the % of the country's statistics

2.4 Trend in yield and production of major crops

Bangladesh has been making remarkable advances in rice production. At the country level total rice production has 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 has increased from 1.23 to 3.04 tonne/ha at the country level. Production increases have 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 rice (Figure 2.15) due to replacement of low yielding local varieties with the high yielding and hybrid (recently) 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-weighted the growth in population. In the early nineties, with the total population of 106 million net import of food gain was around 3 million tonne/year (Islam and Mondal, 1992). Currently (2012-13), with the population of 152 millions, Bangladesh has gained self-sufficiency in rice production (The Daily Star, 2013).

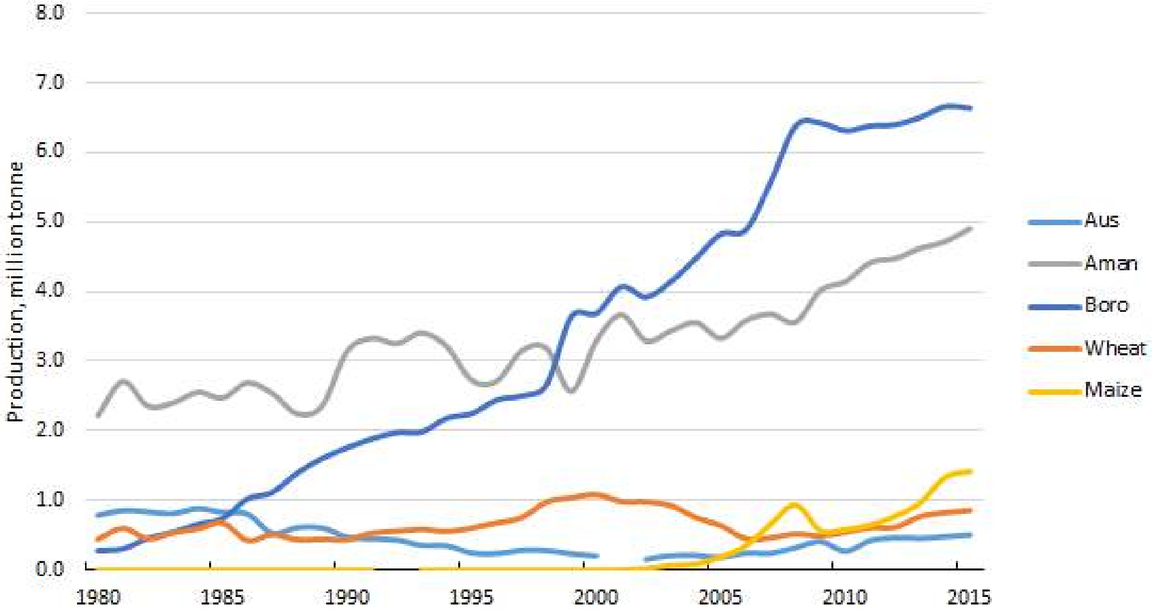

Figure 2.14 Trend in total production of major crops in the northwest region

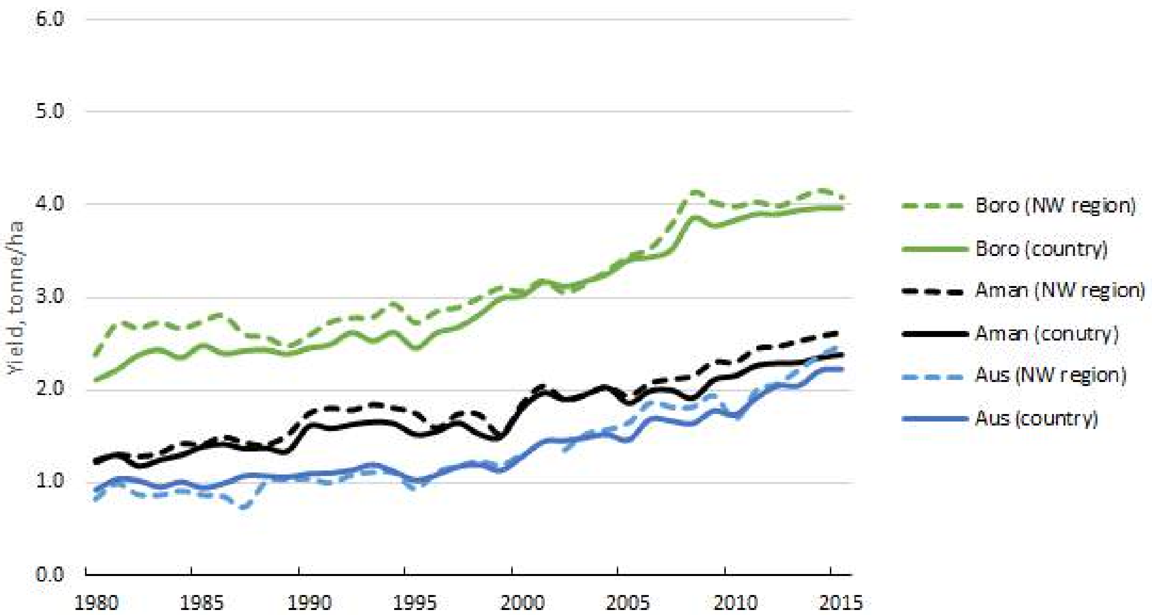

Figure 2.15 Average yield of rice in the northwest region (dotted lines) and at the country level (solid lines)

Average yield of Aus, Aman and Boro rice has increased consistently all over the country, with some ups and downs as shown in Figure 2.14. 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 fully irrigated crop so the risk of this being suffer 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 to that, Aus and Aman rice (particularly Aman) also suffer damage due to inundation and flood from heavy rainfall (Roy, 2013a).

There is significant spatial variation at the district level in the yield and its growth (Figures 2.16 to 2.18). 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 Bogra and lower in the Pabna and Rangpur. Yield fluctuates from year to year but in general 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.

The variation in the yield of Aman among the districts is similar to that of Aus within the region (Figure 2.17). Currently (2014-15), average yield is higher and almost similar in the greater districts of Bogra, Rangpur, Rajshahi, and Dinajpur. The lowest yield were in Pabna. In all districts, average yield has increasing trends. For the region, the average yield has increased from 2.12 tonne/ha ion 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 2.17). The CV of average yield for the districts varies from 4.4 to 6.4% over the last 10 years (2005-2015). For Aus this was 10.7 to 26.0% and for Aman 8.8 to 11.4%. There is no growth in 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 2.16 Spatial variation and trend in the yield of Aus rice during 2006-07 to 2010-11

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

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

While there is linear growth in rice production and yield, wheat production and yield were going through ups and downs (Figures 2.14 and 2.19). At the country level, the maximum production 1.9 million tonnes was in 1998-99. In the northwest region, this was 1.085 million tonnes in 1999-00. Currently (2014-15) the production of wheat in the northwest region is about 0.856 million tonnes. The increase in total production up to 2008 was mainly due to the increase in total area of cultivation as 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; in the northwest region yield increased from 2.02 tonne/ha in 2009 to 3.15 tonne/ha in 2015. The average yield is slightly higher in the region than the country average.

The total production of maize has dramatically increased since 2001 (Figure 2.14). The total production in the northwest region was 3,430 tonne which has increased to 1.415 million tonne (412 times) in 2015. This is both due to increase in area and yield. Over this period the area has increased from 1,314 ha to 210,997 (161 times) ha 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 sector. The average yield of maize in the region is at par with the country average yield (Figure 2.19).

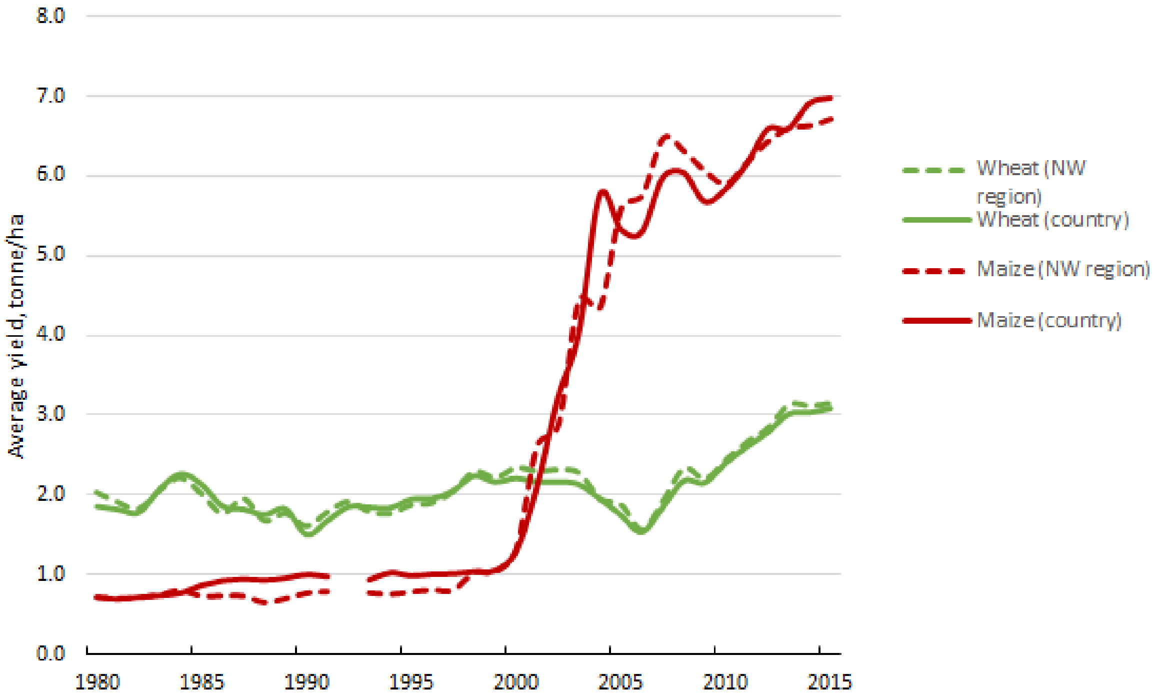

Figure 2.19 Average yield of wheat and maize

The growth in cropping intensity (discussed in Section 2.2) and the manyfold increase in rice production was driven by increased cultivation during the dry season, particularly Boro rice, made possible by the growing availability 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 phenomenal 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 has increased from 1.52 million ha in 1983 (18% of the net cultivable area) 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 as shown in Figure 2.20. The number of STWs has increased from 93 thousand to 1.55 million during this period. The number of deep tubewells (DTWs), which also pump groundwater, has increased from about 14 thousand to about 37 thousand. 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 80% of the total area (4.22 million ha) is irrigated using groundwater sources.

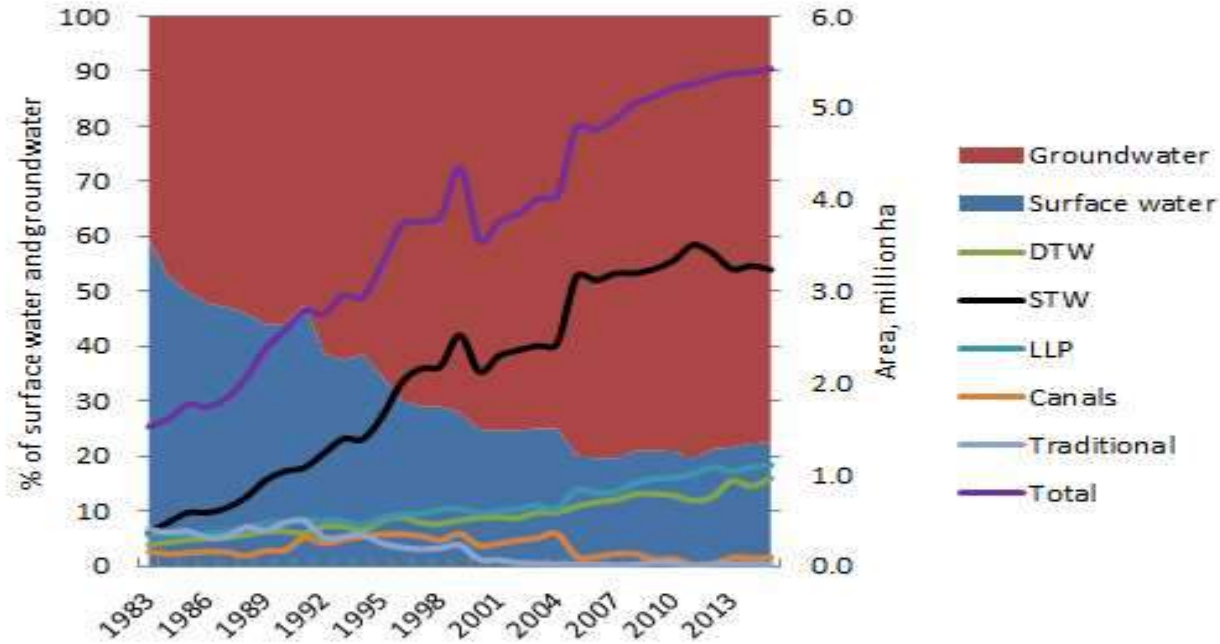

Figure 2.20 Area irrigated by different technology and source of water in Bangladesh (data source: BADC data)

The growth in irrigation, more specifically groundwater irrigation, was not uniform over the whole country. Northwest region is the most intensively irrigated area of the country. Currently, 83% of the net cultivable area (NCA) is irrigated in the northwest region compared to the 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 (Figure 2.22 and 2.23). On average, there are more than 28 STW and 1 DTW per 100 ha of cultivable area of the region.

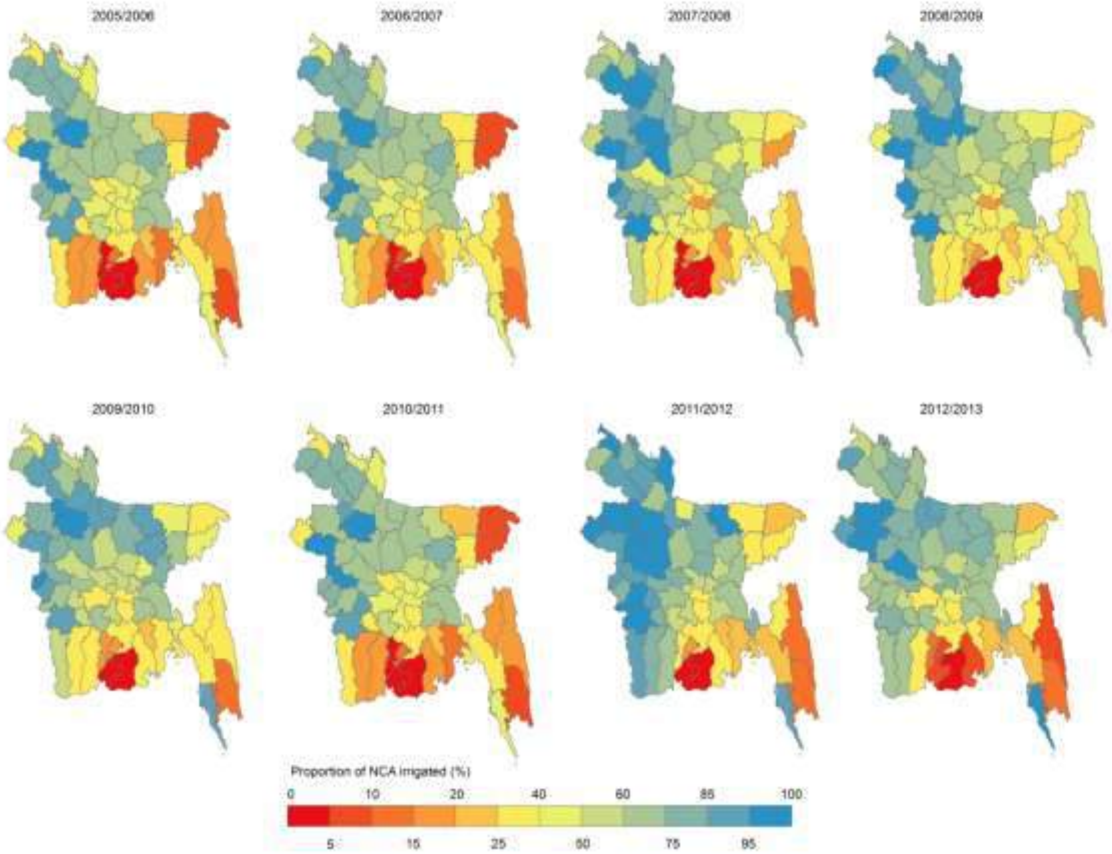

Figure 2.21 Proportion of net cultivable area (NCA) irrigated (data source: BADC)

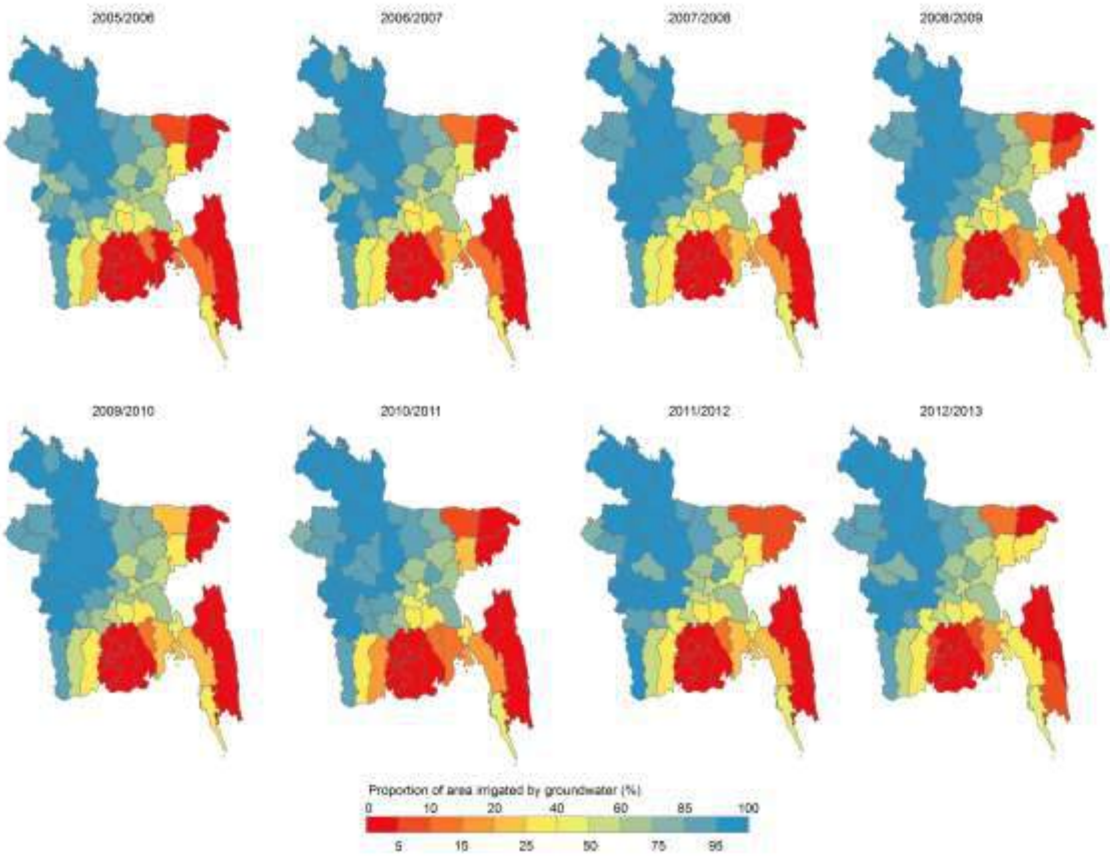

Figure 2.22 Proportion of net cultivable area (NCA) irrigated by groundwater during 2005–06 to 2012–13 (data source: BADC)

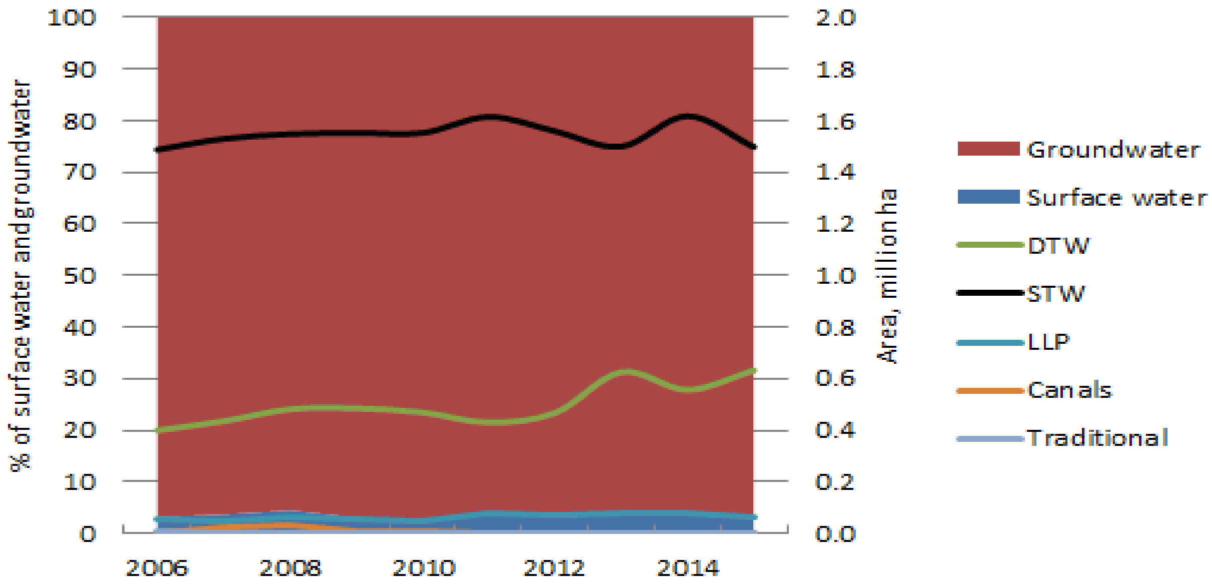

Figure 2.23 Area irrigated by different technology and source of water in the northwest region

The growth in irrigation appears to have slowed down in recent years (Figure 2.24). At the country level, the 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 the last year (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 are for Boro rice (Mainuddin et al. 2015).

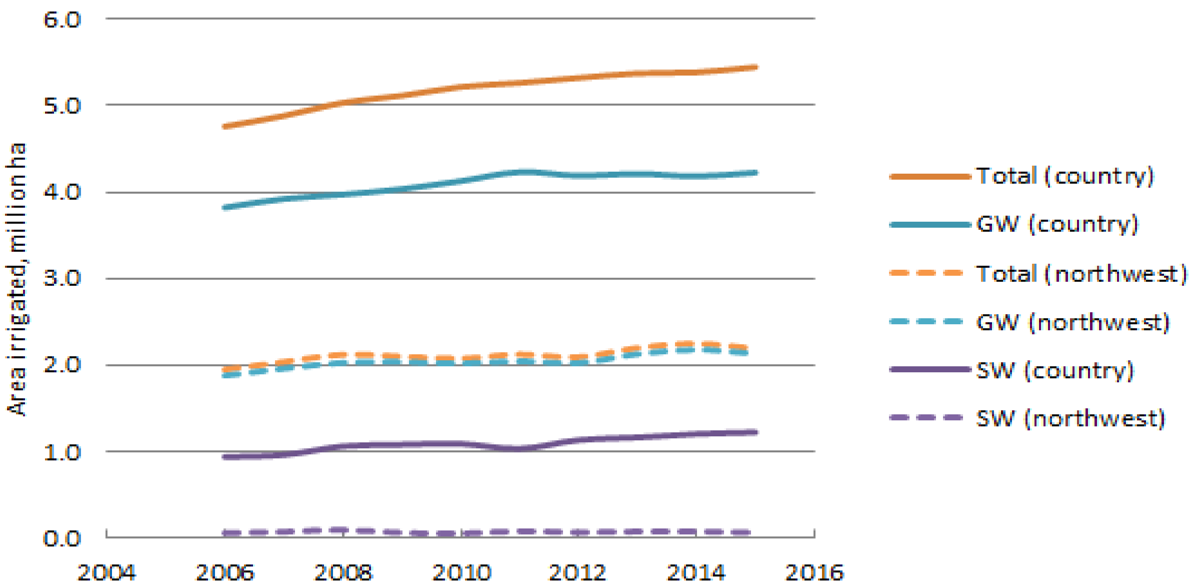

Figure 2.24 Trend in irrigated area in recent years for the country and the region

2.6 Sustainability of groundwater irrigation

There are serious concerns about the sustainability of the 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), Salem et al. (2017), all show that groundwater levels are falling in the Barind Tract and that current abstraction is unsustainable. Imon and Ahmed (2013) also show 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), conclude that the use of shallow aquifers for irrigation in some area 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) depletes the aquifers. The deepest groundwater conditions are from April to May 15, i.e. pre-monsoon, whereas the shallowest water tables are in November, i.e. 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, 2014). The groundwater table in northwest and north-central regions (with or without Dhaka district) is deeper than in other regions. The spatial variation in pre-monsoon groundwater depth is shown in Figure 2.25 (CSIRO, 2014). The 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.

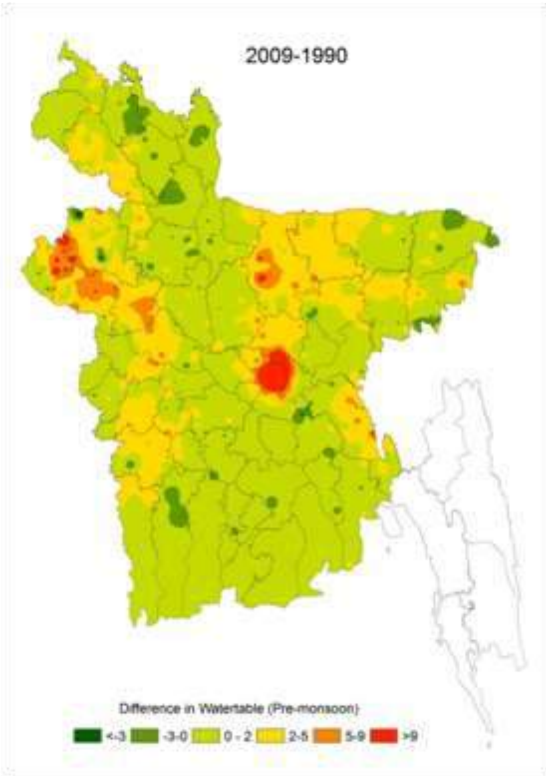

Figure 2.25 Spatial variation (difference in water table between 2009 and 1990) in pre-monsoon groundwater depth (m) across Bangladesh. The Eastern Hill Tracts in south east Bangladesh were excluded from the analysis (source: CSIRO, 2014)

Hodgson et al. (2014) also analysed the groundwater trends in 704 monitoring boreholes across Bangladesh (excluding the Eastern Hill Tracts). Some wells show stable water levels, and others show declining water levels. 56 % of the wells show declining water levels, and 44 % show stable 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 the northwest region, are dominated by wells with stable groundwater levels.

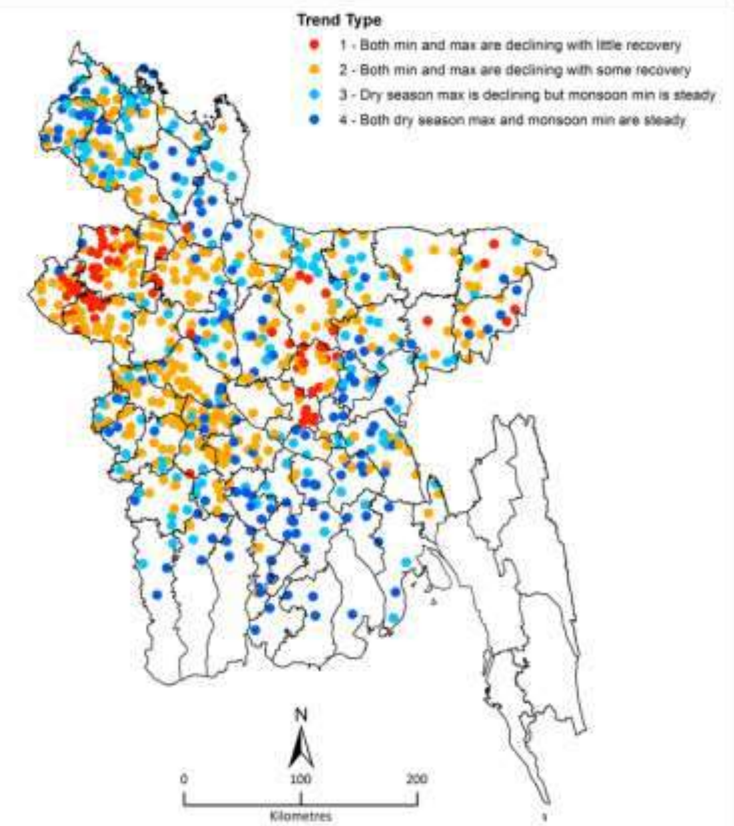

Figure 2.26 Distribution of wells of different trends in groundwater level. The Barind Tract is in the region in the west of Bangladesh dominated by a concentration of declining trend wells (indicated by red points). (Source: Hodgson et al., 2014)

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 (STW) and hand pumps inoperative (they cannot lift the water higher than 8 m), which leads to a lack of access to water for drinking and irrigation. There are many such STW in the northwest region particularly in the Bogra district. So to ensure irrigation supply to the crops, farmers install the STW below the ground level (Figure 2.27). Falling groundwater water 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, 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 tubewell has declined (Figure 2.28) slightly in recent years. The reason for this could be the declining of groundwater level below the suction limit of the STW which has resulted in farmers now installing more DTWs instead of STWs. In our monitoring site in Bogra (discussed in the next Chapter), we have found that farmers have installed a DTW replacing STW due to problem with pumping groundwater during driest months.

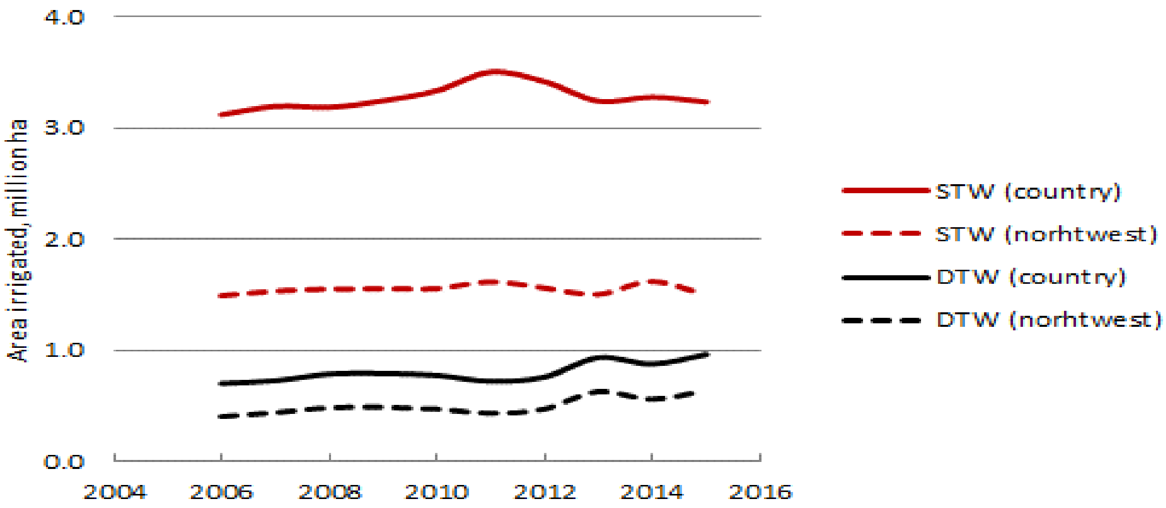

Figure 2.28 Area irrigated by shallow tubewells (STW) and deep tubewells (DTW) in the northwest region and in the country

2.7 Conclusion

Northwest region is at the heart of the current agricultural development of the country and produce the majority of the country's main agricultural products as shown in Table 2.1. However, due to the concerns of the sustainability of groundwater use, the Government of Bangladesh intends to decrease dependence on groundwater by increasing use of surface water for irrigation (Government of Bangladesh, 2010) and also reduce pumping through crop diversification; replacing *boro* rice with other non-rice crops particularly wheat (Government of Bangladesh, 2010).

Due to risk of floods and other natural disasters in the monsoon season, the dry season is the most productive, risk free and diversified cropping season. Therefore, the yield of *boro* rice is the highest among the three types of rice grown in Bangladesh as shown in Figure 2.15. Currently (2012), the contribution of *boro* rice to total rice production is 55% (Mainuddin et al. 2014). Apart from *boro* 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 from the current 151 million to 185 million in 2030 and 202 million in 2050 (UN Population Division, 2012) for medium variant population growth. Mainuddin and Kirby (in review) 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 *boro* 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 expected to be done through intensive monitoring of the groundwater irrigation by the farmers in the region.

To select the specific site for monitoring, we have used following criteria for the selection of the monitoring sites.

1. Select 4-6 sites with a good geographical spreads within the northwest region (probably 1 each in Rajshahi, Pabna, Bogra, Rangpur, Dinajpur and Thakurgaon Districts)
2. Each site will have a group of deep tubewell (DTWs) and shallow tubewell (STWs) covering a considerable area (10 to 20 ha), selecting an area bounded by the village home.
3. 2 (DTW) and 4 (STW) sites. DTW sites can be in Rajshahi and Thakurgaon Districts.
4. Both diesel and electric pump (1 DTW site and 2 STW sites in each)
5. Irrigate rice and other crops (such as potato, tomato, wheat and maize) as well. STW site in Bogra 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, fix land area based water charge, smart card, diesel + fixed charge, etc.).
7. Convenient for communication (but not biased).

For selection of study sites, we have extensive visited the fields in 6 districts of the region and selected sites for monitoring and data collection (Figure 3.1). The major mode of irrigation of the district was taken under consideration. With that consideration Rajshahi and Thakurgaon were selected as DTW irrigation zone. STW irrigation is the main mode of irrigation in other 4 sites though both DTW and STW irrigation is being practiced. 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
iii) Rice is the main dry season crop of the area

Figure 3.1 Selected sites for monitoring and data collection

The description of each site is given below:

Thakurgaon: We visited about eight DTWs and finally selected three electrical operated DTWs based on the selection criteria in the villages of Dhandogaon and Jogonnathpur (Figure 3.2). 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 which also represents the special demographic character of the area. There is 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 site 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 electrical operated STWs and finally selected 5 STWs at Gurnurpur village of Kaharol upazila (Figure 3.3). Two of the selected STWs are electrical driven and 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. A large number of tribal people live in this area. All the STWs represent the crops cultivated and cropping patterns practiced in the area. There are large number of marginal and tenant farmers in the area.

Figure 3.3 STW site at Kaharol Upazila, Dinajpur

Rangpur: We visited about 20 STWs at Pirganj and Mithapukur Upazila to find out the diesel operated and electrical operated STWs and finally selected 6 STWs at Ramnatherpara village of Mithapukur upazila, of which 1 electrical driven and 5 diesel operated STWs based on the selection criteria (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. All the STWs represent the crops cultivated and cropping patterns practiced in the area. There are large number of marginal and tenant farmers in the area.

Figure 3.4 STW site at Mithapukur Upazila, Rangpur

Bogra: We visited about 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. Maize, Wheat, Potato, vegetables, Spices, oil seeds and pulses are the major non-rice crops. There are large number of marginal and tenant farmers in the area.

Figure 3.5 STW site at Sherpur Upazila, Bogra

Pabna: We visited about 25 STWs at Pabna Sadar, Chatmohar and Ishurdi Upazila to find out the diesel and electrical operated STWs and finally selected 5 STWs at Baliadangi village of Muladoli union, Ishurdi upazila, of which 3 electrical driven and 2 diesel operated STWs (Figure 3.6). Irrigated Rice is the main dry season crop of the area. But maize, wheat, potato, vegetables, spices, oil seeds and pulses are also cultivated in the highland. There are large number of marginal and tenant farmers in the area. The static water level crosses the suction limit of STWs during the dry season. Therefore, the STWs are installed in deep by digging pit with 1-2 meter depth.

Figure 3.6 STW site at Ishurdi Upazila, Pabna

Rajshahi: DTW irrigation is practiced in Rajshahi as static water level is far below the suction limit of STW coverage. We visited about 10 DTWs and Mini-DTWs at Tanore Upazila to find out the 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 are installed by the Barind Multipurpose Development Authority (BMDA). Some low capacity private DTWs (Mini-DTW) are also used for irrigation. All DTWs are electrical driven. 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 STW and 6 DTWs in six sites. For monitoring, we considered all the plots under the command area of the STWs. Command area of the DTW are very big. The irrigation water is supplied to the field through underground pipes with outlets and certain interval 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 detail of each STW and DTW and their command area is given in Table 3.1.

3.2 Monitoring of data in the farmers field

We have monitored and all the plots within the command area STW. In DTW irrigation systems, plots belongs 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. Input 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 details are given in the forms in the Appendix.

The discharge of the irrigation units were measured during the initial, middle and later part of crop growing season. Amount of irrigation water applied in each irrigation 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.

Table 3.1 Characteristics of the selected STWs and DTWs

Site	Type of tubewell	Power source	Discharge capacity (lit/sec)	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

3.3 Irrigation water pricing

Variation exists in irrigation water pricing in 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 for a unit area (1 bigha=33 decimals or approximately 1336 m^2) a certain amount of money is fixed prior to the whole season (for Boro rice) or an individual irrigation (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 seasons. Most of their DTWs are pre-paid card metering system. Some STWs use this irrigation charge system for non-rice crop and supplementary irrigation of Aman and Aus rice. The cost of energy or fuel is included within the charge.

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

Mixed charge: This system combine area based charge with actual fuel consumption. In this system, a fixed charge per unit area is taken in addition with the fuel used for irrigation. Water users bring their fuel and irrigate as long as their wish. The money fixed per unit area is the charge for the irrigation unit and locally termed as “handle charge”.

Table 3.2 Current irrigation water pricing systems in different areas of Bangladesh.

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
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, Bogra	Rice	DTW STW (with diesel engine)	Tk. 2000 /bigha Tk. 3000-3200 /bigha	1 bigha = 33 decimal
	Non-rice			
Faridpur	Boro	Crop share	25% of grain	
Faridpur	Onion	Area basis (for any frequency)	Tk. 20/decimal	
Bhola	Boro	Area basis (for any frequency)	Tk. 5000-6000/kani	1 kani=160 dec
Panchgor	Boro	Area basis (STW- diesel) Area+Fuel (STW-diesel) DTW (BMDA) Area basis STW (electric)	Tk. 2000/ bigha Tk. 1000/bigha+ fuel Tk. 130/hour Tk. 1500-2000/bigha	1 bigha = 33 decimal
Sirajgonj	Boro	Crop share	20-25% of grain	
Joypurhat, Pabna	Boro	Crop share Area basis (STW- diesel) Area+Fuel (STW-diesel) DTW	3/16 or 4/16 Tk. 1800-2000/ bigha Tk. 800/bigha+ Fuel Tk. 1000-1200/ bigha	1 bigha = 33 decimal
Kustia	Boro	Area basis (STW- diesel) Area basis STW (electric)	Tk. 4000/ bigha Tk. 2000/ bigha	1 bigha = 33 decimal

Price information collected during the field visit in April 2018 by Mainuddin

Thakurgaon:

DTW water charge – 110 Taka/1 hour

DTW discharge rate – 60 lit/sec

Operator gets 10 Taka out of 110 taka per hour charge. BMDA gets 100 taka/hour

Birganj (SOLARGAO):

- Irrigation charge for Boro rice is based on area 7000 Taka/acre or 70 taka/decimal
- For non-rice crops, 6 Taka/decimal/irrigation
- Rate varies from place to place

Mithapukur:

- Water charge for the whole season- electric pump 2000 Taka/50 decimals or 4000 Taka/acres for rice
- 500 Taka/irrigation/50 decimals for maize or all rabi crops i.e. 1000 Taka/acre/irrigation
- Discharge of the pump is 25 lit/sec
- For diesel pump- machine charge 3,200 Taka/acre, farmers bring his own diesel. Last year the rate was 2,400 Taka/acre
- 36-40 litre of diesel is necessary for 50 decimal for the whole season.
- Diesel price is 68 Taka/litre
- For Rabi crops (wheat/maize) 1000 Taka/acre/irrigation. Farmers do not need to bring his diesel. Pump owner provide diesel.

Bogra:

- Irrigation cost 3,000 Taka/33 decimals (include all costs)
- With farmer's own diesel, 1200 -1500 Taka/33 decimals (machine charge)
- 20-22 litre/bigha (33 decimal) of diesel are required.
- 20-24 irrigation per season are given by the farmers.
- DTW nearby – 2000 Taka/bigha (33 decimal)

Ishurdi:

- For STW ¼ of rice (grain + straw). Usually, the farmers and the pump owner divide the field in 4 equal segment. Pump owner then get on quarter. He harvest and take everything. Pump owner provides fuel for the STW. Farmers do not share. In this season, the pump owner spent 270 lit of diesel for 20 bigha (33.3 decimal per bigha) of land for irrigation.

3.4 Estimation of irrigation water requirements of the crops

We have 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, Bogra (for Sherpur), Rangpur (for Mithapukur), Dinajpur (for Kaharol) and Sayedpur (representing Thakurgaon). Using these data, we have 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 Agricultural 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 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 coefficients approach is described in Allen et al. (1998) and Doorenbos and Kassam (1979). More detail about the model can be found elsewhere (Mainuddin et al. 2014, and 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, and Mainuddin et al. 2015).

Soil properties (field capacity, wilting point, water holding capacity, percolation rate, etc.) are important parameters for the SWB model. Based on field observation, 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 has also clay loam soil. Mainuddin et al. (2014) collected soil data (percentage of sand, silt and clay) for the 3 major (covering maximum area) soil series 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. We have used percolation rate of 6.0, 3.0 and 2.8 mm/day respectively for the sandy loam soil, clay loam soil and silty loam soil as used by Mainuddin et al. (2014). Crop coefficients, and yield response factors are 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 were used from the field observation. The length of the growth stages was taken primarily from the FAO Irrigation and Drainage Paper 56 but were adjusted based on the actual duration of the crops in the field.

Water is supplied from the pump to the fields by various distribution system such as buried pipes, lined and earthen channel, and polythene pipe. So there are conveyance losses in the distribution system. The amount of loss depends on the type of distribution system used, their condition and the distance from the pump to the field; longer the distance of the field, higher 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 given in Table xx.

Table 3.2 Percolation rate 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, polythene pipe and unlined channel. Lined	5% (Belal et al. 2014)

		channel in Ishurdi is made of brick wall with cement neat finishing	
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 were few). So, loss will be 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)

Rahman et al. (2011) conducted a study on the irrigation water loss in 8 DTWs of Bogra, Thakurgaon and Godagari (close to Tanore) area. In Thakurgaon buried pipe irrigation water distribution systems were used. The conveyance loss was 6.53% 7.48% and 8.06%.

4 Observations, results and discussions

In this chapter, we present the results and observation based on the analysis of the data collected from the farmers' field. We monitored 336 plots across six locations in 2015-16 and 195 plots in 2016-17 across 5 locations. Size of monitored plots ranged from 0.02 ha to 0.87 ha for 2014-15 and 0.02 ha to 0.47 ha for 2016-17. The mean and average plot sizes were was 0.15 ha and 0.13 ha respectively for the crop years. We compare the variation in the input use patterns and performance of crops at different level such as plot to plot with a command area of the STW or outlet of a DTW, different STW, STW 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 others sites.

4.1 Socio-economic profile of the farmers of the monitored plots

At the beginning of the season in 2015-16, we recorded the socio-economic information of each farmer of the monitored plot. Table 4.1 presents classification of farm households in the selected locations of 2015-16 (Tanore, Ishurdi, Sherpur, Mithapukur, Kaharol, and Thakurgaon). 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), Ishrudi (Pabna), Mithapukur (Rangpur) and Thakurgoan. 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. In the contrary, on average about 66% of 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 Kahrol (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). It may be because of farming is less or no profitable in the rented lands.

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

Farm types	Sherpur (n=12)	Kaharol (n=24)	Ishrudi (n=50)	Tanore (n=22)	Mithapukur (n=110)	Thakurgoan (n=18)	All (n= 36)
Farm size:	Percent 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 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 is indicated that most head of 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. Average farm size in the

study locations is 0.70 ha, with ranges between 0.50 ha to 1.05 ha. It was also the case that on average 70% of total operated area of the farm household is own land. On the other hand, number of farm machineries per households (power tractor, pump and threshers) indicates that most of the farmers relied on service providers for tillage, irrigation and threshing of crops in the study villages. The ownership of livestock in particular cattle and poultry per households indicates that livestock rearing in an important component of farming systems in the study villages.

Table 4.2 Agricultural statistics of farm households at different locations

Items	Sherpur	Kaharol	Ishrudi	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 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 poultry	20	7	7	15	13	4	11

Table 4.3 presents annual income of farm households in the study locations. Household income 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 representation of agriculture including crops, livestock and fisheries in the total household income is about 78%. On average, contribution of crops sector is 51% of total household income followed by livestock (19% of total income). The 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	Ishrudi	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

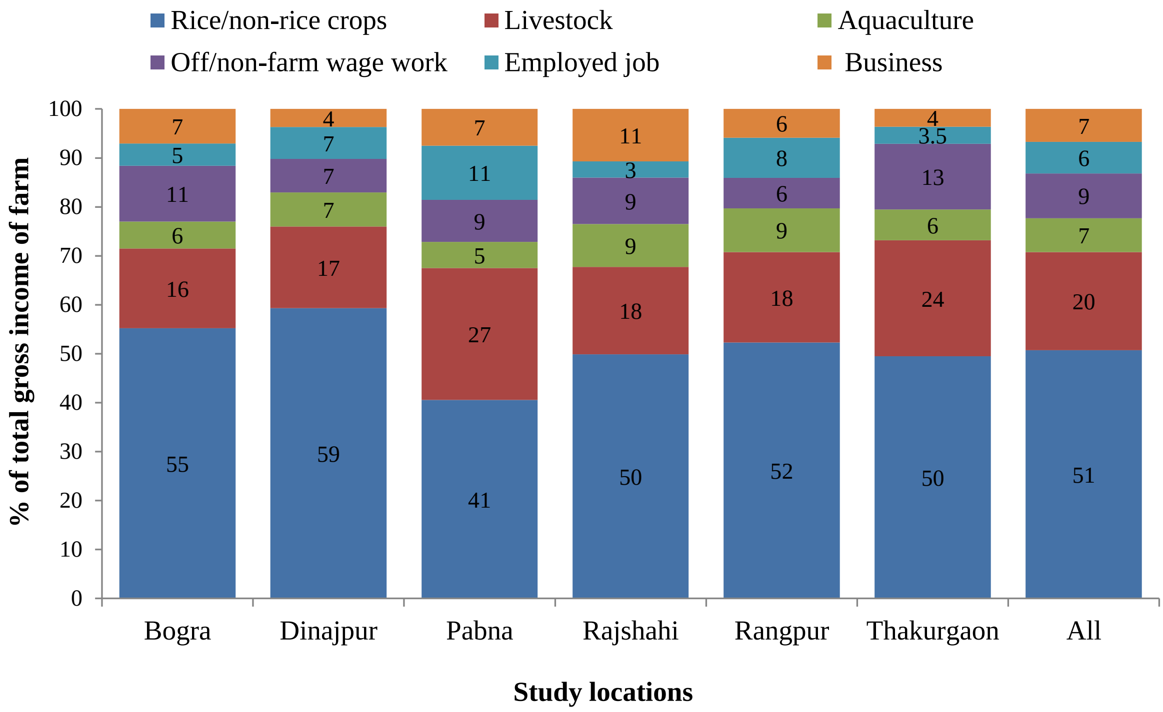

Figure 4.1 Representation of different sources in the total household income of farm households at different locations (district name has to be replaced by the site name)

4.2 Rice varieties cultivated

Rice is the predominant crops grown in all sites. Of the total 336 plots we monitored in 2015-16, rice was cultivated in 235 plots (35.05 ha). Wheat, maize, potato, lentil, mustard, cauliflower and okra are grown in the remaining 101 plots (13.05 ha) across six sites. So about 27% of the total area were under non-rice crops in 2015-16. In 2016-17, we concentrated our monitoring activities in 4 of the previous sites excluding Tanore of Rajshahi and Kaharol of Dinajpur. We have also added one additional site at Badarganj, Rangpur where irrigation pumps are run using solar energy. We monitored 195 plots in these 5 locations of which only 10 were with crops other than rice.

Among the study areas, maximum number of rice plots were in Mithapukur (69 plots in 2014-15, 62 plots in 2015-16), whereas, only eighteen plots were in Thakurgaon (Table 4.4 and Table 4.6). 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, eighty-three percent of the total plots were irrigated by STW, of which 49% (of the total) were by the diesel operated STW; the rest were 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 a farmers' intensive program that's included some seed 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*' usually are Aman or Kharif-2 varieties grown in monsoon period. The name of this variety is '*Jira*' however farmers call it Jirashail and 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, Bogra.

It is clear from Table 4.4 that maximum of two varieties (except Mithapukur where there are 4 plots with a third variety and Badarganj where there are 2 plots with 3rd 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 is getting popular because of their high yield with comparatively 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 at various locations with varieties of rice

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		
Kajal lata			21								
Minikit		21	31	45							

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

4.3 Time of transplanting of rice

Transplanting of rice started in late December and completed by the end of February in 2015-16. But most of the plots (80.5%) are 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 are transplanted during the period of 2nd half of January to the 1st half of February. Transplanting in Kaharol are 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.

In 2016-17, in Ishurdi of the 39 plots, 34 were transplanted during 27 January to 05 February. All the plots in Sherpur were transplanted during 25 January to 03 February. In Thakurgaon except 4 plots all were transplanted on 14 February. In Badarganj, all the plots were transplanted during 01-09 February. Mithapukur had the longest transplanting period again in this year. The transplanting started around 15

January and ended in 15 February though the overwhelming majority of the plots were transplanted during 01-15 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 the harvesting can be done on time.

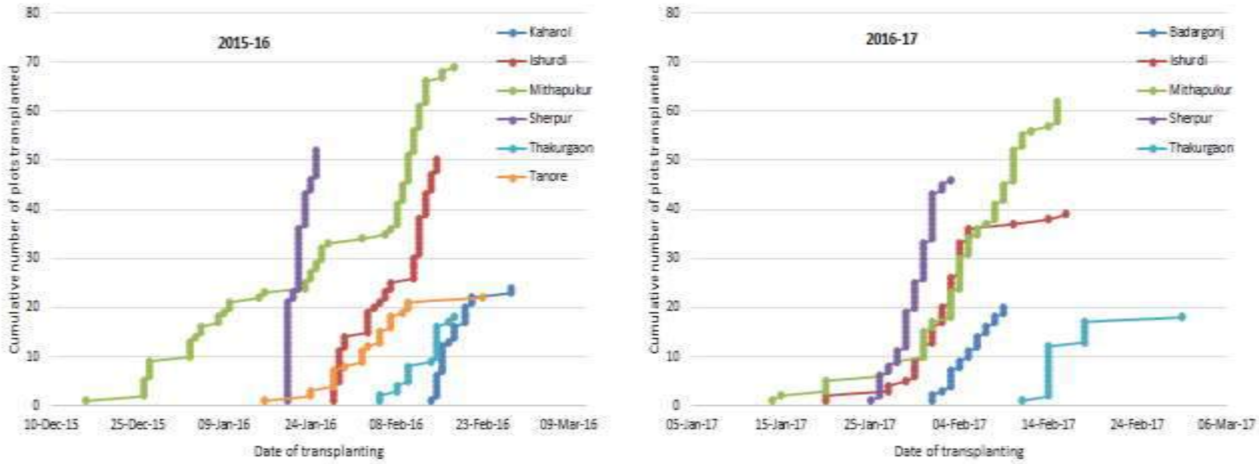

Figure 4.2 Transplanting period of rice at different locations (please note x-axis are not the same period in these two charts of 2 years)

4.4 Input cost of production of rice

We recorded input and labour used in every plots from nursery preparation to temporarily storing of the production after harvesting. The paid-out cost of production are 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 ha for the plots monitored for the crop years 2014-15 and 2016-17. The average seedling cost per hectare was 3,403 Taka/ha in 2014-15 and 4,036 Taka/ha in 2016-17. The ranges of the costs were between 1,420 to 6,693 Taka/ha in 2014-15 and between 2,410 to 9,139 Taka/ha in 2016-17. In 2014-15, Substantial variation was observed in the per hectare cost of fertilizer ranging from 4,141 to 20,400 Taka/ha. Average irrigation cost per hectare was 16,459 Taka/ha in 2014-15 which represents higher proportion (23%) of total paid-out (TPC). This is followed by the harvesting (crop cutting, transporting and threshing) cost (e.g., 22% of TPC) and fertilizer cost (17% of TPC) of the total paid-out cost.

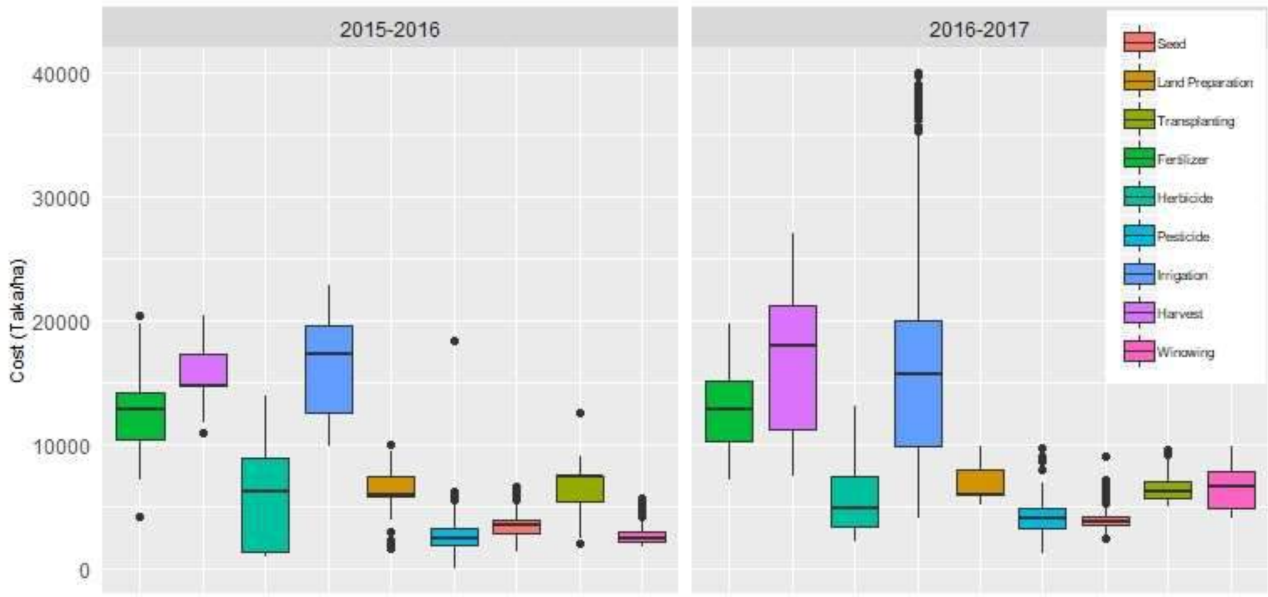

Figure 4.3 Variation of total paid-out cost for different inputs for growing rice

Average paid-out cost for different inputs used varies slightly from STW to STW within a location. In 2015-16 season, we monitored 5 STWs in Ishurdi; 3 of them (STW-1, STW-2, and STW-3) are used only for rice cultivation and the rest 2 (STW-4 and STW-5) are used for wheat and lentil cultivation. Three of the STWs (1, 4 and 5) are operated by diesel engine and the rests (1 and 3) are operated by the 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.

Table 4.5 Detail data of the STWs for Ishurdi

STW No.	Energy source	Discharge capacity (litre/sec)	Number of plots under each crops			Total cultivated area, ha
			Rice	Wheat	Lentil	
2015-16						
STW-1	Electric	12.86	6			1.87
STW-2	Diesel	14.0	19			2.94
STW-3	Electric	15.02	25			4.60
STW-4	Diesel	8.12		6	5	1.63
STW-5	Diesel	8.56		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 shows the Average total paid-out cost of different inputs for rice cultivation in Ishurdi for 2015-16 and 2016-17. Among the 3 STWs of 2015-16, the average cost of irrigation was lower (16,671 Taka/ha) under STW-1 compared to the costs in other STWs (above 21,000 Taka/ha). In 2016-17, average

irrigation cost was much higher 37,550 Taka/ha in STW-1 and 35,669 Taka/ha in STW-3. In this location, irrigation pricing is based on the share of crops. The tubewell owner supplies water to the field of the farmers for the whole season as and when required. When rice is ready to harvest, the field is divided into 4 equal parts. The tubewell owners harvest and take 1 parts (25%) as fees for irrigation. Here the fees are calculated using the price of rice and straw collected by the tubewell owner. So the fee varies from plot to plot due to the variation in yield. The advantage of this pricing is that farmers do not need to invest on irrigation at the beginning of the season. If for some reason the yield is not good or the field is damaged then the farmers' loss are less. The main disadvantage is that if the yield is high then the farmers are paying more for irrigation. There are both advantage and disadvantages also for the pump owner. While he is sharing the risk of failed harvest, he is also likely to gain more compared to the other pricing mechanisms.

Cost of irrigation is the highest among the inputs which 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 harvesting and carrying (17% in 2015-16, 10% in 2016-17). There is almost no variation in cost of different inputs due to the cultivation of different rice varieties (Figure 4.4, see the comparison of STW-3 with different varieties).

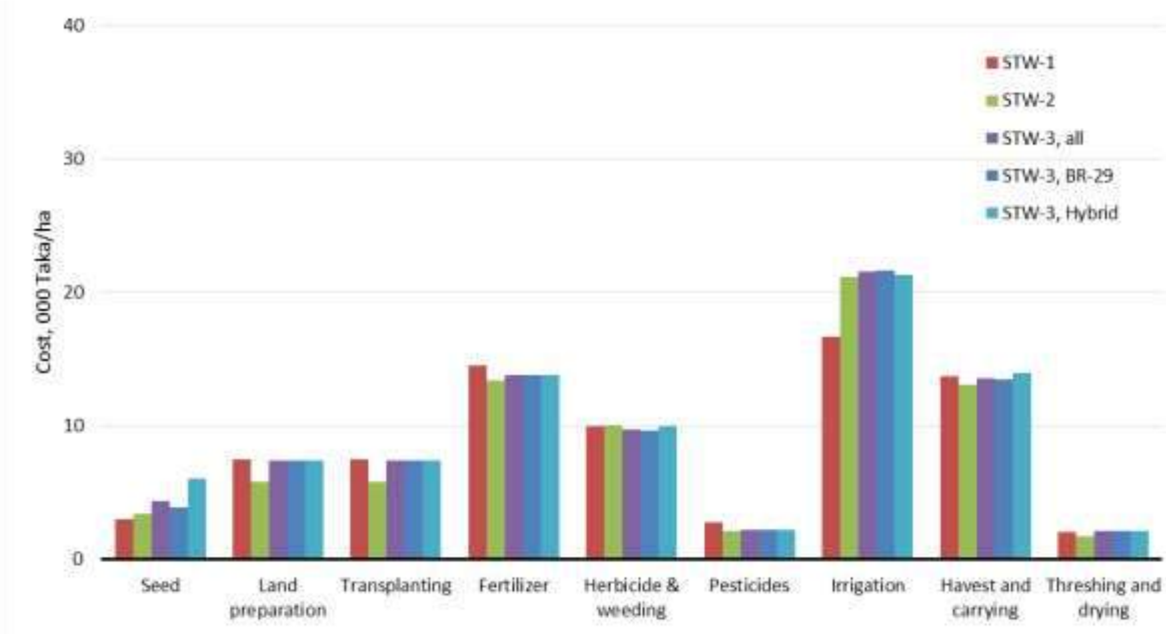

Figure 4.4 Average total paid-out cost of different inputs for rice cultivation in Ishurdi for 2015-16

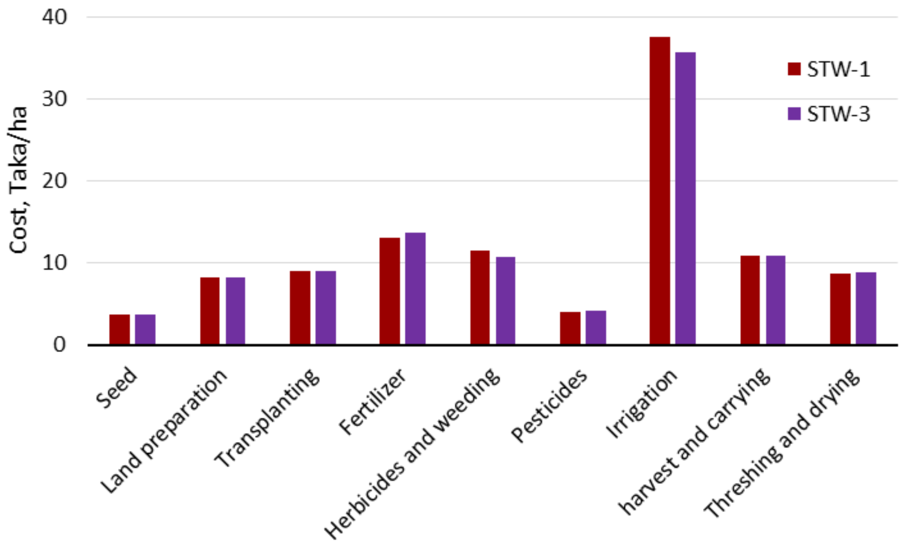

Figure 4.5 Average total paid-out cost of different inputs for rice cultivation in Ishurdi for 2016-17

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

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

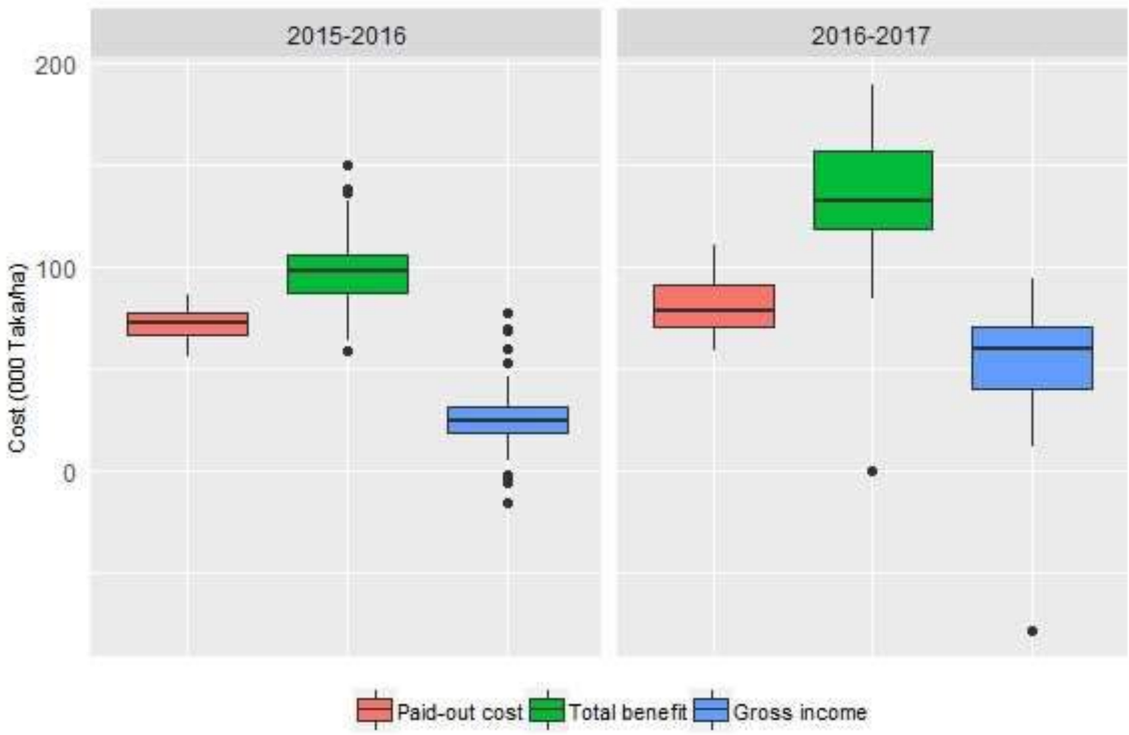

Figure 4.6 Variation (box plot) of total paid-out cost, total benefit and gross income of rice

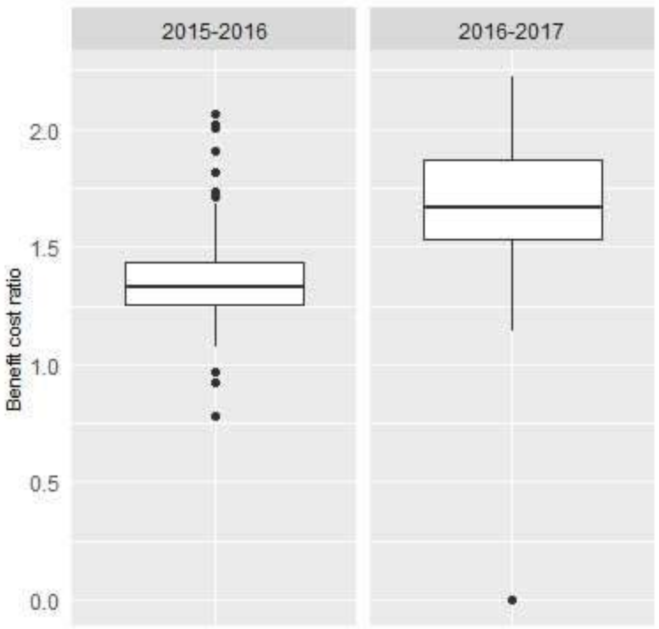

Figure 4.7 Variation in benefit cost ratio of rice

Considering all the plots, mean gross benefit and gross income were respectively 97,360 Taka/ha and 25,080 Taka/ha in 2015-16. Minimum value of negative gross income indicates loss from the specific plot, whereas, the maximum gross income was estimated as 77,640 Taka/ha. Total 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 plots with various background characteristics

Item	2015-16					2016-17				
	No. of plots	Yield tonne/ha	Total cost, Taka/ha	Gross benefit Taka/ha	Gross income, Taka/ha	No. of plots	Yield tonne/ha	Total 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	5.40	74,639	5.33	52,151
BRRI dhan29	61	6.72	78,231	103,949	25,717	43	6.81	84,510	6.81	67,198
Hybrid	43	7.39	72,582	100,344	27,762	28	6.05	78,515	6.06	64,226
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	5.18	43,068

Date of transplanting										
January	107	0.15	5.87	72,780	24,439	60	0.15	5.35	86,416	45,196
February first	104	0.15	6.49	73,683	26,896	113	0.13	5.92	80,913	58,052
February last	24	0.15	6.05	63,971	20,025	12	0.11	6.18	75,426	63,498

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'

We aimed to compare mean cost, income, productivity, and profitibility for various categories for background characteristics (location, pump type, variety, and transplanting date). The Analysis of Variance (ANOVA) technique has been utilised in the comparison. The ANOVA method assesses the relative size of variance among group means (between group variance) compared to the average variance within groups (within group variance). The ratio of 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 the 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 shows the results of ANOVA test conducted to test if statistically significant differences exist in total paid-out cost among various locations, types of pumps, variety of rice and date of transplanting. For the data obtained from 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 cost significantly differ among the locations, types of pumps used for irrigation, varieties of rice and transplanting dates. However, in 2016-17, the average costs did not differ much among the varieties of rice cultivated or the date of transplanting. The costs were significantly different across the locations and type of pumps used for irrigation.

Table 4.7 ANOVA for total paid out cost ('000 Taka/ha)

Source	2014-15				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 2014-15, Statistically significant variation in gross benefit were observed among the locations and variety 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 total benefit were not statistically significant among transaplanting dates. Type of pumps used for irrigation did not make significant variations in average gross benefit in the crop year 2014-15.

The ANOVA results for gross income for the two studied crop seasons is presented in Table 4.9. While analysing the data for the crop year 2014-15, Ssignificant vatiation ($p < 0.05$) in gross income were observed for the variables, location, pump type and varieties of rice. Transplanting date did not observed as a significant factor in the variation in gross income (Table 4.9). In 2016-17 crop year, along with the transplanting date, type of pump did not show a significant impact on gross income from cultivated rice.

Table 4.8 ANOVA for gross benefit ('000 Taka/ha)

	2014-15				2016-17			
Source	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
Trans 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 ('000 Taka/ha)

	2014-15				2016-17			
Source	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
Trans 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 has been utilised to compare total gross income between pairs of locations and pump types, and the results have been presented in Tables 4.10 and 4.11, respectively for years 2014-15 and 2015-16. Table 4.10 indicates that, in 2014-15 crop year, significant variations in total profit were observed between the pairs of locations, Mithapukur-Kaharol, Tanore-Kaharol, and Thakurgaon-Kaharol ($p<0.05$). The result indicate that, as compared to Kaharol, gross income is significantly higher in Mithapukur, Tanore and Thakurgaon. While considering the data from the crop year 2016-17, gross income for Sherpur was significantly lower than Ishurdi, Mithapukur, Thakurgaon and Badargonj. However, the gross income for Mithapukur is significantly lower than Ishurdi and Thakurgaon. The differences were not statistically significant for other pairs of locations.

Table 4.10 Differences in gross benefit across locations (2015-16)

	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 across locations (2016-17)

	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 2014-15, the results of post-hoc multiple comparison test for gross income across pump types is represented in Table 4.12. The result indicate that gross income from rice production is higher for the STW driven by electric motor compared to STW with diesel engine. However, the difference is statistically significant at less than 0.1 level (p = 0.06). The comparison was not made for the crop year 2016-17 as the variable did not come as statistical significant in ANOVA test. Alternatively, gross income for crop varieties has been conducted 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 among the types of pumps used for irrigation for 2015-16

	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 gross income across varieties of rice, 2016-17

	difference	LCL	UCL	p-value (adjusted)
BRRI 29-BRRI 28	4.27	-3041	11.94	0.47
Hybrid-BRRI 28	13.11	4042	21.81	0.00
Minikit-BRRI 28	5.90	-1.04	12.84	0.13
Hybrid-BRRI 29	8.85	-0.03	17.73	0.05
Minikit-BRRI 29	1.63	-5.53	8.80	0.93
Minikit-Hybrid	-7.21	-15.46	1.03	0.11

The variation of total paid-out cost, gross benefit, gross income, and benefit cost ratio for the plots within the command area of the tubewells for Ishurdi are shown in Figures 4.8 and 4.9. From Figure 4.8, it is obvious that, as compared with 2015-2016, total paid out cost increased significantly in 2016-17. However, because of higher price of the products, both gross income and gross benefit were higher in the latter year (2016-17). Considering the data for the same year, total paid-out cost was consistent across and within pumps (STWs). However, a relatively higher variation in gross income and gross benefit were observed for the plots within the command area of the STWs. In general, there is high variation from plot to plot in total paid-out cost, gross benefit, and gross income within a STW.

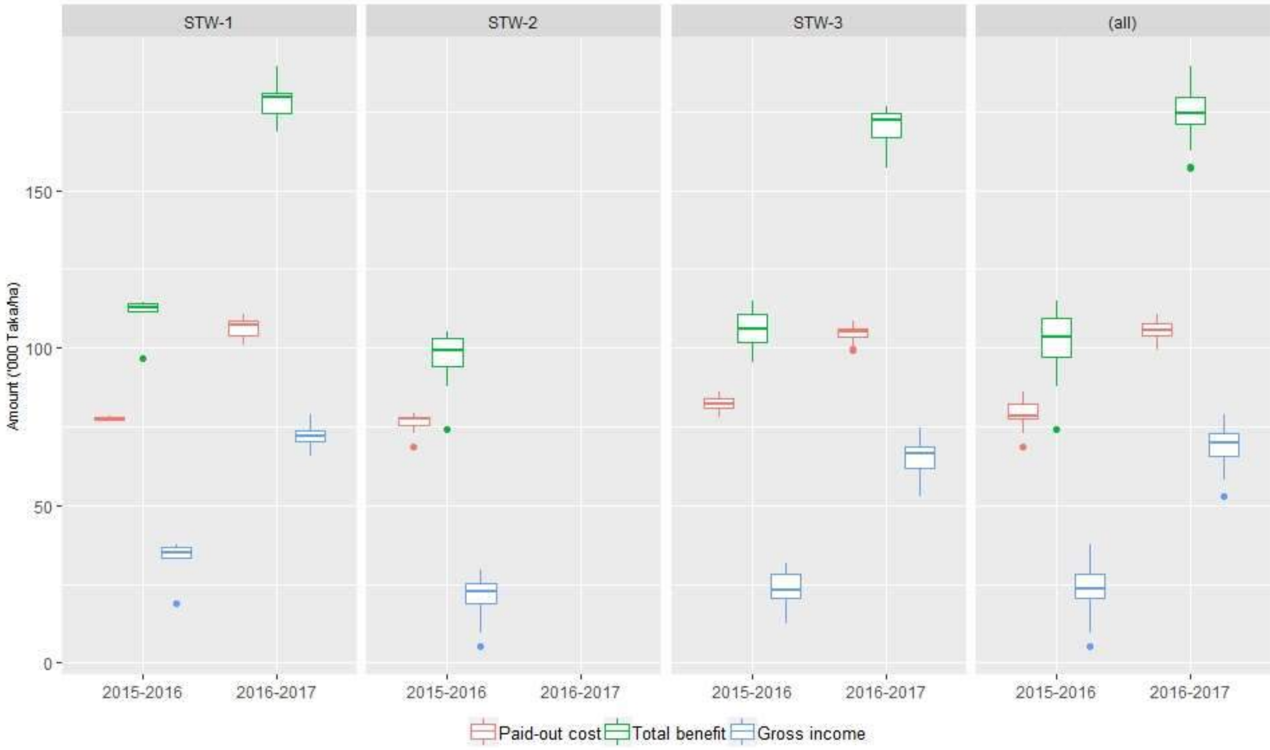

Figure 4.8 Variation in total paid-out cost, gross benefit, and gross income of rice plots in Ishurdi

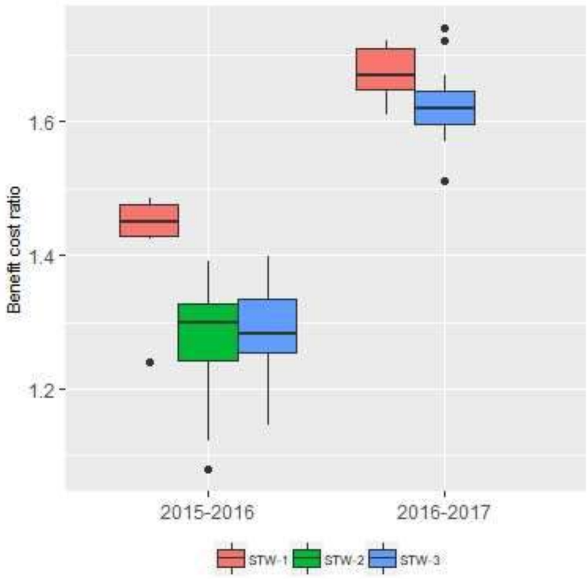

Figure 4.9 Variation in Benefit over cost ratio and yield in Ishurdi

The average per hectare 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 seed cost for BRRI dhan29 (3,040 Taka/ha) compared to Hybrid rice (6,088 Taka/ha). Despite average yield of Hybrid rice under STW-3 was slightly higher than that for under STW-1, per hectare gross income (27,013 Taka) of Hybrid rice was about 18% lower than average per hectare gross income (32,777 Taka) of BRRI dhan29 for the area under STW-1 (Figure 4.10). This is the reflection of higher cost of inputs in particular seed costs of Hybrid rice than inbred varieties (Figure 4.4). On the other hand, per hectare paid-out costs of rice under STW-2 (76,485 Taka) was lower compared to that for under STW-3 (81,605 Taka) for the same variety (BRRI dhan29) because of lower doses of inputs (fertilizer, pesticides, etc.) application. Consequently, average per hectare yield and gross income was lowest (76,485 Taka) 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 same variety (BRRI dhan29) under STW-2 despite lower average yield because of lower paid-out cost (Figure 4.11).

The average paid-out cost of BRRI dhan29 in 2016-17 was 104,410 Taka/ha which was about 35% higher than that of 2015-16. The main reason for this is 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 over cost ratio was significantly higher in 2016-17 compared to 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. Gross income (71,961 Taka/ha) and BCR (1.68) 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).

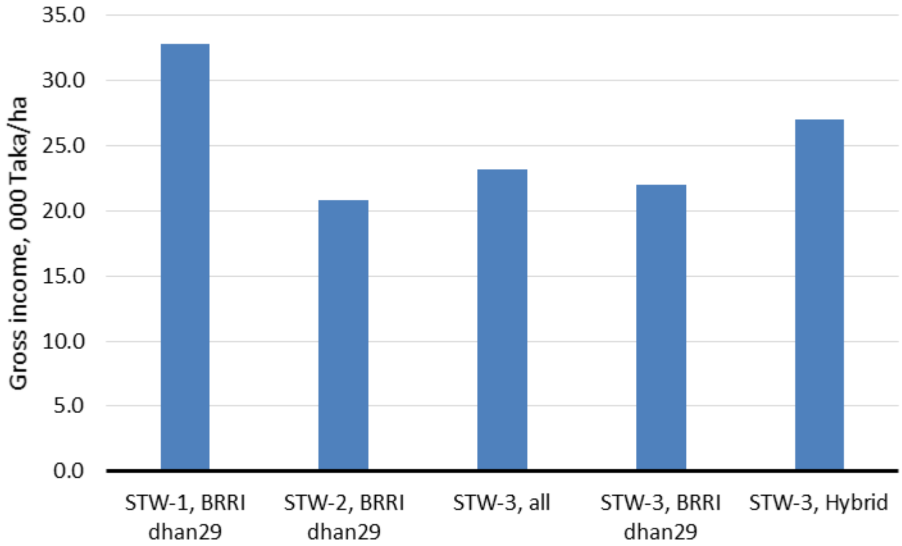

Figure 4.10 Gross income (Gross benefit' minus 'total paid-out cost') of rice cultivation at Ishurdi in 2015-16

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

4.6 Yield of rice

There are significant variation in the average yield of rice due to location, type of pump and the varieties cultivated as shown in Table 4.6. This variation is mainly due to the variation in cultivation is 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 highest in Thakurgaon and the lowest in Sherpur. Most of the plots in Thakurgaon were under BRRI dhan29, the yield of which was 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 highest (7.39 tonne/ha) for hybrid rice, followed by BRRI dhan29 (6.72 tonne/ha), and BRRI dhan28 (6.14 tonne/ha). According BRRI (*Adhunik Dhaner Chas*), the average expected yield of BRRI dhan29 and BRRI dhan28 are 7.5 and 6.0 tonne/ha respectvely. So the average yield achieved in these plots are very close to the expected yield. In fact in case of BRRI dhan28 this is 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 yield 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 compared to 2015-16 whereas the yield of Minikt was slightly higher in 2016-17. There is variation in yield due to time of transplanting (Table 4.6). But this variation is embedded with varieties and locations. Mean and median of yield 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 is presented in Table 4.14. For the results of 2014-15 crop year, smaller p-values (< 0.05) for study location and rice variety indicate statistically significant variations in average yield among the levels of these variables. No statistically significant variation in average yield is observed among various type of pumps or planting dates. While analysing the data for the crop year 2016-17, all the variables except for the planting dates appeared as statistically significant.

Table 4.14 ANOVA for Yield (tonne/ha)

	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
Trans 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 to Tables 4.18. From Table 4.15, we can conclude that with exceptions for Thakurgaon–Mithapukur and Tanore–Sherpur, all other combinations of locations have significant difference in the yield for crop year 2014-15. Among these pairs, Thakurgaon–Mithapukur observed the highest yields and the yields were the lowest for Tanore–Sherpur. In the crop year 2016-17, the highest yielding location was Ishurdi, however, no significant difference for this location was observed with Thakurgaon. The insignificant difference for the pair Badargonj-Thakurgaon indicate that, the second and third highest yielding sites do not observe any significant difference. All the other pairs of locations showed significant statistical differences in the yield. Like the previous crop year, the yield was the lowest for Sherpur (Table 4.6).

In 2015-16, yield of Hybrid rice was significantly higher than all other varieties, except for Minikit (Table 4.17 **check this with Masud bhai seems not correct**). Minikit, The second highest yielding variety, did not show any statistical difference in the yield with the varieties, BRRI dhan29, Jirashail or Kajallata. Significantly lower yield was observed for BRRI dhan28 as compared with Minikit and BRRI dhan29 had significantly higher yield than BRRI dhan28 due to varietal characters. For the crop year 2016-17, the yield of Hybrid rice was significantly higher for all other varieties. Difference in the yield for BRRI dhan29 and BRRI dhan28 was also statistically significant.

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

	difference	LCL	UCL	p-value (adjusted)
BRRI 29-Hybrid	-0.511	-0.884	-0.138	0.002
BRRI 28-Hybrid	-0.926	-1.304	-0.548	0.000
Minikit-Hybrid	-0.435	-0.876	0.006	0.056
Kajallata-Hybrid	-0.649	-1.147	-0.150	0.003
Jirashail-Hybrid	-0.521	-1.012	-0.031	0.030
BRRI 28-BRRI 29	-0.415	-0.760	-0.070	0.008
Minikit-BRRI 29	0.076	-0.337	0.489	0.995
Kajallata-BRRI 29	-0.138	-0.611	0.336	0.960
Jirashail-BRRI 29	-0.010	-0.476	0.455	1.000

Minikit-BRRI 28	0.491	0.073	0.909	0.011
Kajallata-BRRI 28	0.277	-0.201	0.755	0.555
Jirashail-BRRI 28	0.404	-0.065	0.874	0.136
Kajallata-Minikit	-0.214	-0.743	0.315	0.855
Jirashail-Minikit	-0.086	-0.608	0.436	0.997
Jirashail-Kajallata	0.127	-0.444	0.699	0.988

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

	difference	LCL	UCL	p-value (adjusted)
BRRI 29-BRRI 28	0.43	0.11	0.75	0.004
Hybrid-BRRI 28	0.94	0.58	1.30	0.000
Minikit-BRRI 28	0.28	-0.01	0.57	0.066
Hybrid-BRRI 29	0.51	0.14	0.88	0.002
Minikit-BRRI 29	-0.15	-0.45	0.15	0.562
Minikit-Hybrid	-0.66	-1.01	-0.32	0.000

Within a location, among the STWs of Ishurdi, the average yield (7.0 tonne/ha) of rice in the plots under the STW-1 (Figure 4.12) was higher than that for plots under STW-2 (6.2 tonne/ha) in 2015-16. STW-1 had only 6 plots, all with BRRI dhan29. Of the six plots, all received over 7.0 tonne/ha (maximum of 7.34 tonne/ha) with only one having yield of 6.2 tonne/ha. All the plots of STW-2 were also under BRRI dhan29. However, none of the plot received yield of 7.0 tonne/ha. The maximum yield was 6.75 tonne/ha. In general, there is high variation from plot to plot in yield 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) are 6.2, 8.0 and 6.2% respectively. Considering all plots (50 plots), the CV is 8.2%. In 2016-17, CV of yield for STW-1 (20 plots) was 4.6% and for STW-3 (19 plots) was 4.1%.

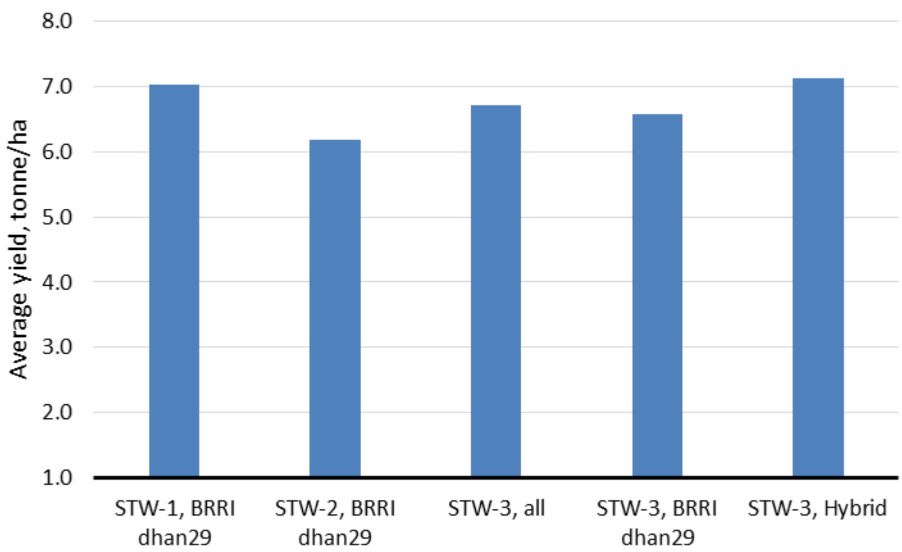

Figure 4.12 Average yield of Boro rice/ irrigated dry season rice in Ishurdi in 2015-16

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 within the command area of the STW-3 was slightly (8.2%) higher (7.12 tonne/ha) than the average yield of BRRI dhan29 (6.58 tonne/ha (Figure 4.12). It should be noted here that average yield of Hybrid rice was the average of 6 plots whereas 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 by the Hybrid rice. For the 6 plots under STW-1, the maximum and average yield of BRRI dhan29 was 7.34 and 7.03 tonne/ha, respectively which was almost equal to that of Hybrid rice under STW-3 with same number of plots. So, the difference in yield between 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. Except one all the plots under STW-1 were under 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; the rest were with Minikit. The maximum and average yield 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 are operated by the diesel engine. As we can see 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 STW was found to be statistically significant (at 5%). 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 cost (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/with other some issues with the pump.

4.6.1 Effect of transplanting date on the yield of rice

Figures 4.13 and 4.14 show the scatter plot of yield of different varieties with the date of transplanting respectively for 2015-16 and 2016-17. 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 others plots were planted during 2nd half of January and 1st half of February and there is almost no variation in the average yield. Higher yield of BRRI dhan 28 was also achieved while transplanting early in 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, delay transplantic occurs due to the potato harvest of the same plots. Biswas et al. (2001) reported that both growth duration and grain yield of rice are affected due to time of transplanting.

Hybrid rice seems not affected by the transplanting time. For Hybrid rice the highest yield was achieved (7.73 tonne/ha) when tranplanted 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 almost no variation in average yield. However, there is general trend of increasing yield with late transplanting.

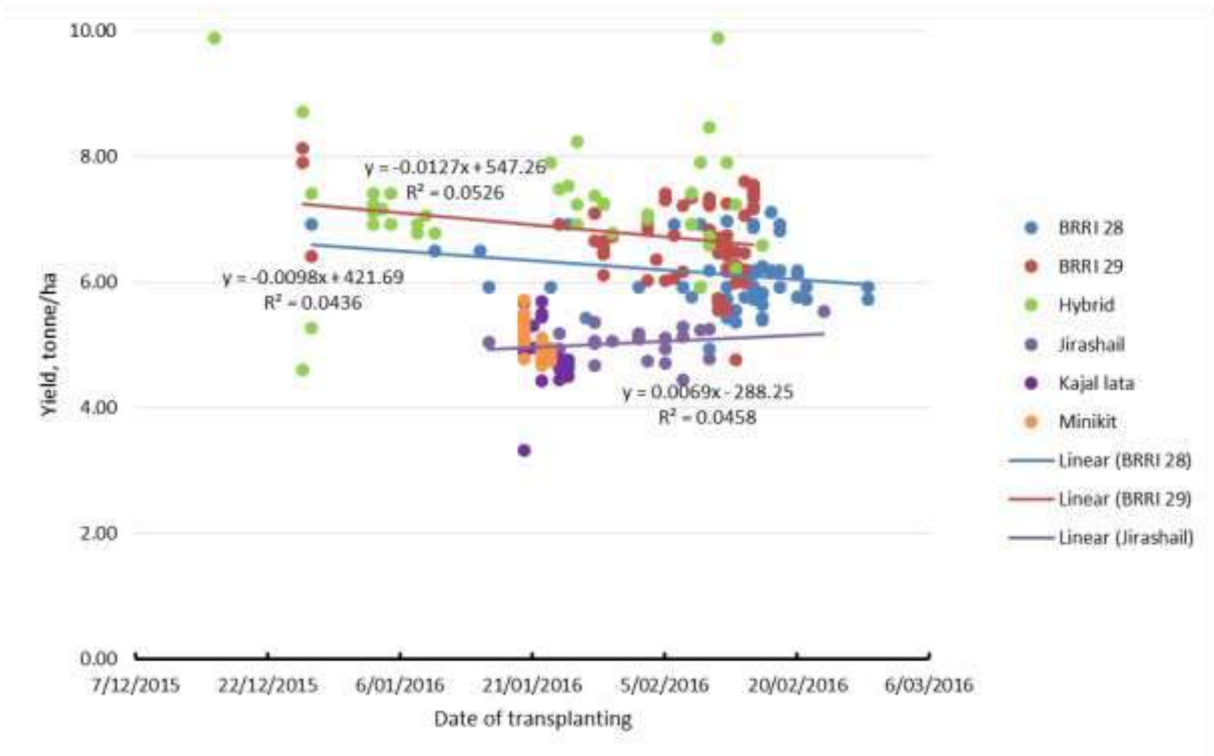

Figure 4.13 Scatter plot of the yield of different varieties of rice with the date of transplanting for 2015-16

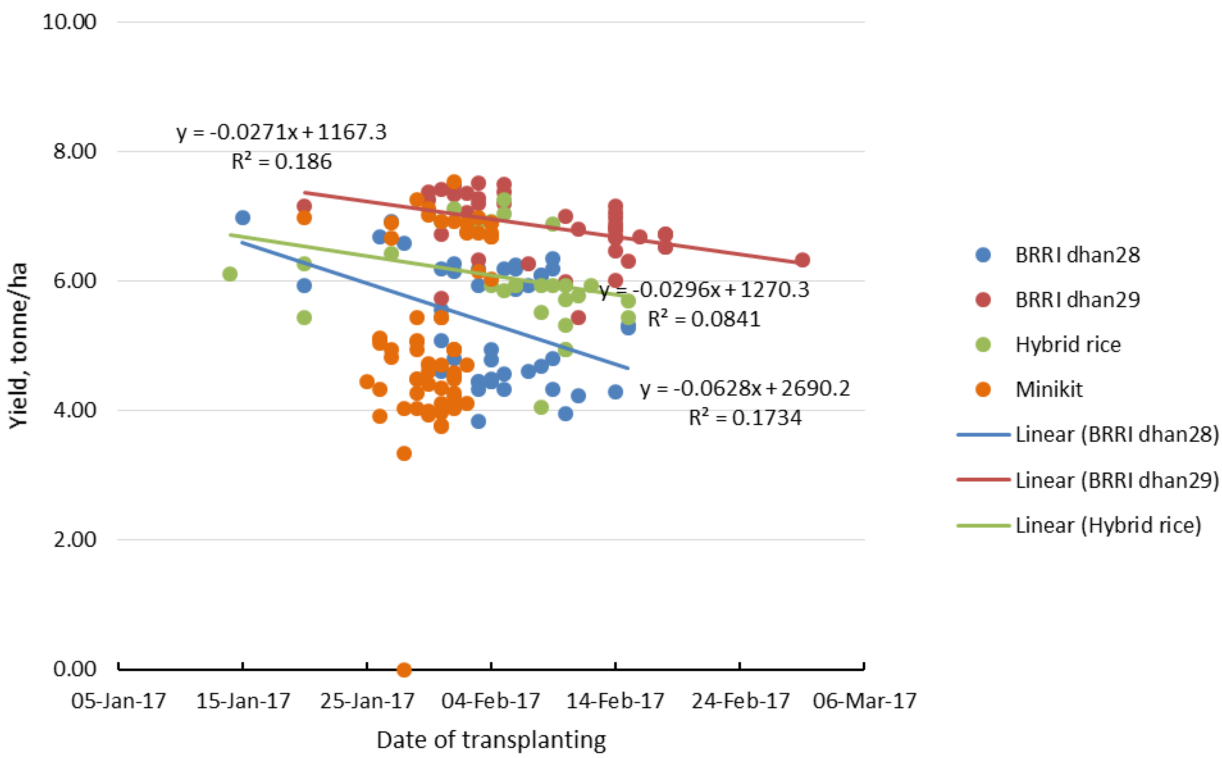

Figure 4.14 Scatter plot of the yield of different varieties of rice with the date of transplanting for 2016-17

Table 4.19 Average yield of different varieties of rice with different transplanting time

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 age of seedlings on the yield of rice

The age of seedlings is also a factor in the yield of rice (Figures 4.15 and 4.16). It seems higher the age of seedlings lower is the yield for BRRI dhan28 and BRRI dhan29. The recommended age of seedlings for these two varities is 40 days (*Adhunik Dhaner Chas*). However, the average seedlings age was 64 and 58 days respectively for BRRI dhan28 and BRRI dhan29 in 2015-16. For Hybrid rice, Jirashail, Kajallata and Minikit the average age of seedlings were 48, 43, 44, and 41 days, respectively. In 2016-17, the average age of seedlings were 59, 66, 60, and 54 days, respectively for BRRI dhan 28, BRRI dhan 29, Hybrid rice and Minikit. Though 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 supported by Mobasser et al. (2007). They reported that older seedlings reduced the rice yield significantly. There is no trend for Hybrid rice, Kajallate and Minikit. For Jirashail in 2015-16, age of seedlings varied from 37 to 60 days with avearge age of 43 days. Yield increases slightly with the age of seedlings.

It should be noted here that yield of every plot is affeced by many factors such as date of transplanting, age of seedlings, fertilizer and pesticides applications, water application, agronomic management of the crops and the climatic factors. So the impact on yield is the impact of all these factors. However, these trend provide the likely impact of date of transplanting and age of seedlings on the yield of rice.

Age of seedlings though reduces the yield of rice it is 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 location 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 on time. In this region, farmers grow 3 crops in a year. After harvesting monsoon season Aman 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 is not ready for preparation and transplanting with seedlings with recommended age. Transplanting was done late so to harvest the rice on time farmers transplant older seedlings. Otherwise, the harvest will be late and will be affected by early monsoon rainfall. 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.

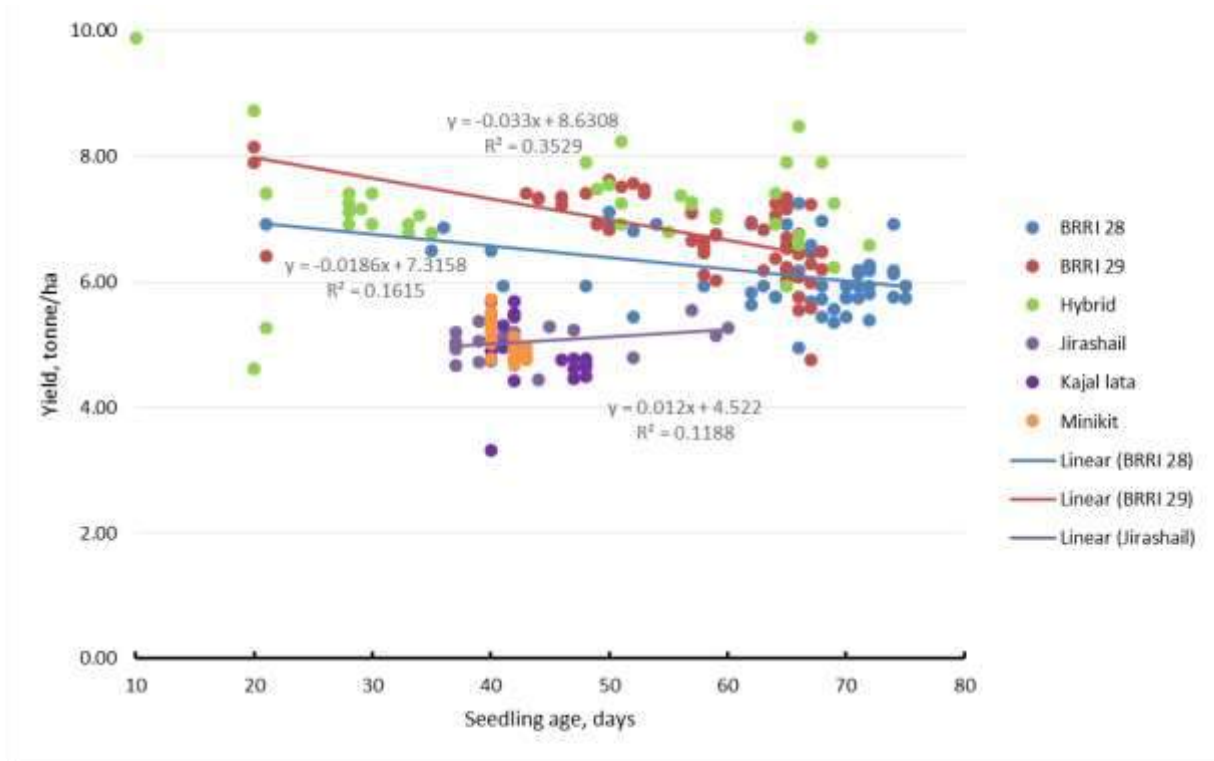

Figure 4.15 Scatter plot of the yield of different varieties of rice with the age of seedlings, 2015-16

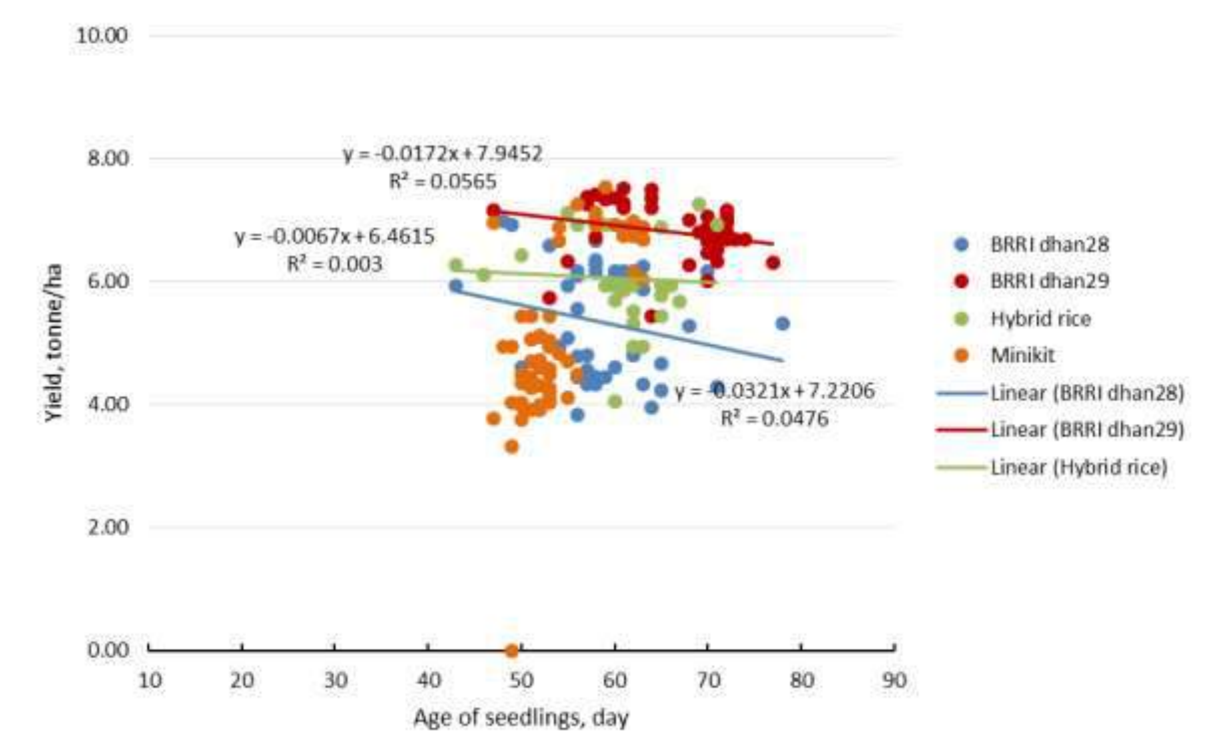

Figure 4.16 Scatter plot of the yield of different varieties of rice with the age of seedlings, 2016-17

4.6.3 Probability of yield and gross income of growing rice

There is significant difference in the average yield (at 50% probability of exceedance) for 2015-16 between Hybrid rice, BRRI dhan29 and BRRI dhan28 as shown in Table 4.18. The yield of other 3 varieties (Jirashail, Kajallata and Minikit) are almost similar but significantly lower than the Hybrid rice, BRRI dhan28 and BRRI dhan29. Though the yield of Hybrid rice was higher than the other varieties, the variability in yield was also higher as shown in the probability of exceedance of the observed yield (Figures 4.17 and 4.18). In 2015-16, the 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% respectively 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%; though it has the higher potential than the other rice.

In 2016-17, the yield of BRRI dhan29 was significantly higher (Figure 4.18) than the Hybrid rice contrary to the results of the year 2015-16. The variation in yield was also higher for Hybrid rice (CV = 12.5%) compared to that of BRRI dhan29 (CV = 7.1%). The variation in yield of BRRI dhan28 and Minikit was much higher in 2016-17 compared to that in 2015-16. The CV were 17.0% and 25.8% respectively for BRRI dhan28 and Minikit. The 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 was lower with higher variability in the 2nd year (2016-17).

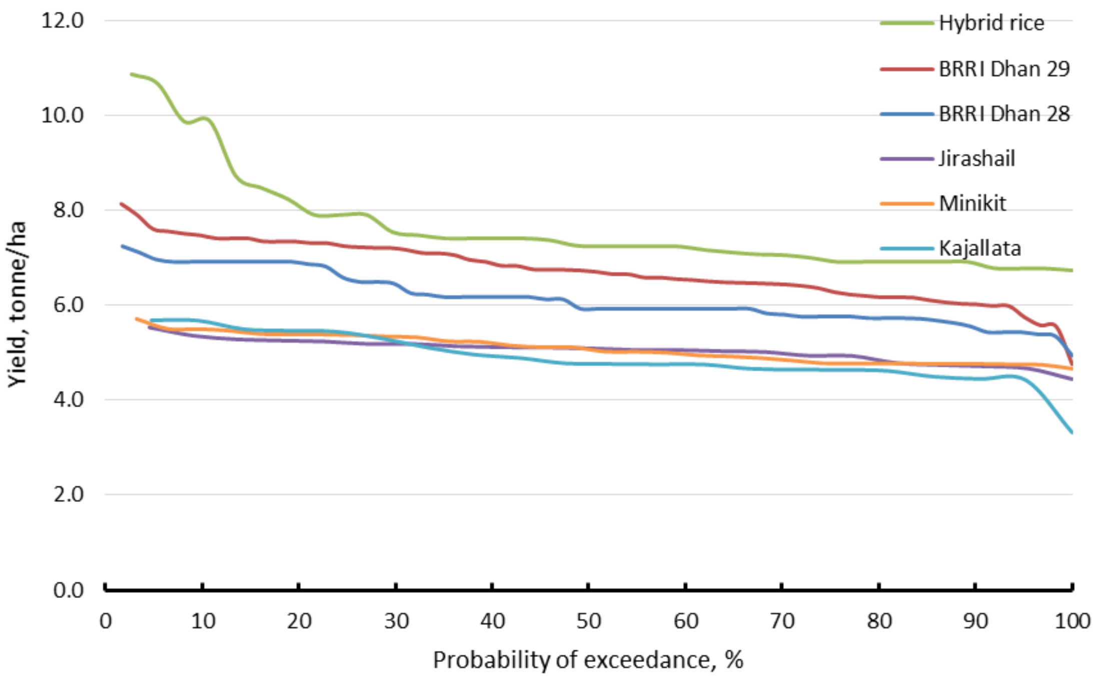

Figure 4.17 Probability of the yield of different varieties of rice grown in the sites for 2015-16

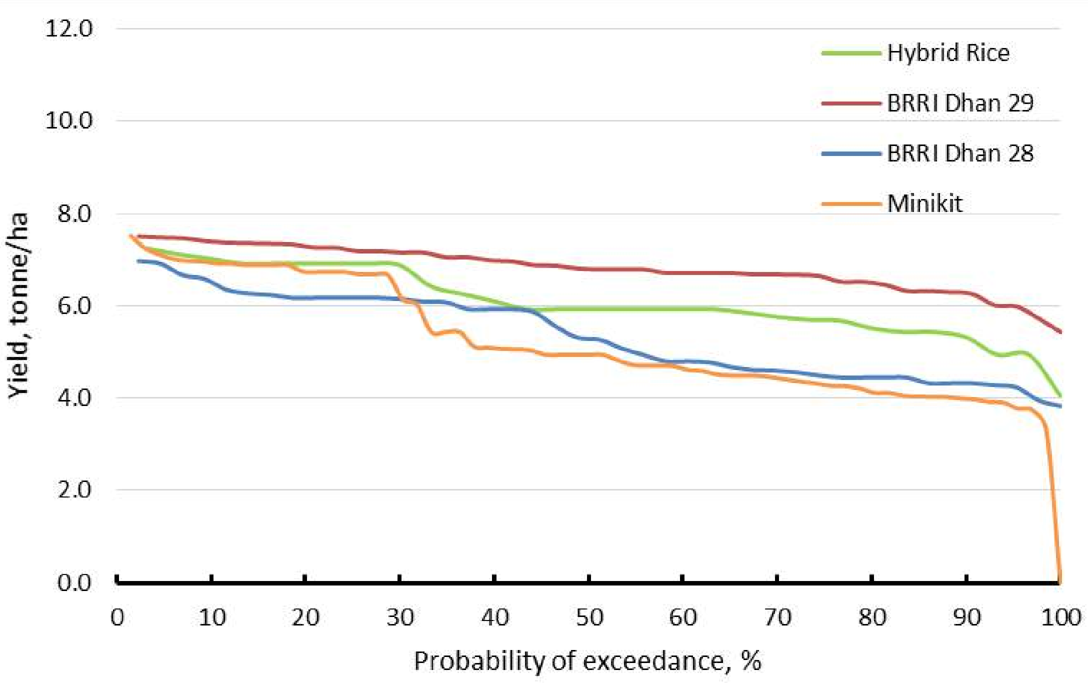

Figure 4.18 Probability of the yield of different varieties of rice grown in the sites for 2016-17

The probability distribution of gross income is different than yield (Figures 4.19 and 4.20). In 2015-16, the average gross income was highest for Jirashail, lowest for Kajallata; BRRI dhan28 was just above Kajallata. The average gross income of Kajallata and BRRI dhan28 is significantly lower than Jirashail, Hybrid rice, BRRI dhan29 and Minikit. The average gross income of Hybrid rice, BRRI dhan29 and Minikit were almost similar.

The result was quite different in 2016-17. 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 for both BRRI dhan29 and Hybrid rice. The CV were 10.0 and 27.1% respectively for BRRI dhan29 and Hybrid rice in 2016-17 compared to 34.7 and 47.6% in 2015-16. The CV of gross income for BRRI dhan28 and Minikit were 25.2 and 27.7%, respectively in 2016-17 compared to 51.6 and 23.6% in 2015-16.

Comparing the results of two years, it is clear that BRRI dhan29 is much more stable with lower risk compared to the other varieties both in terms of yield and gross income. Hybrid rice may produce higher yield and gross income in one year but could be different in other year. Jirashail and Minikit has the potential to give more gross income (as shown in Figure 4.17) but it has also higher risk (as shown in Figure 4.19).

The distribution of yield and gross income also indicate two important things. i) Farmers who needs to grow rice for own consumption should grow hybrid rice or BRRI dhan29 as their yield is higher. Farmers will get more production which will sustain them for longer period. 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, then for subsistence it could be better to cultivate BR-28 even the gross income from this could be lower. ii) Farmers who are growing rice for selling to the market, it could be better for them to grow Jirashail or Minikit. The gross income of BRRI dhan29 and Hybrid rice are also at par with Minikit. However, Minikit may be easier to sell because of high demand in the market. Due to better taste, some farmers also prefer to grow Minikit for their own consumption. The decision to cultivate a certain variety of rice is complex and depends on also other factors such as availability of seeds, time of transplanting, local conditions, and traditions, etc.

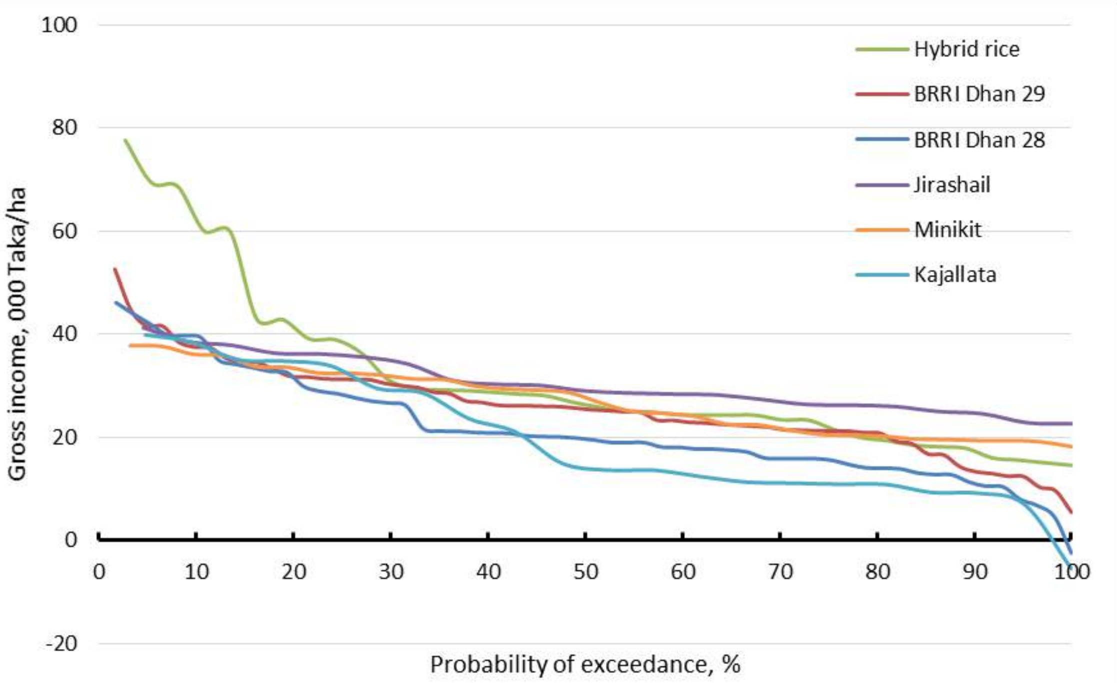

Figure 4.19 Probability of the gross income of different varieties of rice grown in the sites for 2015-16

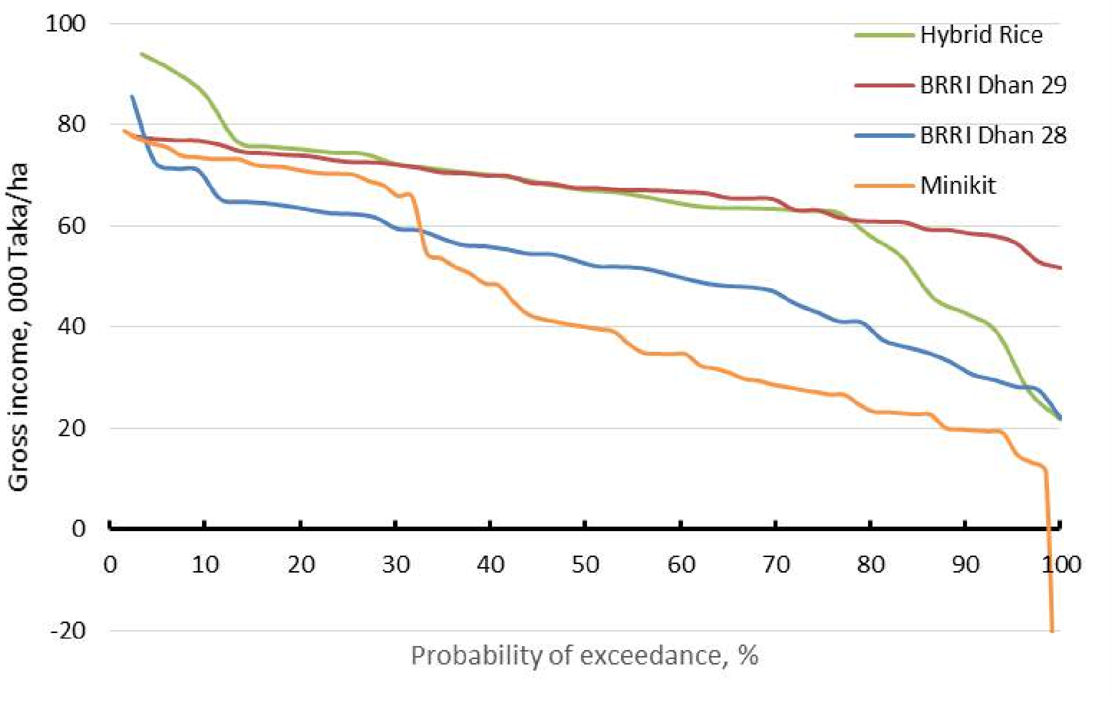

Figure 4.20 Probability of the gross income of different varieties of rice grown in the sites for 2016-17

4.6.4 Yield prediction model of rice (under further revision)

The multivariable linear regression model is fitted to the total yield (tonne/ha) with a set of predictors (Equation 1) and the model parameters have been presented in Table 4.20. In the model, sherpur was considered as the reference location. After controlling for other variables yield for other studied locations were higher than (positive regression parameter) Sherpur and the difference is statistically significant (p<0.05). For example, after controlling for other factors, the estimated average yield per hectare at Thakurgaon is 4.0154 tonne more than Sherpur. Use of electric motors for irrigation had significant positive effect on yield ($\beta = 0.3398, p = 0.03$). Six varieties of rice were cultivated in the studied plots and the impact of rice variety on yield after controlling for other variables have been studied through the regression model. Rice variety is entered into the model as a categorical one with hybrid rice (the highest yield variaty among the rice cultivated in the studied plots) as reference. The study design had a problem when specific variety was cultivated on only one location and the location had only one variety of rice. For example, Jirashail was cultivated at Tanore only and no other variety of rice was cultivated there. In such situation, the impact of rice (Jirashal, for example) is mixed up with the impact of location (Tanore, for example). Hence, the model was not able to estimate the impact of all varieties of rice, and alternatively, the impact of BRRI dhan29, BRRI dhan28 and Minikit were estimated considering Hybrid rice as reference. After controlling for other variable, the yield of BRRI dhan29 was, on an average, 0.9022 tonne/ha less than the hybrid rice and the effect is significant at 5% level (p= 0.0021). The difference between Hybrid rice and BRRI dhan28 is even higher ($\beta = -1.5973,\ p = 0.00$). The impact of planting date on yield is estimated through the regression model. The variable is considered with five levels, December, January 1-15, January 16-31, February 1-15 and February 16 or latter. The last one is considered as the reference category. Planting date did not have significant impact on yield (p>0.05).

The model considered a set of continuous variable, such as, plot size, seedling cost, herbicide cost, pesticide cost, land preparation cost, cost for urea, cost for Potash, cost for Phosphate, micronutrient cost and seedling age. Plot size, land preparation cost, cost for urea, cost for Poash, micronutrient cost and seedling age did not have significant impact on yield (p> 0.10). , The impact of herbicide and pesticide costs is significant at 10 percent level (p< 0.10). Seedling cost has significant negative ($\beta = -0.2555,\ p = 0.0360$) and cost for phosphate has significant positive ($\beta = 0.1609,\ p = 0.0094$) impact on yield.

The production function:

$$Y_i = \alpha_0 + \alpha_1 L_i + \alpha_2 P_i + \alpha_3 V_i + \alpha_4 D_i + \alpha_5 PS_i + \alpha_6 SC_i + \alpha_7 HC_i + \alpha_8 PC_i + \alpha_9 LC_i + \alpha_{10} UC_i + \alpha_{11} KC_i + \alpha_{12} PC_i + \alpha_{13} MC_i + \alpha_{14} SA_i + U_i \quad \ldots \quad \ldots. \quad \ldots. \quad \ldots. \qquad (1)$$

Where:
Y = Total yield of rice in tons per hectare
L = Location variable (Categorical variable, Reference category: Sherpur)
P = Pump type (Dummy variable: P = 1 for Electric motor, P = 0 for not Electric Motor)
V = Variety of rice (Categorical variable, Reference category: Hybrid rice)
D = Planting Date (Reference: after 15th February)
PS = Plot size (in hectare)
SC = Seedling cost (,000 taka/hectare)
HC = Herbicide cost (,000 taka/hectare)
PC = Pesticide cost (,000 taka/hectare)
LC = Land preparation (Tillage) cost (,000 taka/hectare)
UC = Cost for urea (,000 taka/hectare)
KC = Cost for Potash (,000 taka/hectare)
PC = Cost for Phosphate (,000 taka/hectare)
MC = Micronutrient cost (,000 taka/hectare)
SA = Seedling age (days)
U = error term

Table 4.20 20 Regression parameters with standard error, t-statistics and p-value from the fitted yield model with a set of parameters

Variables	Estimate	Std. Error	t value	Pr (>|t|)
Constant	5.8428	1.1114	5.2572	0.000
Study Location (Reference: Sherpur)				
Tanore	0.8845	0.3745	2.3619	0.0191
Kaharol	2.7773	0.4133	6.7202	0.0000
Ishurdi	3.3172	0.533	6.2235	0.0000
Mithapukur	2.9315	0.4307	6.8061	0.0000
Thakurgaon	4.0154	0.4945	8.1209	0.0000
Pump Type (Reference: Not Electric Motor)				
Electric motor	0.3398	0.1556	2.1835	0.0301
Paddy Variety (Reference: Hybrid)				
BRRI 29	-0.9022	0.2901	-3.1097	0.0021
BRRI 28	-1.5973	0.2212	-7.2225	0.0000
Minikit	0.2732	0.2041	1.3385	0.1822
Planting Date (Reference: February last)				
Feb First	-0.1339	0.216	-0.62	0.5359
Jan Last	-0.173	0.3096	-0.5589	0.5768
Jan First	-0.4628	0.5531	-0.8367	0.4037
Dec	-0.5578	0.7129	-0.7825	0.4348
Plot size	0.0007	0.0017	0.4129	0.6801
Seedling cost	-0.2555	0.121	-2.1107	0.0360
Herbicide cost	-0.0594	0.0346	-1.7171	0.0874
Pesticide cost	0.0785	0.0408	1.9247	0.0556
Land Preparation cost	-0.0543	0.051	-1.066	0.2876
Total cost for urea	0.0752	0.0482	1.5592	0.1205
Total cost for MoP	-0.1371	0.122	-1.1239	0.2623
Total cost for Phosphate	0.1609	0.0614	2.621	0.0094
Micronutrient cost	-0.0147	0.0637	-0.2308	0.8177
Seedling age	-0.0118	0.0131	-0.8985	0.3700

4.7 Cost, benefit, income and yield of other crops

Rice was the dominant crops in all sites. In 2015-16, however, non-rice crops such as maize, wheat, potato, mustard, lentil and few vegetables covered significant area; 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 monitored sites. Some of the crops were cultivated only in very few plots within a location. But in 2016-17 season, the monitored sites had very few non-rice crops; that was mainly in Mithapukur and Thakurgaon sites. 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 with non-rice crops (4 in Mithapukur, 5 in Thakurgaon and 1 in Ishurdi). Seven of these 10 plots were with maize (0.955 ha), 2 with potato (0.445 ha) and the other was with Okra (0.134 ha) in Ishurdi. For the analysis we did not consider the plot with Okra in Ishurdi.

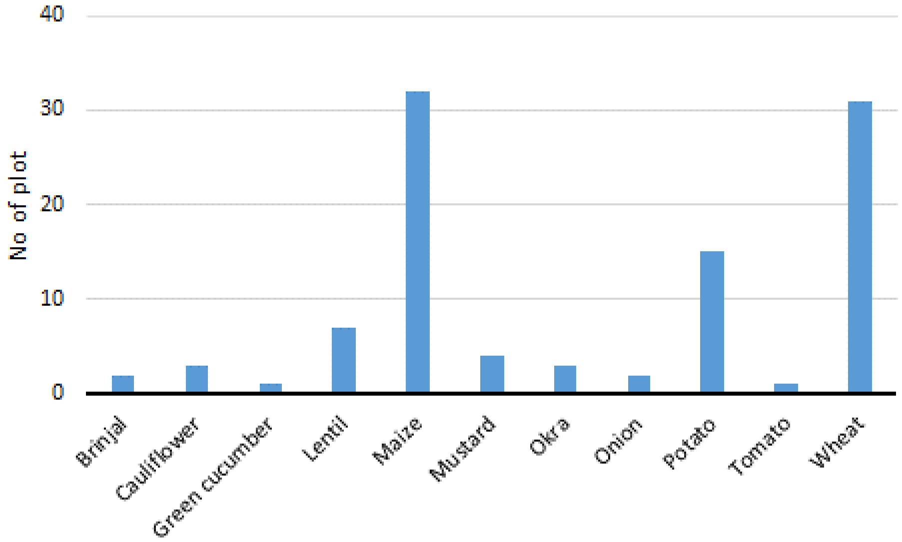

Figure 4.21 No of plots for non-rice crops across the sites in 2015-16

The average total paid-out cost (TPC) of production, gross benefit (GB) and gross income (GI) gained from the cultivation of these crops are compared in Figure 4.22 for 2015-16. Figure 4.23 compares these 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 are highest for potato. Compared to rice, TPC, GB, and GI for potato were 59%, 128%, and 326% higher, respectively in 2015-16. In 2016-17, these were 6, 46, and 106% higher. Potato is the most profitable crop (106,837 Taka/ha in 2015-16, 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 and 86,859 Taka/ha, respectively for 2015-16 and 2016-17), rice (25,076 Taka/ha and 54,254 Taka/ha) and wheat (1,511 Taka/ha). The gross income was much higher for rice (216%) and maize (114%) in 2016-17 compared to that of 2015-16. The main reason for this is the higher price of rice. Wheat was affected by the severe blast disease in 2015-16 (2016).The average yield loss was 25-30 percent, but in severely infected fields it reached up to 100 percent (The Daily Star, 07 February 2017; 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). That has affected the gross income.

Potato is grown in Mithapukur, Sherpur and Tanore due to the suitability of the soil conditions there. Apart from the suitability of the soil, cultivation of potato also need high initial investment. So, the initial investment could be beyond the reach of many farmers. But for maize the investment (cost of production) is lower than rice but the gross income 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 the area of cultivation of maize in the region over the last decade as shown in Figure 2.13).

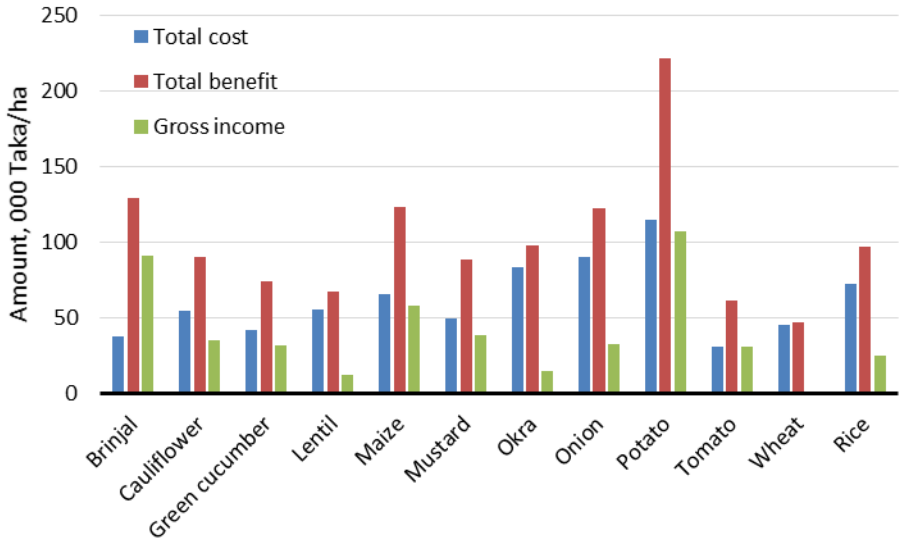

Figure 4.22 Comparison of total paid-out cost, gross benefit, gross income and yield of rice with other crops for 2015-16

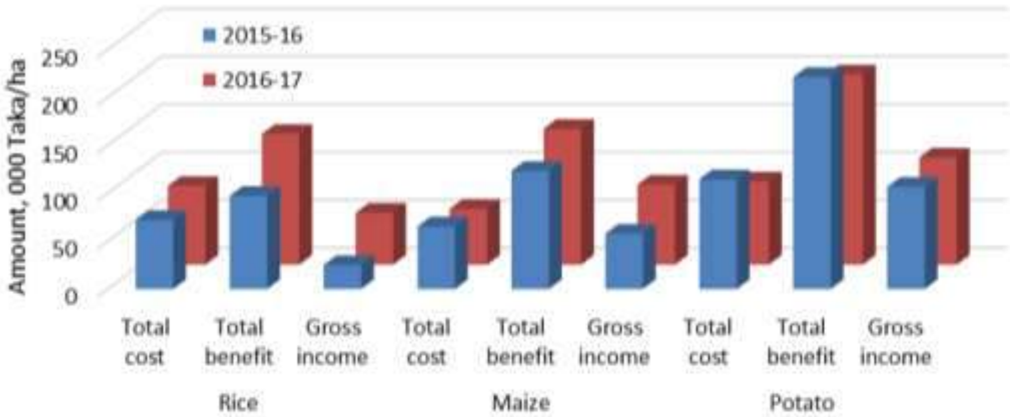

Figure 4.23 Total paid out cost (total cost), total benefit and gross income of rice for 2015-16 and 2016-17

Though potato has much higher GI than rice and maize, the risk of growing potato may be higher. Figure 4.24 shows the probability distribution of GI of rice, maize, wheat and potato for 2015-16. The slope of the curve indicates the risk; the higher the slope the higher is the risk. As we can see there is sharp fall in the GI after about 50% probability of exceedance (i.e. for the 50% of the plots). There is high variation in the GI of potato with the CV of about 52.2%. For rice and maize the CV were 46.6 and 37.8%.

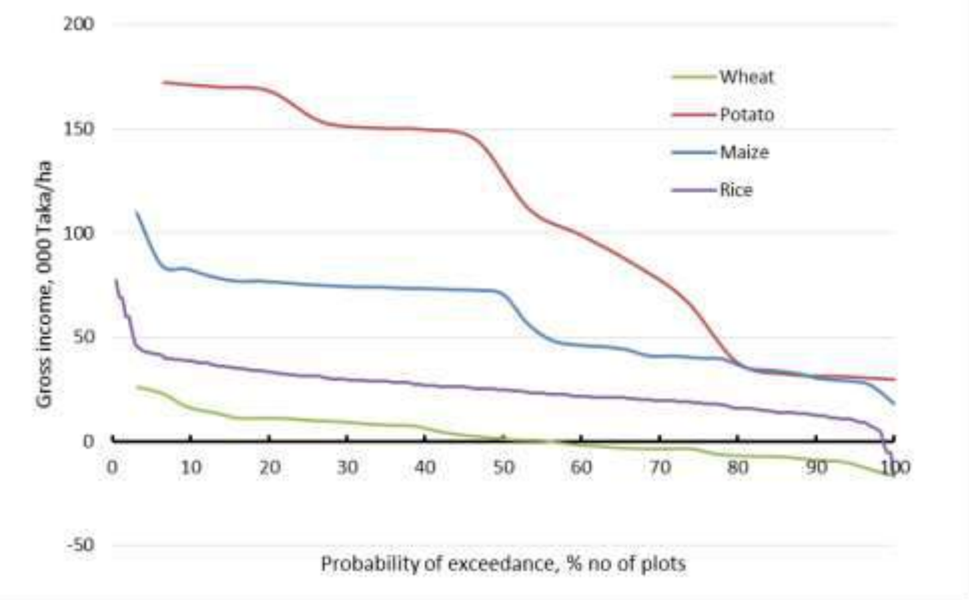

Figure 4.24 Probability distribution of the gross benefit of 4 major crops of 2015-16

While there is 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 were 18.1, 19.1, and 32.9 percent, respectively. So, considering the risk and GI that can be obtained, cultivation of maize may be better (low risk and higher benefit). It should be noted here that the number of observation varies widely for the crops. Potato has the lowest number of plots (15 only) which also may have some impact on the higher variation in yield and net benefit.

Wheat is the most risky crop among the 4 major crops due to the severe disease infestation. In general, potato is the 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. Though the variation in yield is low (CV = 18.8%), the variation in gross benefit is extremely high (CV = 454%).

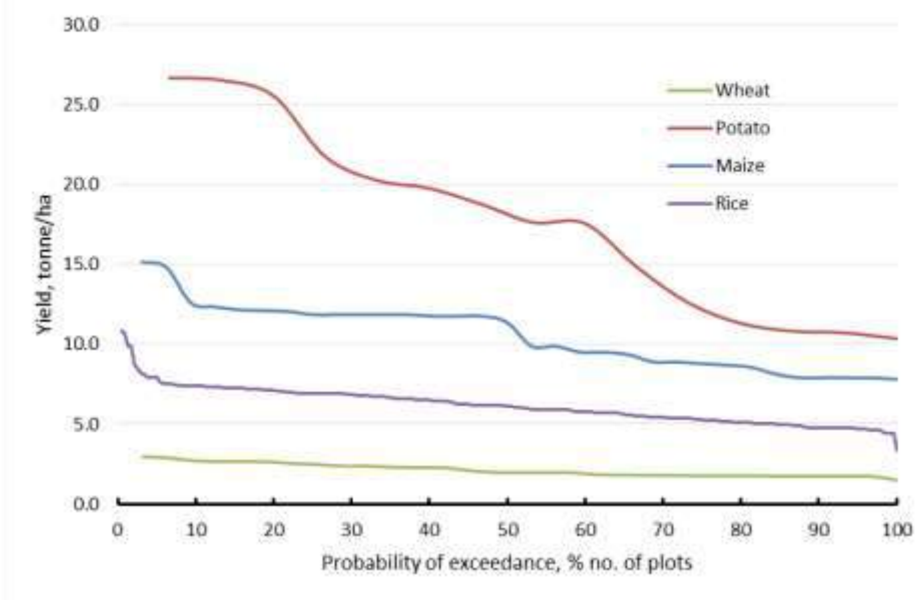

Figure 4.25 Probability distribution of the yield of 4 major crops for 2015-16

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

Table 4.21 Plot size and per hectare costs, returns, yield, water use and productivity of the crops 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	
Whea t (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 over cost, 'total paid out cost' is the 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'

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

Similar to the gross income, irrigation water use is also highest for rice. 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, though the gross income of rice is the highest, 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 area. In Chapter 2, we have discussed in detail about the declining groundwater level in the region. The government is vigorously promoting growing non-rice crops to reduce the pressure on groundwater. Growing non-rice crops such as wheat, lentil and okra will definitely save groundwater in the aquifer. However, this will be at the cost of lower gross income for the farmers in this location. The risk of growing non-rice crops is also very high as we can see in the CV of the yield of these crops. The average CV of the yield or rice is only 8% compared to the 15% in lentil and 17% in wheat though they have much lower number of plots compared to rice.

4.8 Potential evapotranspiration of different crops

We have estimated potential crop evapotranspiration (ETcrop) at 10-15 days interval of the sowing and transplanting period observed in the field. Figure 4.26 shows the potential crop evapotranspiration of the different varieties of rice and the other major crops transplanted (for rice) and sowed (for other crops) at different period for 2015-16 crop season. Figure 4.27 shows ETcrop of rice at different locations for 2016-17 crop season for the transplanting period of 20 December 2016 to 10 March 2017. As shown in the Figures, ETcrop increases with transplanting or sowing dates moving forward. This is mainly because of the increase in temperature. *Boro* rice/Rabi crops starts its journey in cooler and drier conditions and continue grow up to vegetative stage. Its 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 location and transplanting dates with average evapotranspiration of 448 mm due to their longer growth duration. BRRI dhan29 and Hybrid rice was 15 days longer then BRRI dhan28 and 20 days longer than other varieties of rice in the field. Average ETcrop for BRRI dhan28 and others are estimated as 385 and 379 mm, respectively in 2015-16 (Figure 4.26).

In 2016-17, ETcrop of BRRI dhan29 and Hybrid rice were 254 mm for transplanting on 20 Dec 2016 and 497 mm for transplanting on 10 March 2017. For BRRI dhan28 and Minikit they were 208 and 424 mm. ETcrop was the highest in Ishurdi and the lowest was in Mithapukur.

Of the non-rice crops, maize has the highest ETcrop which varied from 276 to 528 mm across location and different sowing dates for 2015-16 crop season. The average ETcrop (393 mm) is almost equal to that of BRRI dhan28. The average ETcrop for potato and wheat are estimated to be 241 and 222 mm, respectively.

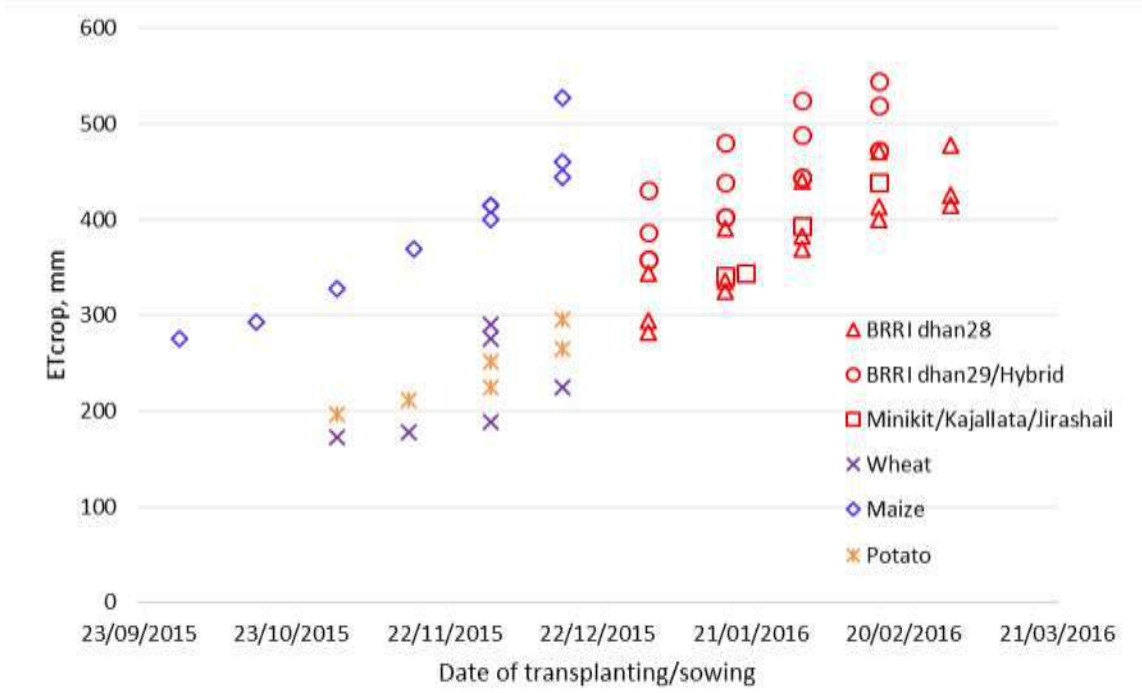

Figure 4.26 Potential crop evapotranspiration (ETcrop) of different crops for 2015-16 (same marker at vertical position shows the ETcrop for different locations)

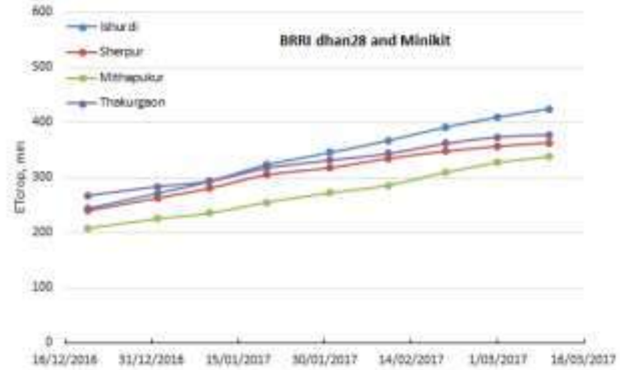

Figure 4.27 Potential crop evapotranspiration (ETcrop) of different varieties of rice at different locations for 2016-17

4.9 Irrigation water supplied and estimated requirements for rice

Irrigation water supplied to each plot was estimated by multiplying the pump capacity with the duration of time pump operated. Farmers decide to irrigate the field based on the field condition, usually when they see there is no standing water in the field. Within a 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 for different locations. In 2015-16, among the sites water supply was higher in Mithapukur (890 to 1601 mm) and the lower was in Ishurdi (472 to 539 mm). For the other 4 locations water supply varied from 563 to 871 mm, 615 to 802 mm, 768 to 958 mm, and 889 to 1052 mm, respectively for Kaharol, Sherpur, Tanore and Thakurgaon.

In 2016-17, water supply was higher in the plots in Ishurdi (565 to 965 mm) and the lower was in Sherpur (460 to 625 mm) (Figure 4.28). The variation in water supply to the plots for 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%).

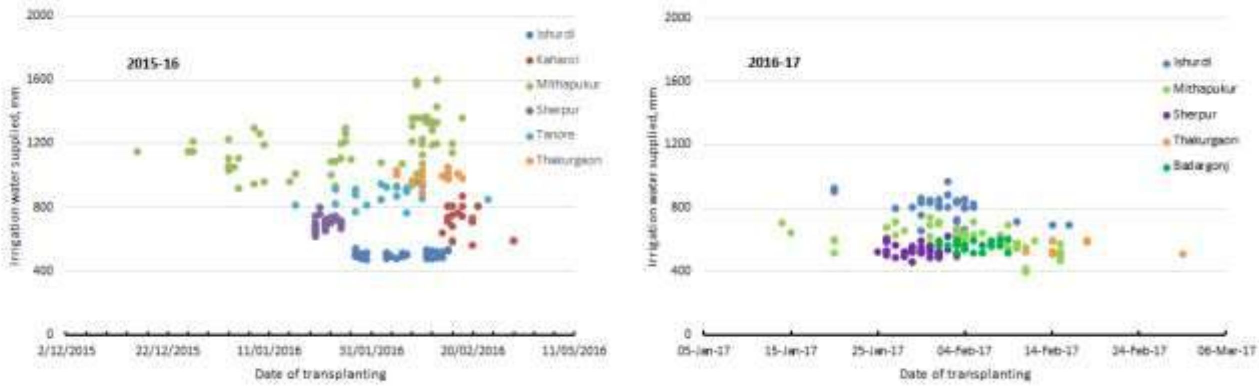

Figure 4.28 Scatter plot of irrigation water supplied to the plots at different sites

Irrigation water requirement of rice varies due to its geographical locations, climate variations, soil properties, varieties of rice cultivated, and the time of transplanting. To compare the irrigation water supply with the requirements for full yield potential, we estimated the irrigation water requirements for rice at different planting dates for all sites using the soil water balance model described in Section 3.3. In estimating the irrigation, we considered the transplanting date at regular interval within the transplanting period for the sites. Figures 4.29 and 4.30 shows 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 no of plots) water supplied and the requirements and Figure 4.32 shows the % of undersupply or oversupply compared to the estimated requirements.

In 2015-16, actual 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 other 3 sites (Mithapukur, Thakurgaon, and Tanore) 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, actual water supply was reasonably close to the estimated requirements in Mithapukur (7%), Sherpur (4%) and Badarganj (3%) (Figures 4.30-4.32). Water supply was higher in Ishurdi (36%), and Thakurgaon (57%).

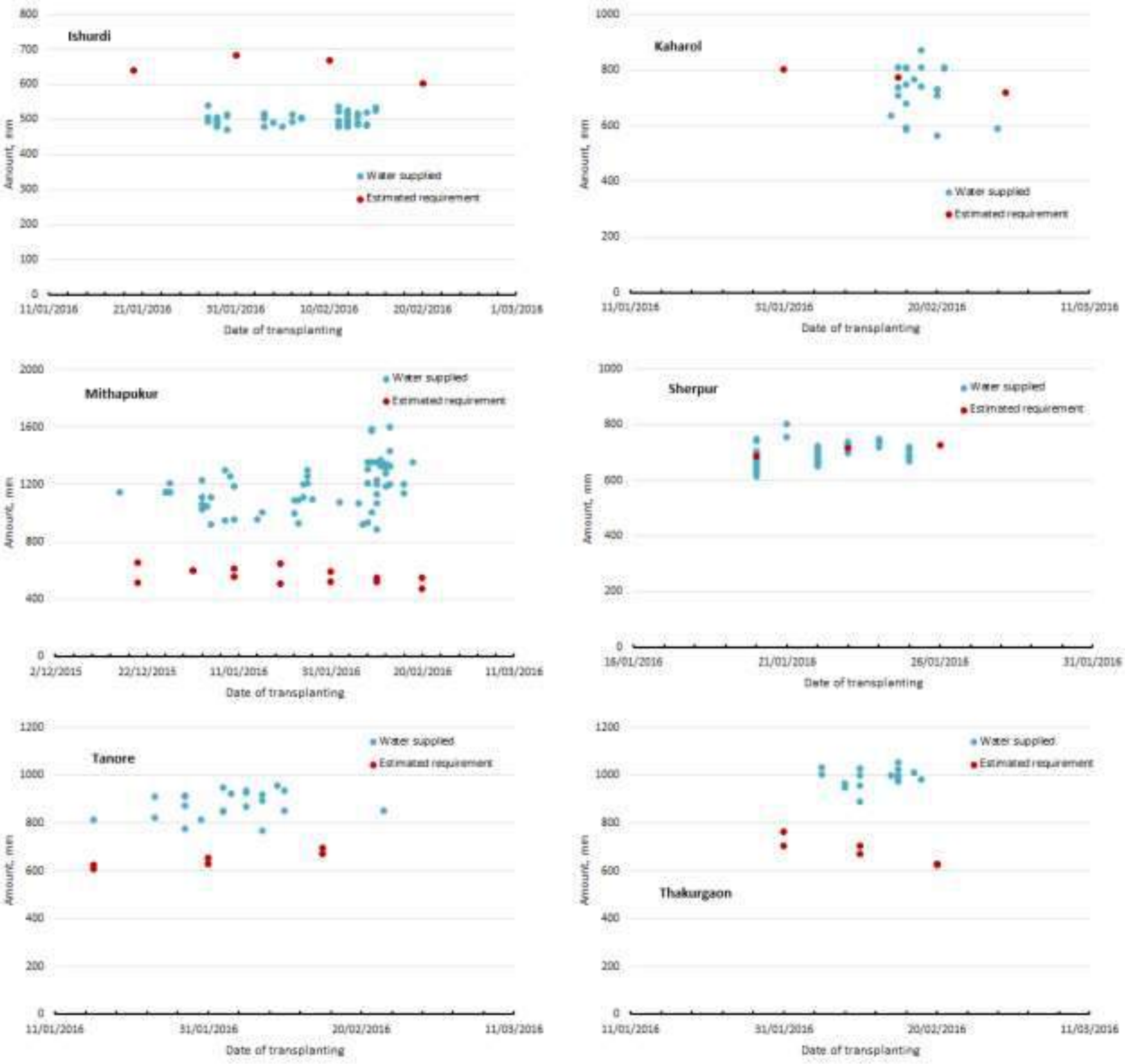

Figure 4.29 Comparison of irrigation water requirements with actual water supplied to the plots for rice at different locations for 2015-16

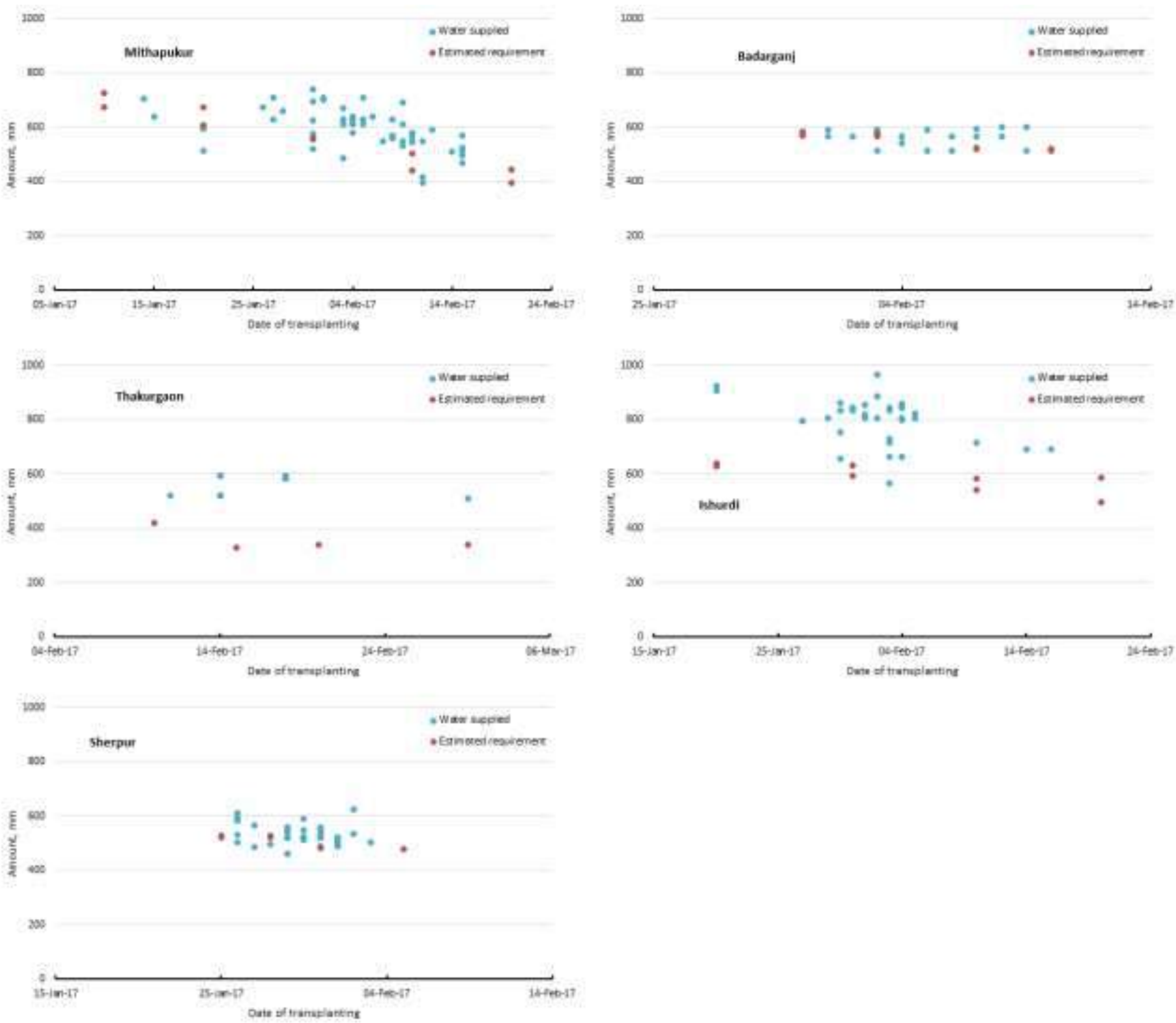

Figure 4.30 Comparison of irrigation water requirements with actual water supplied to the plots for rice at different locations for 2015-16

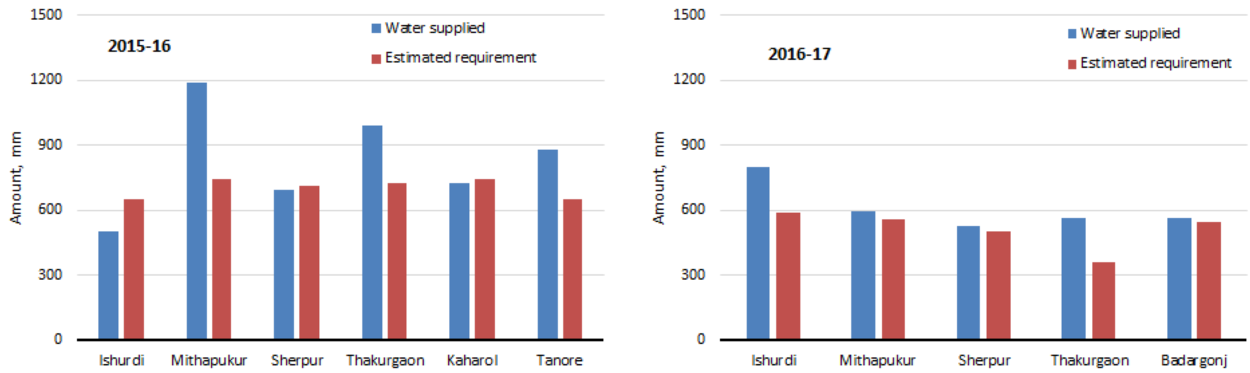

Figure 4.31 Comparison of average irrigation supplied and requirements for rice at different locations

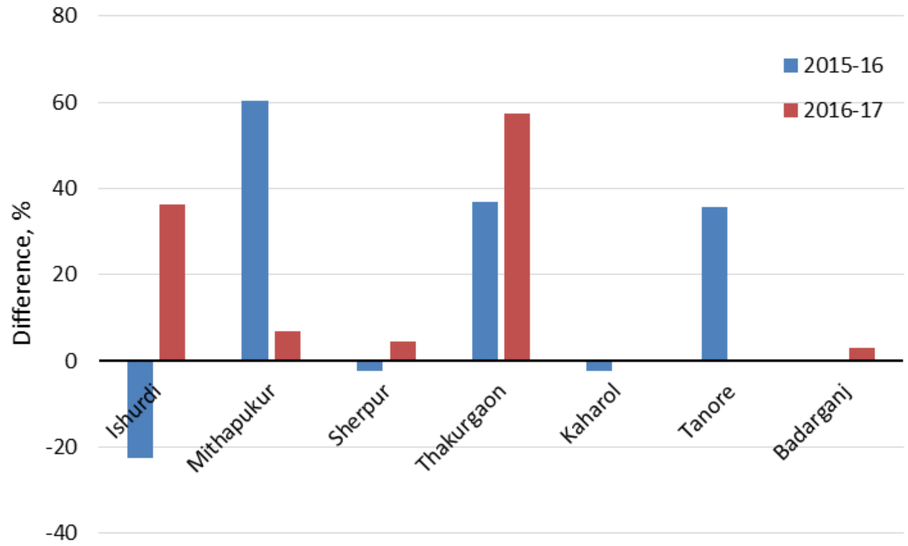

Figure 4.32 Difference of water supply and estimated requirements as % of requirements

In Ishurdi, one of the STWs we monitored (STW-1 or STW-3 check with BRRI) was using a centrifugal pump operated by electric motor in 2015-16. Due to decline in water level (Figure 4.33), it was difficult to pump water with full capacity of the pump. There was long stopping period for the pump as well. So the pumping of water was constrained which 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 constraints of pumping water which might have contributed to the higher supply of water in the field in 2016-17.

In all location, 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 year 2016-17. Due to higher supply of water in the fields of Thakurgaon and Mithapukur in 2015-16, we actively promoted to the farmers AWD method of irrigation or less supply of water in the field. There was 3 demonstration of AWD in Thakurgaon and 5 in Mithapukur where we have actively monitored the water supply (refer to the other report). Apart from that there was xx farmers in Thakurgaon and xx farmers in Mithapukur who used the AWD method for irrigation in their plot. While this awareness might have helped to some extent significant reduction in water use in 2016-17 (11% oversupply) compared to water use in 2015-16 (67% oversupply). But that was not the case in Thakurgaon. In 2016-17, water supply was 57% higher over the estimated requirements; in 2015-16 this was 37%.

Thakurgaon is a DTW site where there is no problem of pumping water. Farmer 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 to the farmers to supply more water in the field. As we found in both season, farmers oversupplied water in the field in Thakurgaon (DTW site). This is also true for another DTW site, Tanore, for the season 2015-16 (36% oversupply).

In both season, water supply was very close (within -2 to 4% of the requirements, Figure 4.32) to Sherpur. Among the STW sites, the highest decline in groundwater level was in Sherpur (Figure 4.33). The water level declined to xx meter in 2015-16 and xx meter in 2016-17 at the beginning of April which is very close to the suction limit. The capacity of pumping water gets reduced at that time. Farmers are aware of that condition, so they are very wise in applying water. That could be the main reason of highly efficient water supply to the plots of Sherpur in both season. In Badarganj, water is supplied by commercial provider using solar energy. Qualified agriculture and irrigation management professional are in charge of 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 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 which 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 be some difference due to the variation in soil condition, condition of the bund, and location of the plot.

Nonetheless, in general, following inference can be made from the comparison of the water supply with the estimated requirements for the sites in two season.

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

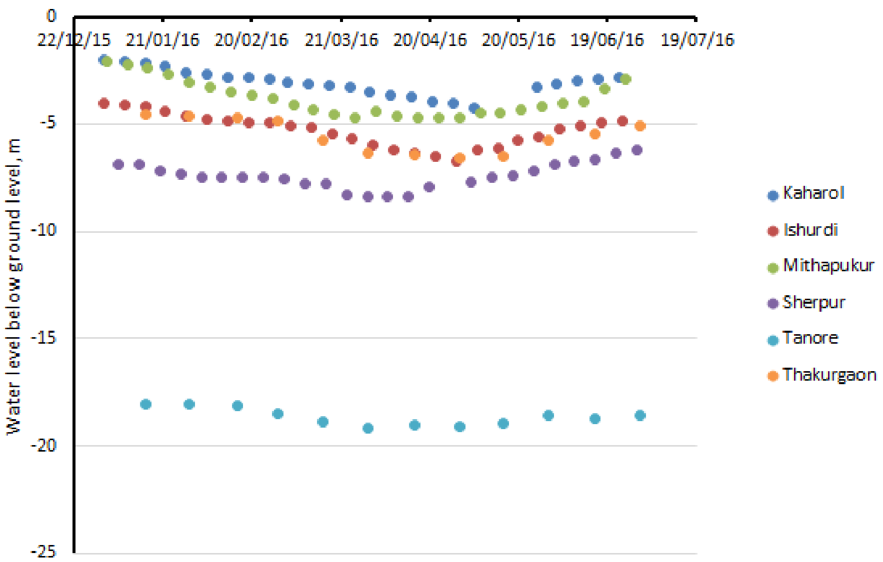

Figure 4.33 Observed groundwater level in the selected sties (update this figure)

There is general perception with the researchers and policy makers that farmers apply too much water (refer to the document of Dr. Moshiur) in the field than is required. This results of this study do not support that perception at least for the STW area. For the STW irrigated area the results suggest that farmers are very careful and wise in applying water in the field. There are some over application in the DTW area. However, the scale of it may not be as big as the general perception.

Figure 4.34 shows irrigation water supplied to the plot to produce one Kg of rice for all the plots for the years 2015-16 and 2016-17. Irrigation water supplied varied from 670 to 2683 lit/kg in 2015-16 and 701 to 1593 lit/kg in 2016-17. The average for all the plots were 1,086 and lit/kg and 1,402 lit/kg respectively for 2015-16 and 2016-17. In 2015-16 water supply was higher (29%) than that of 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. So the general perception of overuse of water to the extent of 3,000 to 5,000 lit to produce a Kg of rice is nowhere near the reality in the field. As we discussed earlier, due to high price of water, reduced availability, and experience of the farmers, farmers are very wise in supplying water to the field. Over the years, yield of rice increased linearly (as shown in Figure 2.15, also see Mainuddin et al. 2015) while the actual water supply may have been reduced which is also a contributing factor in the lower water use for producing rice.

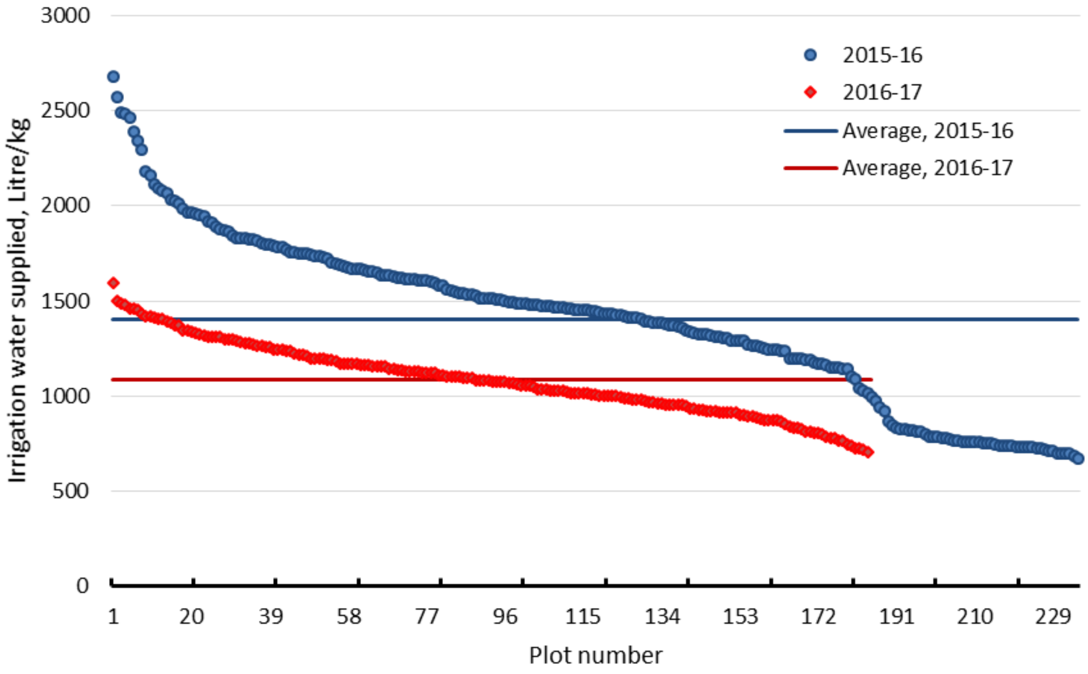

Figure 4.34 Irrigation water supplied to grow a kilogram of rice

Not all water supplied to the rice field are actually 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 more or less 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. They are going back to the aquifer as recharge. Irrigation water is extracted from the aquifer below the field in the northwest region in the dry season. Due to that groundwater level goes down, create 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 they are not visible in the water level hydrographs. Without that recharge, water level would have dropped further below what we observe 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 Eastern Gangetic Plains.

Actual water used to produce rice is the actual evapotranspiration during the cropping period. The potential (maximum that is possible) crop evapotranspiration for the two seasons are given in Figures 4.26 and 4.27. In 2015-16, maximum potential evapotranspiration was 545 mm for BRRI dhan29. In that year lowest yield of BRRI dhan29 was 4.76 tonne/ha. So the actual water use to produce 1 kg of rice was 873 litre. In 2016-17, maximum potential crop evapotranspiration was 497 mm for BRRI dhan29 and the lowest yield was 6.68 tonne/ha; requiring 1,344 lit of water to grow a kg of rice. These results clearly indicate that the perception of actual water use (potential crop evapotranspiration) or water supplied to the field to grow 1 kg of rice is far from the reality in the field.

4.10 Irrigation water requirements and use for other crops

For crops other than rice grown in the monitored area, the estimated irrigation water requirements in general is higher than actual irrigation water supplied to the field (Figure 4.35). In estimating the irrigation requirements, we did not consider the capillary rise of groundwater water which usually contributes to the plant water uptake by the non-rice crops. Some of the monitored plots are adjacent to the rice field from which water seeps to the non-rice fields (as there is no standing water in these fields) requiring less water for irrigation. Pricing of water for non-rice crops is different from the rice crop. Usually pricing is based on per irrigation or by time of pump operation unlike rice where pricing is mainly based on area and supplying of irrigation water for the whole season. It is likely that due to these factors, actual supply of irrigation water in the field is less than the estimated requirements.

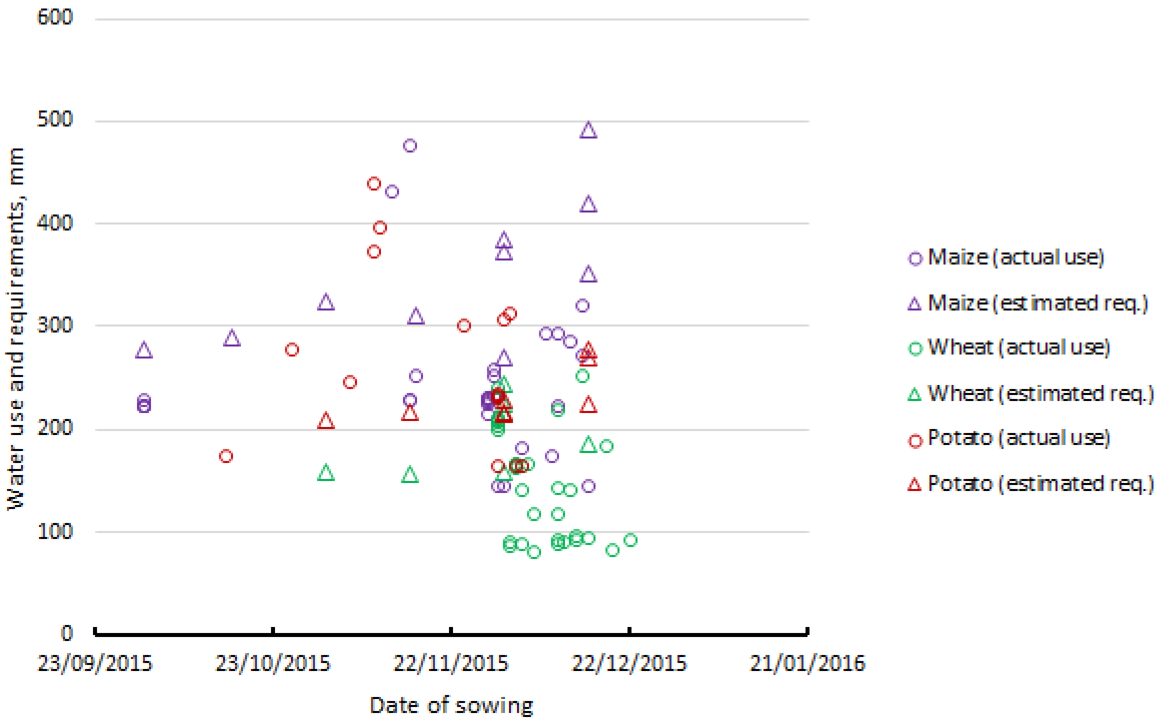

Figure 4.35 Comparison of irrigation water requirements with actual water used for other crops (except rice)

4.11 Real price of irrigation water

In Section 3.2.1, we discussed different water pricing method currently being used in the monitored area. None of these pricing methods are based on actual volume of water. Using the amount of irrigation water supplied to the monitored plots, we estimated the real cost of irrigation water based on volume. Figure 4.36 shows the estimated average cost of irrigation water for different locations, varieties, and the pump types. Among the location, the cost of irrigation water was the highest (above 4.00 Taka/m^3) in Ishurdi in both 2015-16, and 2016-17 and the lowest was at Thakurgaon (about 1.00 Taka/m^3). As discussed earlier, water pricing is based on crop sharing in Ishurdi which makes the water costliest in this location. Thakurgaon is a DTW site where water price is fixed at 110 Taka/hour of operation. DTW water is the cheapest among the different pump types.

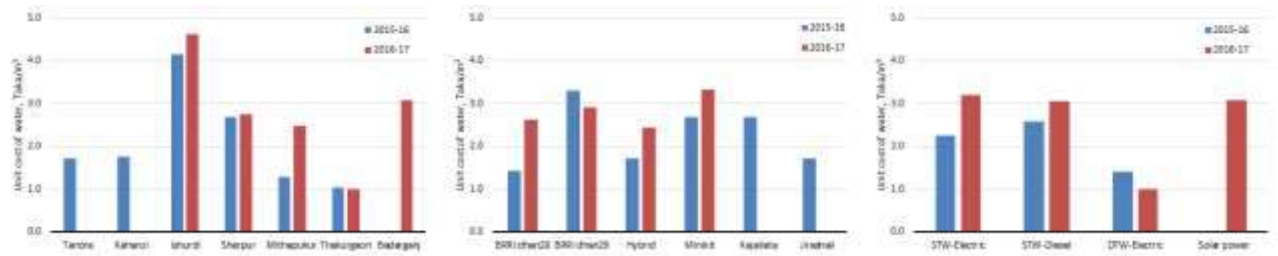

Figure 4.36 Real cost of irrigation water for rice by location, varieties, and type of tubewells

4.12 Water productivity

Water productivity analysis combines physical accounting of water with 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, there are three types of crop water productivity that can be distinguished (Cook et al., 2006; Immerzeel et al., 2008; Abdullaev and Molden, 2004).

(i) Physical water productivity (kg/m^3) defined as the mass of product per unit water consumed.

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

(iii) Non-economic (such as 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 value.

In this study, we defined physical water productivity as the crop yield per unit of water supplied to the field. Economic water productivity was calculated by dividing the gross income (Gross benefit' minus 'total paid-out cost') by water supplied to the field.

The physical water productivity depends on the rice production and water used. The yield and water used varied from variety to variety, climatic conditions and soil properties. It has some influence on mode of tubewell operated. The physical water productivity of rice varied from 0.37kg/m^3 to 1.47 kg/m^3 for all plots during 2015-16 (Figure 4.37). In 2016-17 productivity varied from 0 to 1.43 Kg/m^3. One plot of Sherpur was completely damaged; there was no yield. So the productivity of this plot was 0. The economic productivity 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 4.37). Due to higher price of rice in 2015-16 and lower use of irrigation water, economic productivity was significantly higher in 2016-17.

Figures 4.38 and 4.39 show the physical and economic water productivities of rice by location, varieties, and type of tubewells. In 2015-16, highest water productivity was in Ishurdi due to higher rice yield and lower water use and the lowest water productivity was in Mithapukur due to comparatively lower yield and high amount of irrigation water used. In 2016-17, highest physical water productivity was in Thakurgaon and the lowest was in Sherpur. Among the rice varieties, physical water productivity was highest from BRRI dhan29 in 2015-16. In 2016-17, highest was physical water productivity was surprisingly for Minikit. The reason for this is comparatively higher yield and lower irrigation water use. The findings of our study are similar with Bouman and Toung (2001) who reported 0.3 to 1.1 kg grain m^{-3} water productivity with continuous submergence regimes. Among the type of tubewells, there was significant difference in economic water productivity for DTWs for 2015-16 and 2016-17. For others, there was no significant variation from year to year. Economic water productivity follows, in general, the pattern of physical water productivity for the locations, varieties and type of tubewells (Figure 4.39). The economic water productivity was significantly higher in 2016-17 as compared to 2015-16.

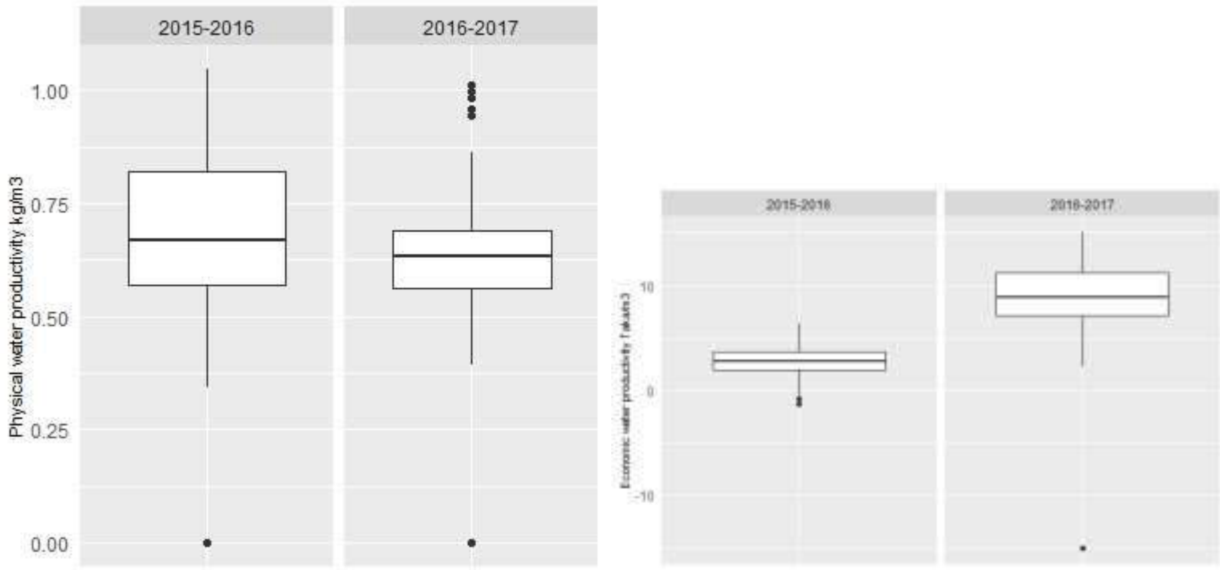

Figure 4.37 Physical (left) and economic (right) water productivity of rice

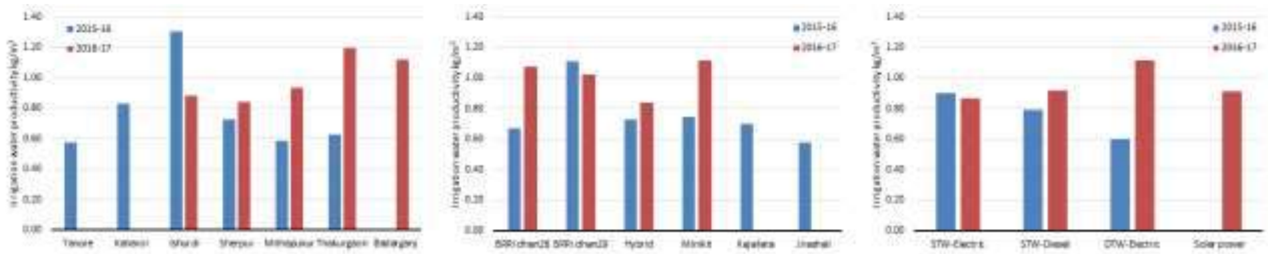

Figure 4.38 Physical water productivity of rice by location, varieties, and type of tubewells

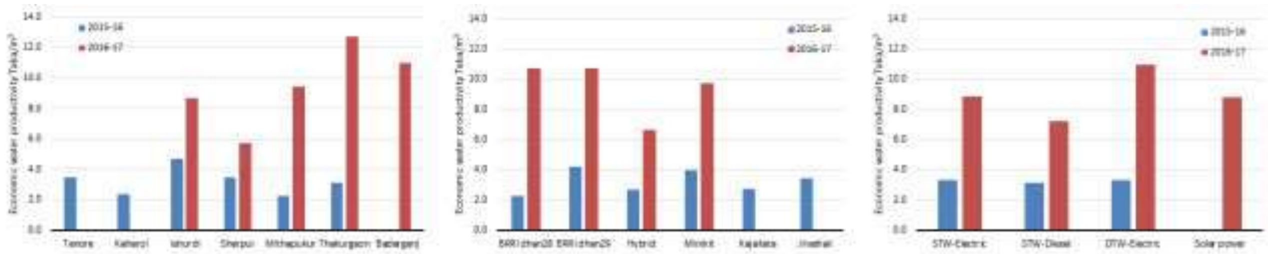

Figure 4.39 Economic water productivity of rice by location, varieties, and type of tubewells

Within the command area of tubewells in Ishrudi, the physical water productivity 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 4.40). The difference in water productivity between 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) are insignificant. However, the variation is higher with the productivity of BRRI dhan29 under the same tubewell (0.91 kg/m^3). The variation in physical productivity is 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 4.40) is similar to that of gross income (Figure 4.10).

Though the physical water productivity was highest with hybrid rice plots under STW-3, the economic water productivity is the highest for the plots with BRRI dhan29 under STW-1 (4.52 Taka/m^3), which is about 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 ranging from 0.79 kg/m^3 to 1.286 kg/m^3. For Minikit the average productivity was 0.84 kg/m^3 ranging from 0.699 to 1.086 kg/m^3. The average economic water productivity were 8.37 and 8.87 Taka/m^3 respectively for BRRI dhan29 and Minikit.

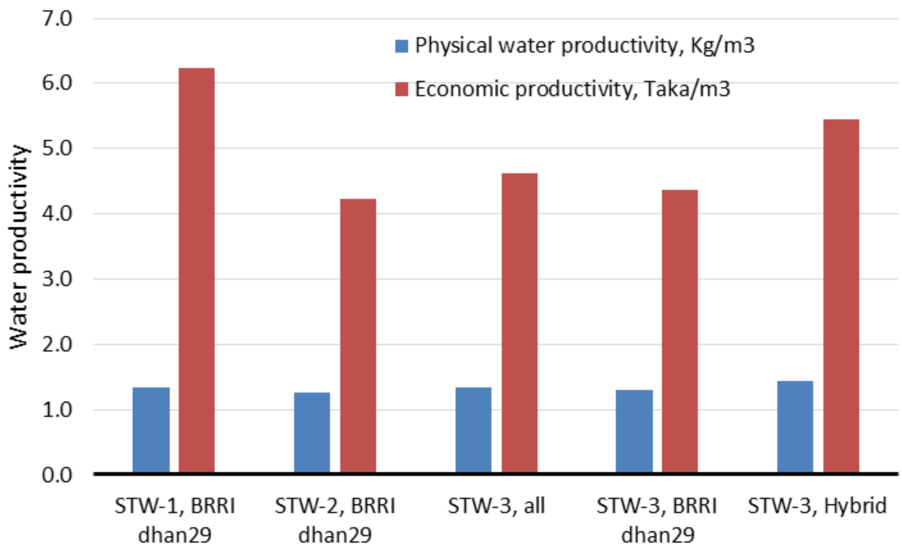

Figure 4.40 Water productivity of rice for the STWs of Ishurdi

Figure 4.41 compares the economic water productivity of rice, maize and potato (3 major crops grown in the region) for 2015-16 and 2016-17. 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, economic water productivity of potato was several fold higher than that in 2015-16 due to higher production, higher price and less amount of water used.

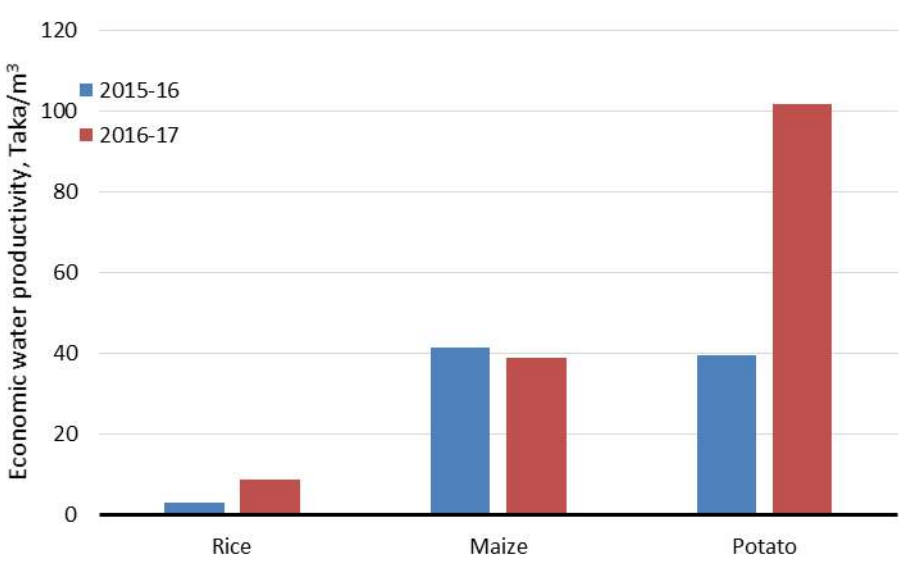

Figure 4.41 Comparison of economic water productivity of rice, maize and potato

5 Conclusions, recommendations and key messages

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. The region is most diversified agricultural region of the country and the average yield of the major crops are higher than the country average. 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 the northwest region. Many studies show that groundwater levels are falling and that the use of shallow aquifers for irrigation in the area is unsustainable. However, the availability of water for irrigation is 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. However, there are lack of 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 region based on both the historical data and primary information collected from the field. To the best of our knowledge, we didn't come across any literature on the state of irrigated agriculture of the region based on such comprehensive analysis.

5.1 Conclusion

1. Northwest region is the most intensively cultivated region of the country. Most diversified crop growing region.
2. The average cropping intensity of the region in 2012 was 205% compared to the country average of 190%. The cropping intensity is greater than the national average in all districts and rising.
3. Average yield of rice is higher in the NW region. Though in general yield is higher and rising, still there is spatial variation. Sudden increase in yield of maize is triggered by the higher price due to market demand (farmers are using good seed and lot of inputs).
4. Groundwater is the main driver of the phenomenal growth of irrigation and 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 evidence that GW levels are falling in some parts of the northwest region. Water table drops below the suction limit of HTW and STW in some areas. Still use of STW and DTW is increasing. STW installed below the ground level to pump water in Bogra.
6. Groundwater level is declining in some areas particularly in the Barind region. STW are unable to pump water in the driest period (April-May). Area irrigated by STW are decreasing as farmers are installing DTW to pump water.
7. Boro rice area is steady over the last few years. Maize is increasing rapidly mostly at the expense of other crops not rice.
8. The initial drivers for the change in cropping system was availability of irrigation, research and development and extension and education. Current change (e.g. growth of maize) is mostly driven by market demand, availability of water, risk (e.g. climate, disease, market), 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 cropping system, farmers' requirements and choice, subsistence vs profit making, etc.
10. Decreasing trend in yield with the delay in transplanting for BRRI Dhan28 and BRRI Dhan29. Most of the plots were planted during 2nd half of January and 1st half of February. Hybrid rice seems not affected by the transplanting time.
11. It seems higher the age of seedlings lower is the yield for BRRI Dhan28 and BRRI Dhan29.
12. Total cost significantly differ among the locations, types of pumps used for irrigation, varieties of rice and transplanting dates. Significant variation in total income among the locations and variety of rice. Significant variation in net benefit for location, pump type and varieties of rice.
13. In 2015-16, the average net benefit of Hybrid rice, BRRI dhan29 and Minikit are almost similar. But in 2016-17, net benefit of Hybrid and BRRI dhan29 was higher than the others (Minikit and BRRI dhan28) – mainly because of higher yield. Price of all varieties was higher in 2016-17, Minikit price was much higher in 2015-16. If the rice price in general is high, then the price difference between fine and coarse rice becomes lower.
14. Cost of irrigation was as high as around 35% of the total production cost of rice. 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. Estimate cost is the highest in Ishurdi because of crop sharing model. DTW is the cheapest (110 Taka/hour, 60 lit/s). Solar irrigation is costlier than STW (7,000 Taka/acre vs 4,000 taka/acre in Mithapukur).
15. Volumetric cost of water (estimated based on the water supplied to the plot by the farmer) varies widely - 45 Taka/ha-mm to 10 Taka/ha-mm. DTW is the cheapest and solar irrigation is costlier (30 Taka/ha-mm) than STW operated by diesel engine or electric motor.
16. Significant variation in yield among location and varieties. Not significant for various type of pumps or planting dates. Yield is significantly affected by the location, variety, pesticides and herbicides, application of phosphate fertilizer.
17. Hybrid rice and BRRI dhan29 produced higher yield. Variation in yield is less in BRRI dhan29. For own consumption better to grow hybrid rice or BR-29 as their yield is higher. Jirashail, Minikit, and Kajallata are low yielding but can be more profitable (depending on the market).
18. The probability of achieving yield of 8.0 tonne/ha for hybrid rice is only 20%. The average net benefit of Hybrid rice, BR-29 and Minikit are almost similar. For own consumption better to grow hybrid rice or BR-29 as their yield is higher. Farmers who are growing rice for selling to the market, it could be better for them to grow Jirashail or Minikit.
19. 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. High variation in the net benefit of potato with the CV of about 52.2%.
20. ETcrop for rice varies from 283 mm to 545 mm. ETcrop for maize varies from 276 to 528 mm. So for water saving, maize may not be a good replacement for rice.
21. Yield and net benefit varies from plot to plot and location to location but in general rice is profitable cultivation contrary to the popular belief (that there is no profit)
22. Contrary to the popular belief, farmers are in general very efficient in applying water to the crops. In general, in STW sites farmers are very efficient in applying water. DTW sites have some oversupply. Irrigation water use is higher in DTW site – price is much lower than compared to STW. Average irrigation water use was less than 800 mm except Mithapukur and Thakurgaon in 2015-16. Variability was higher in 2015-16.
23. Average water applied is to the crops other than rice less than required estimates. The difference is very high for maize (the average water applied is about 50% of the required estimates).

24. General perception is 3000-5000 lit of water is required to grow a kg of rice. Average of 2015-16 was 1402 lit/kg, 2016-17 1086 lit/kg. Water use in DTW is higher particularly in 2015-16, low cost. Water is costly in STW, so farmers are prudent in applying water.
25. Percolation rate from the rice field on average is 3 mm/day. Percolation is recharging groundwater during the irrigation season – so they are not lost. Less pumping – does not mean aquifer is saved unless this reduces the ET of crop. Current water saving measures (such as AWD, etc.) are based on conception of less pumping – no study on whether they reduce ET. But less pumping saves cost and reduce emission (economic and environmental benefit).
26. Water productivity of rice varies from site to site due to variation in yield, net benefit and irrigation water use. Economic productivity of maize and potato are several times higher than rice Water productivity is much higher for potato and maize.

5.2 Recommendation

To be written

5.3 Key messages (to be revised)

1. Irrigation is essential for dry season cropping – need to explore multiple sources (not fully dependent on groundwater)
2. Need to understand the availability of the resources particularly groundwater – so that no concerns arise after some years
3. Use of STW may be promoted – potential for water market
4. Non rice crops should be promoted from the beginning – need market development for the non-rice crops
5. Water efficient agricultural practices should be promoted
6. Farmers are well trained on cropping practices and up to date with the current event and market conditions – (research and extension services in Bangladesh is very highly developed
7. So provide adequate training to the farmers, access to information

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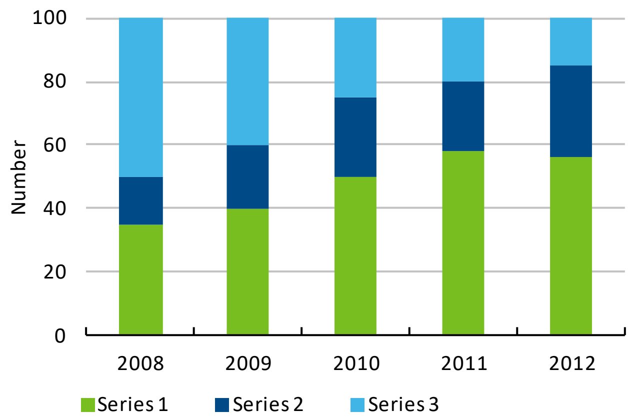

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References

Aziz MA, Majumder MAK, Kabir MS, Hossain MI, Rahman NMF, Rahman F, and Hosen S (2015).Groundwater Depletion with Expansion of Irrigation in Barind Tract: A Case Study of Rajshahi District of Bangladesh. International Journal of Geology, Agriculture and Environmental Sciences 3(1): 32-38.

Sumiya NN and Khatun H (2016). Groundwater variability in Bangladesh: assessment based on rainfall variation and use of water in irrigation. J. Asiat. Soc. Bangladesh, Sci. 42(2): 177-189.

World Bank (2016). Dynamics of rural growth in Bangladesh: Sustaining Poverty Reduction (available at http://documents.worldbank.org/curated/en/2016/05/26377500/dynamics-rural-growth-bangladesh-sustainting-poverty-reduction.

Habiba U, Shaw R, Takeuchi Y(2014). Farmers' adaptive practices for drought risk reduction in the northwest region of Bangladesh. Nat Hazards (2014) 72:337–359.

Shahid S (2011). Impact of climate change on irrigation water demand of dry season Boro rice in north-west Bangladesh. Clim Change 105:433–453

Shahid S, Chen X, Hazarika MK (2005). Assessment aridity of Bangladesh using geographic information Center, Dhaka, Bangladesh.

Riches, C.R. (2008). The High Barind Tract: a challenging drought-prone agricultural environment. In: Riches, C.R., Harris, D., Johnson, D.E. and Hardy, B., (eds.) Improving agricultural productivity in rice-based systems of the High Barind Tract of Bangladesh. International Rice Research Institute, Los Baños (Philippines), pp. 3-6. ISBN 978-971-22-0229-2.

Jahan CS, Mazumder QH, Islam ATM, Adham MI (2010). Impact of irrigation in Barind area, NW Bangladesh—an evaluation based on the meteorological parameters and fluctuation trend in groundwater table. J Geol Soc India 76:134–142.

Hasanuzzaman M, Song X, Han D, Zhang Y, and Hussain S (2017). Prediction of Groundwater Dynamics for Sustainable Water Resource Management in Bogra District, Northwest Bangladesh. Water 2017, 9, 238; doi:10.3390/w9040238.

Mustafa SMT, Abdollahi K, Verbeiren B and Huysmans M (2017). Identification of the influencing factors on groundwater drought and depletion in north-western Bangladesh. Hydrogeol J DOI 10.1007/s10040-017-1547-7.

Qureshi AS, Ahmad ZU and Krupnik TJ (2015). Moving from Resource Development to Resource Management: Problems, Prospects and Policy Recommendations for Sustainable Groundwater Management in Bangladesh. Water Resour Manage (2015) 29:4269–4283.

MacDonald AM, Bonsor HC, Ahmed KM, Burgess WG, Basharat M, Calow RC, Dixit A, Foster SSD, Gopal K, Lapworth DJ, Lark RM, Moench M, Mukherjee A, Rao MS, Shamsudduha M, Smith L, Taylor RG, Tucker J, van Steenbergen F and Yadav SK (2016). Groundwater quality and depletion in the Indo-Gangetic Basin mapped from in situ observations. Nature Geoscience, DOI: 10.1038/NGEO2791.

Salem GSA, Kazama S, Komori D, Shahid S., and Dey NC (2017). Optimum Abstraction of Groundwater for Sustaining Groundwater Level and Reducing Irrigation Cost. Water Resour Manage DOI 10.1007/s11269-017-1623-8.

Kirby JM, Mainuddin M, Mpelasoka F, Ahmad MD, Palash W, Quadir ME, Shah-Newaz SM and Hossain MM (2016). The impact of climate change on regional water balances in Bangladesh. Climatic Change 135:481–491.

Kirby JM, Ahmad MD, Mainuddin M, Palash W, Quadir ME, Shah-Newaz SM and Hossain MM (2015). The impact of irrigation development on regional groundwater resources in Bangladesh. Agricultural Water Management 159: 264–276.

CEGIS (Center for Environmental and Geographic Information Services) (2013) Description of physical and environmental parameters. CEGIS, Dhaka.

Maniruzzaman M, Muttaleb MA, Choudhury AK, Akhter S, Ahmed F, Aziz MA, Rahman MM, Miah MM, Biswas JC, Hamid MA, Kalra N (2017). Characterization of Inter-seasonal Climatic Variability through Dry-season Rice Productivity in the North-west Region of Bangladesh. Italian Journal of Agrometeorology 1: 5-18. DOI:10.19199/2017.1.2038-5625.005

Biswas JC, Hossain MB, ChoudhuryAK, Kalra N and Maniruzzaman M (2017). Climatic Variability and Wet Season Rice (*Oryza sativa* L.) Production in North-West Bangladesh. The Agriculturists 15(1): 68-80. DOI: http://dx.doi.org/10.3329/agric.v15i1.33430

Rahman MM, Mahbub AQM (2012). Groundwater depletion with expansion of irrigation in Barind Tract: A case study of Tanore Upazila. *J. of Water Res. and Protection,* 4, 567-575.

Samsudduha M, Chandler RE, Taylor RG, Ahmed KM (2009). Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-Meghna Delta. *Hydrol. Earth Syst. Sci.*, 13, 2372-2385.

Bouman BAM, and Tuong TP (2001). Field water management to save water and increase its productivity in irrigated rice. Agric. Water Manage. 49(1): 11–30.

Biswas JC, Sarker UK, Sattar SA (2001). Performance of some BRRI varieties planted year round. Bangladesh Rice J., 10(1&2): 55-59.

Mobasser HR, Tari DB, Vojdani M, Abadi RS and Eftekhari A (2007). Effect of seedling age and spaces on yield and yield components of rice (Neda Varity). Asian J of Plant Sciences, 6(2):438-440.

Malaker PK, Barma NCD, Tiwari TP, Collis WJ, Duveiller D, Singh PK, Joshi AK, Singh RP, Braun HJ, Farman ML, Valent B (2016). First report of wheat blast caused by *Magnaporthe oryzae* pathotype *triticum* in Bangladesh. J of plant disease, 100(11): p 2330

Abdullaev, I., Molden, D., 2004. Spatial and temporal variability of water productivity in the Syr Darya Basin, Central Asia. Water Resources Research 40, W08S02, doi:10.1029/2003 WR002364.

Cook, S., Gichuki, F., Turral, H., 2006. Agricultural Water Productivity: Issues, Concepts and Approaches, Basin Focal Project Working Paper No. 1. Available at http://www.waterandfood.org/fileadmin/CPWF_Documents/Documents/ Basin_Focal_Projects/BFP_restricted/Paper_1_Final_14JY06.pdf.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. Food and Agricultural Organization, Rome.

Molden, D., 1997. Accounting for Water Use and Productivity. International Water Management Institute, Colombo.

Molden, D., Sakthivadivel, R., Habib, Z., 2001. Basin-level Use and Productivity of Water: Examples from South Asia. International Water Management Institute, Colombo.

Molden, M., Murray-Rust, H., Sakthivadivel, R., Makin, I., 2003. Water productivity framework for understanding and action. In: Kijne, J.W., Barker, R., Molden, D. (Eds.), Water Productivity in Agriculture: Limits and Opportunities for Improvement.. CAB International, Wallingford, UK.

Boonjung, H., 2000

Mainuddin et al. (2014). --

Mainuddin et al. (2015). --

Shahid and Hazarika (2010). ---

Imon and Ahmed (2013). ---

CSIRO (2014). ---

Hodgson et al. (2014). --

Haq (2013). --

GoB (2010). ---

UN Population Division (2012). --

Allen (2011). --

Allen et al. (1998). ---

Doorenbos and Kassam (1979). --

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