LAND AND WATER FLAGSHIP
www.csiro.au

Sustaining water resources for food security in Bangladesh

A report contributing to Objective 1 of the Australian Government's South Asia Sustainable Development Investment Portfolio – confident and cooperative decision-making across jurisdictional borders for the effective and equitable management of shared water resources

Mohammed Mainuddin, Mac Kirby, Glen Walker, Jeff Connor (editors)
November 2014

Australian Government
Department of Foreign Affairs and Trade
Australian Aid
INSTITUTE OF WATER MODELLING IWM
THE UNIVERSITY of ADELAIDE

Copyright

Important disclaimer

CSIRO advises that the information contained in this publication comprises general statements based on scientific research. The reader is advised and needs to be aware that such information may be incomplete or unable to be used in any specific situation. No reliance or actions must therefore be made on that information without seeking prior expert professional, scientific and technical advice. To the extent permitted by law, CSIRO (including its employees and consultants) excludes all liability to any person for any consequences, including but not limited to all losses, damages, costs, expenses and any other compensation, arising directly or indirectly from using this publication (in part or in whole) and any information or material contained in it.

Citation

Mainuddin M, Kirby M, Walker G and Connor J (editors) (2014) Sustaining Water Resources for Food Security in Bangladesh. CSIRO Sustainable Development Investment Portfolio project. CSIRO Land and Water Flagship, Australia. 110pp

This report designed and implemented by CSIRO contributes to the South Asia Sustainable Development Investment Portfolio and is supported by the Australian Government.

Contributors

Chapter 1: Mac Kirby[1] and Mohammed Mainuddin[1]

Chapter 2: Mohammed Mainuddin, Mac Kirby and Geoff Hodgson[2]

Chapter 3: Mac Kirby, Mobin-ud-Din Ahmad[1], Mohammed Mainuddin, Wahid Palash[3], Muhammad Enamul Quadir[3], Sardar M Shah-Newaz[3]

Chapter 4: Glen Walker[4], Tarikul Islam[3], Jakir Hossain[3], Geoff Hodgson, Mobin-ud-Din Ahmad

Chapter 5: Iffat Ara[5], Jeff Connor[4], Bertram Ostendorf[5], John Kandulu[4]

Chapter 6: Mohammed Mainuddin, Mac Kirby, Glen Walker, Jeff Connor

[1] CSIRO Land and Water Flagship, Black Mountain Laboratories, Canberra, ACT 2601

[2] CSIRO Land and Water Flagship, Floreat, WA 6014

[3] Institute of Water Modelling (IWM), House # 496, Road # 32, New DOHS, Mohakhali, Dhaka, 1206, Bangladesh

[4] CSIRO Land and Water Flagship, Waite Campus, Urrbrae, SA 5001

[5] The University of Adelaide, Adelaide, SA 5000

Foreword

In April 2013 the Australian Department of Foreign Affairs and Trade (DFAT) formally released the Sustainable Development Investment Strategy (SDIS). The strategy is based on a portfolio partner approach that aims to increase water, food and energy security in South Asia, facilitate economic growth and improve livelihoods; targeting the poorest and most vulnerable, particularly women and girls. The portfolio of partners and associated work is managed under the Sustainable Development Investment Portfolio (SDIP). The SDIP targets three inter-related sectors where Australia is uniquely placed to contribute; water resource management, agricultural productivity and energy access. The SDIP is based on a 12 year design with around $50m secured for the first 4 years (2012-16). The SDIP focuses on the three major Himalayan river basins, the Indus, Ganges and Brahmaputra, which span North-East India, Pakistan and the bordering countries of Bangladesh, Nepal and Bhutan.

Within the SDIP the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and DFAT entered into a joint funding agreement in October 2013, to support a range of scientific and technical activities towards improving water resource management capability in south Asia. The overall intent of the work is to establish a coherent and integrated portfolio of activities that assist governments and communities to understand the linkages and trade-offs between water management decisions and economic growth, energy security and food security. The activities are designed to achieve tangible capacity building in key institutions and focal regions, influence water management policy and planning, support infrastructure development, and livelihood assessment.

CSIRO had previously been involved in an Integrated Water Resource Assessment for Bangladesh in 2010-2014. This project identified areas of future research that were closely aligned with SDIP objectives. Consequently, in 2013-14 a project was set up under the CSIRO-SDIP to examine agricultural production, regional water balances, groundwater levels and exchange of water between the groundwater and surface water, together with a study on econometric assessment of livelihoods outcomes within the northwest and north-central regions of Bangladesh.

To deliver on this project CSIRO has drawn on the scientific leadership and technical expertise within CSIRO as well as a local (Institute of Water Modelling) and an Australian partner (The University of Adelaide). This report is made possible due to the efforts of CSIRO scientists and other partners. CSIRO values the contributions of others as well as the relationships that have been built up as part of this work.

This report provides some valuable insights into the relationships between climate, rivers, recharge, groundwater use for irrigation and the sustainability of groundwater systems. It also considers the relationships between the physical aspects of water and how this relates to livelihoods of the population, particularly women and the poor and landless people in the regions. Understanding the strong relationship between groundwater, irrigation, food production and livelihoods is a big step towards more sustainable management of the water resources of Bangladesh. The report also recognises that more needs to be done to have a regional scale understanding of the sustainability of surface and groundwater resources.

This is a valuable piece of research that clearly supports the SDIP objectives and hopefully supports Bangladesh on its water resource management journey.

Geoff Podger

Project Director South Asia Sustainable Development Investment Portfolio

CSIRO

Contents

Figures

Tables

Executive summary

Bangladesh intends to revise and update its National Water Management Plan. The study reported here follows on from the Bangladesh Integrated Water Resources Assessment work of 2010–2014 and aims to provide information to support the revision. This report describes the first phase of the study, which was a preliminary study to scope out the second phase of detailed modelling and scenarios analysis. The geographic scope of the study was the irrigation intensive northwest and north-central regions which are vital for future food security of Bangladesh.

The main findings are:

1. Groundwater irrigation is the main factor behind the current self sufficiency in rice production. Sustaining groundwater irrigation is vital for the future food security of Bangladesh.
2. The increased area of irrigation and increased volume of groundwater pumping over the last three decades has contributed to declines in groundwater levels. The regional average trend in declining groundwater level appears to be at least partly explained by the trend in increasing irrigation rather than the absolute level of irrigation. A halt in the trend of increasing irrigation may see a reduction in the trend of decreasing groundwater level, albeit at lower groundwater levels.
3. The lower groundwater levels referred to above, combined with further lowering in drought years, will in some areas cause difficulties with access for drinking water and irrigation water in the future (as they already do in some areas).
4. Within the region are areas, particularly in the Barind Tract, of unsustainable over-use of groundwater.
5. Lower groundwater levels in the pre-monsoon period have meant a shift towards less groundwater moving to streams and more water moving from streams; more water infiltrating through the land surface, with a probable reduction in surface runoff and reduced return flow to streams.
6. Aquifers are losing water to most major streams. The exceptions appear to be above junctions of major rivers and/or in areas where landscape is flattening. The influence of the streams on the groundwater appears to be constrained to within a few kilometres of the stream.
7. The total surface water-groundwater fluxes for the northwest region appear to be smaller than previously thought and are not likely to be more than 20 billion cubic metres per year.
8. Socio-economic development through industrialisation that creates wage income is a major contributor to both household income and nutritional well-being.
9. Women should be incorporated into mainstream development activities to enjoy better livelihoods.

Based on the findings, we recommend that studies should be conducted to:

1. Examine the impact of different external drivers (such as population growth, climate change, upstream development, construction of barrages, etc.) on the overall water balance and surface-water groundwater interaction, availability, and sustainability.

2. Examine the impact of future water availability on the irrigated agriculture, regional socio-economy, livelihoods, and the environments and, in particular, conduct a social cost-benefit analysis of potential investments or policies.
3. To enable the previous two aspects, develop regional scale understanding and evaluation of the surface water and groundwater resources, surface water and groundwater interaction, recharge/discharge mechanisms and trends, sustainable limit of groundwater use using hydrological and hydro-geological information, and detail modelling.

The findings and recommendations are based on a preliminary examination of agricultural production, regional water balances, groundwater levels and exchange of water between the groundwater and surface water, together with a study on econometric assessment of livelihoods outcomes within the northwest and north-central regions of Bangladesh.

1 Introduction

Contributors: Mac Kirby, Mohammed Mainuddin

1.1 Background

Bangladesh intends to revise and update its National Water Management Plan. The study reported here aims to provide information to support the revision, and follows an earlier study, the Bangladesh Integrated Water Resources Assessment (CSIRO, 2014). The earlier study provided a general overview of Bangladesh's water availability, use and demand, including the impacts of changing water availability on the national economy and on vulnerable households.

A main finding of the earlier study was that, despite concerns over falling groundwater levels, the levels of sustainable use of groundwater cannot currently be adequately assessed for most of the country. The key reason for this inadequacy was that the volumes of water exchanged annually have not been assessed, other than in a small pilot assessment conducted as part of the earlier study (IWM, 2014a). We concluded that this is a major gap and in need of further detailed study.

The northwest and north-central regions have the largest areas of cropping and are crucial to the recent attainment of rice grain food security in Bangladesh. The northwest region alone supplies about 35 percent of the irrigated *Boro* rice and about 60 percent of the wheat of the whole country. The northwest region is also the region of greatest concern over falling groundwater levels (Kirby et al., 2013; CSIRO, 2014) which leads to a lack of access to water for drinking (Haq, 2013) and irrigation in some areas. The falling groundwater level within the Barind Tract area in the northwest region is clearly a result of excessive pumping for irrigation (Kirby et al., 2013; CSIRO, 2014). However, it is not clear whether the declining groundwater levels in the rest of the region result from an observed decline in rainfall, or from excessive use, or from some combination of these and possibly other factors.

The previous study recommended that further studies be undertaken in the northwest and north-central regions to examine these issues and to provide greater certainty of the volumes of groundwater that could be sustainably used for irrigation.

Potentially, there are several options for responding to the declining water levels. Groundwater use could be capped. Surface water could be substituted for groundwater – indeed, the Government of Bangladesh intends to decrease dependence on groundwater by increasing use of surface water for irrigation. Agriculture could be encouraged elsewhere instead – and greater agricultural development of the south and southwest coastal regions is a Government priority (Ministry of Agriculture and FAO, 2013). Such options have implications for both the sustainability of water use in the northwest and north-central regions, and for crop production and livelihoods.

Our study is in two phases. The first phase, which is the subject of this report, is a narrow study of the regional water balances, groundwater levels and exchange of water between the groundwater and surface water, together with a study of the impact of irrigation on the livelihoods and vulnerability of the people within the region. The outputs of these activities are aimed at providing a strong basis for a second phase involving detailed modelling and scenarios analysis. The detailed analysis is intended to examine the impact of different external drivers (such as population growth, climate change, upstream development, construction of barrage, etc.) on the overall water balance and surface-water groundwater interaction and availability, and to examine the impact of future water availability (objectives 1, 2 and 3 described below) on the irrigated agriculture, regional socio-economy, livelihoods, and the environments and, in particular, conduct a social cost-benefit analysis of potential solutions. The second phase is yet to be agreed, and is not the subject of this report.

1.2 Aims and objectives

The first phase of the project, which is the subject of this report, had three aims.

1. Improve the preliminary regional water balance using more data and information at higher resolution.
2. Analysing the historical data of groundwater water level and the river flow to understanding the surface water and groundwater interaction (vertical recharge, lateral movement, their significance on overall water balance) and its trends.
3. Examining the impact of irrigation on the livelihoods of the population particularly on women and the poor and landless people in some selected districts of the region.

1.3 Scope of the study

The study covered the northwest and north-central regions of Bangladesh (Figure 1.1).

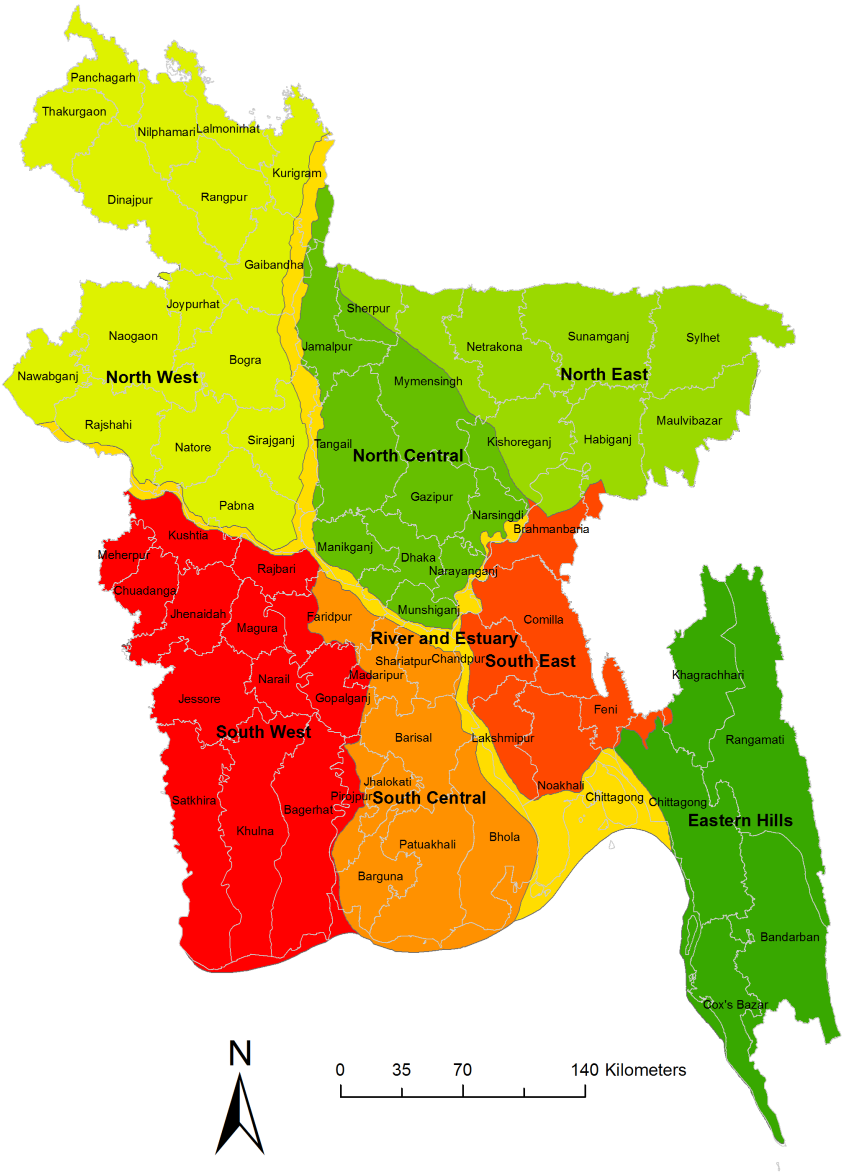


Figure 1.1 Hydrological regions of Bangladesh with districts names and boundary (off white lines)

2 Irrigation, groundwater and food security

Contributors: Mohammed Mainuddin, Mac Kirby, Geoff Hodgson

2.1 Introduction

Irrigation has ensured an adequate global food supply and raised millions out of poverty in Asia (Comprehensive Assessment of Water Management in Agriculture, 2007). Rapid growth in the irrigated area, together with other components of the green revolution, particularly in Asia, led to a steady increase in staple food production and a reduction of real world food prices (Rosegrant et al., 2001). Currently, irrigated agriculture covers about 20% of the cultivated land worldwide and produces about 40% of agricultural production including 60% of the cereals produced in the developing countries (Seckler et al., 2000; Bruinsma, 2003; Fisher et al., 2007). Agriculture is the largest user of water among human activities: irrigation water withdrawals are 70% of the total human use of renewable water resources (Fisher et al. 2007). Irrigation will remain critical in supplying cheap, high-quality food, and thus the consumption of agricultural water will continue to increase during the coming decades (Comprehensive Assessment of Water Management in Agriculture, 2007). However, continued increases in the demand for water by non-agricultural uses have put irrigation water demand under greater scrutiny and threatened food security (Hanjra and Qureshi, 2010).

Bangladesh's agriculture has made considerable strides in the last decades. Both production and mean yields of rice have risen. Production increases have resulted from a substantial intensification of agriculture rather than from increases in land area available for cultivation. This growth in intensity was driven by increased cultivation during the dry season, particularly *boro* rice, made possible by the growing availability of irrigation by groundwater through rapid increase in the adoption of shallow tubewells (STWs).

In this Chapter, we provide a snap shot of irrigation, crop production, groundwater development, dependency on groundwater irrigation for food security and current concerns of the sustainability of groundwater. We start with the description at the country level then focusing on the northwest and north-central regions including these regions' contribution on crop production and country's overall food security.

2.2 Crop production and food security

Bangladesh has gained self sufficiency in rice production (The Daily Star, 2013). This is a significant step towards achieving food security as rice is the staple food for the people of Bangladesh. It provides about 75% of the calorie and 55% of the protein in the average daily diet of the people (BARC, 2011). So, 'rice is life' as declared by FAO (FAO, 2003) and plays a vital role in the country's food security and acts as a main source of nutrition for the millions of resource poor farm families. For the last few decades, the increase in production out-weighed the growth in population. With the population of 76 million in 1977, total production of rice (Figure 2.1) 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). Until recently, Bangladesh was a net importer of rice with a net import of rice was around 3 million tonne/year (Islam and Mondal, 1992).

Production increases have resulted from a substantial intensification of agriculture rather than from increases in land area available for cultivation (Figure 2.2). The overall cropping intensity (usually expressed as percentage, is the ratio of 'total cropped area' in a year with the 'net physical cultivated area' of that year) 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, particularly *boro* rice, made possible by the growing availability of irrigation. Three types of rice are grown in Bangladesh. They are *aus*, *aman*, and *boro*. *Aus* is grown in Kharif-I or pre-monsoon season (March to June), *aman* is grown in Kharif-II or monsoon season (July to October), and *boro* is grown in Rabi (November to February) or dry season which usually extends to pre-monsoon season as well. *Aman* is the main rainfed rice whereas *boro* is fully irrigated. *Aus* is grown in a small area nowadays and is not irrigated (BBS, 2012). *Boro* rice currently (2012) contributes more than 55% of the total rice production of the country (Figure 2.1) from about 42% of the total cultivated area of rice (Figure 2.2). The reason for this is higher yield of *boro* rice (Figure 2.3).

The national average yield of *aus*, *aman* and *boro* rice has increased consistently, with some fluctuations as shown in Figure 2.3, at an average rate of 0.0267, 0.0294, and 0.0536 tonne/ha/year respectively during the period of 1977 to 2012. The growth in average (average of all rice) yield of rice during this period is 0.0508 tonne/ha/year or 5.24 percent per year. The yield growth of *boro* rice is 101% and 83% higher than that of *aus* and *aman* rice, respectively. *Boro* is a fully irrigated crop so the risk of water stress is much less than with *aus* and *aman* 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, 2013). Rainfed *aus* and *aman* together covers 58% of the total rice area and produces 45% of total rice production. So the large increase in *boro* rice production is clearly a key factor in rice self sufficiency of the country. Apart from *boro* rice, irrigation has also significantly increased the production and yields of other crops such as wheat, maize, potato, tomato, and vegetables (Mainuddin et al. 2014).

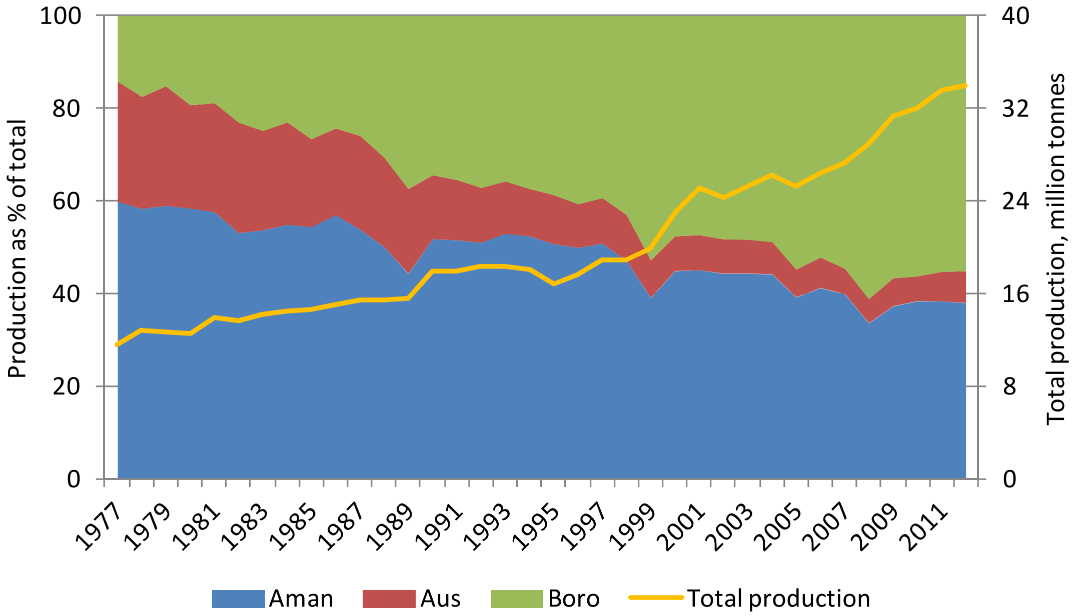


Figure 2.1 Annual total production of rice (line) and relative contribution (% area) of *aus*, *aman,* and *boro* rice to total production

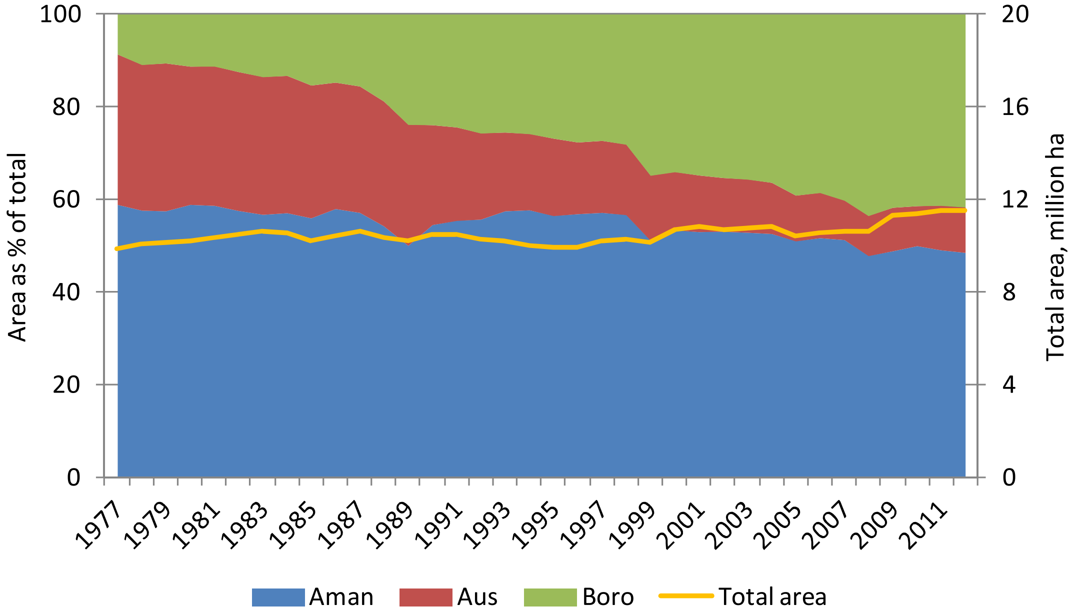


Figure 2.2 Annual total cultivated area of rice (line) and relative contribution (area as %) of *aus*, *aman,* and *boro*

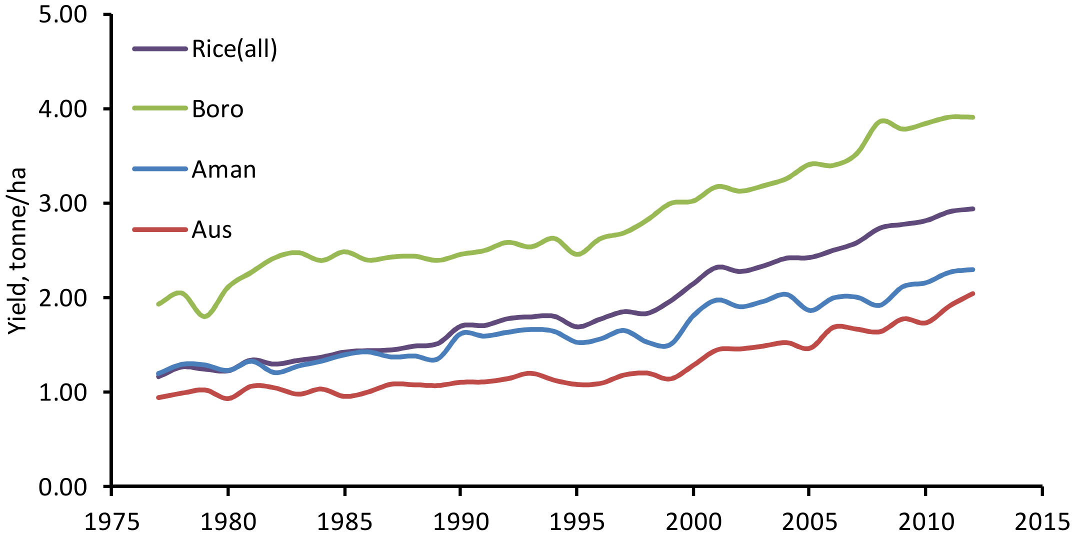


Figure 2.3 Average yield of rice

2.3 Irrigation and groundwater

There was phenomenal growth in irrigation development over the last 3 decades. According to the Minor Irrigation Survey Report prepared by the Bangladesh Agricultural Development Corporation (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 5.4 million ha in 2013 (Figure 2.4), 63% of the net cultivable area). This growth was driven by the growing use of groundwater through rapid increase in the adoption of STWs (Figure 2.4). 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. There was almost no growth in use of surface water for irrigation (0.9 million ha in 1983 to 1.16 million ha in 2013) though the number of low lift pumps (LLP) has increased from about 36 thousand to 171 thousands. While the use of LLP has increased, surface water irrigation area through canals and traditional means has decreased. Currently (2013), 78% of the total area (4.21 million ha) is irrigated using groundwater sources.

The development and growth in irrigation is not uniform over the different regions of the country (Figure 2.5). Northwest region has the highest percentage of net cultivable area (NCA) irrigated in 2012-13 (around 85%) followed by north-central (73%) region. Southeast and southwest region is the least irrigated area (about 45% of the NCA) of the country. The main reason for this is the lack of fresh water for irrigation and salinity in the soil and water during the dry season (Mainuddin et al., 2013).

There is significant spatial variation in the use of surface water and groundwater for irrigation (Figure 2.6). Northwest region has the most intensive use of groundwater; over 97% of the total area is irrigated (2012-13) by groundwater followed by the central (89%) region. Surface water irrigated area is higher compared to the groundwater irrigated area in the northeast and southeast regions.

Boro rice covered more than 85% of the total irrigated area in 2009-10. The irrigated area of wheat remained steady over the period around 325,000 ha (about 7% of the total irrigated area) out of the total cultivated wheat area of around 400,000 ha. About 8% of the total irrigated area is covered by other crops such as maize, potato, tomato, pulses, vegetables, and oilseeds (Mainuddin et al., 2014).

There are no data on irrigated area of *aus* since 2004-05. Until 2003-04, only about 7% of the total cultivated area of *aus* was irrigated. *Aus* is both broadcast and transplanted usually in the low lying area (such as lakes, river beds etc.) that have stored water. Usually, no irrigation is provided and the crop suffers from water stress. This is the main reason for the low yield of *aus* rice; the yield of *aus* is the lowest amongst the three rices as shown in Figure 2.3. The area cultivated has also declined gradually over the years and *aus* are being taken over by *boro* rice where it is possible.

Aman, due to variation in rainfall and prolong-period of no rainfall, sometimes suffer from water stress which affects its productivity. Supplementary irrigation is necessary in some years to achieve a good yield of *aman* (Islam and Mondal, 1992; Jensen et al., 1993). However, only about 10-11% of the total cultivated area is currently (2009-10) under supplementary irrigation and the area irrigated is slowly increasing.

The discussion above indicates irrigation is vital not only for ensuring food security but also is the mainstay of the current agricultural development in Bangladesh. Groundwater is the predominant source of irrigation.

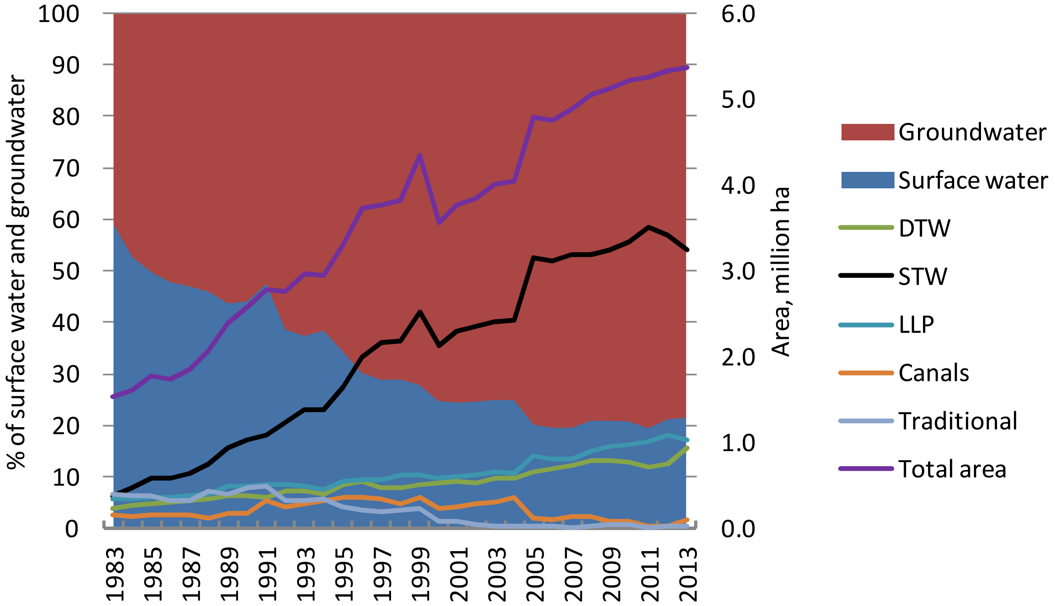


Figure 2.4 Area irrigated by different technology and source of water between 1983 and 2013 (data source: BADC data)

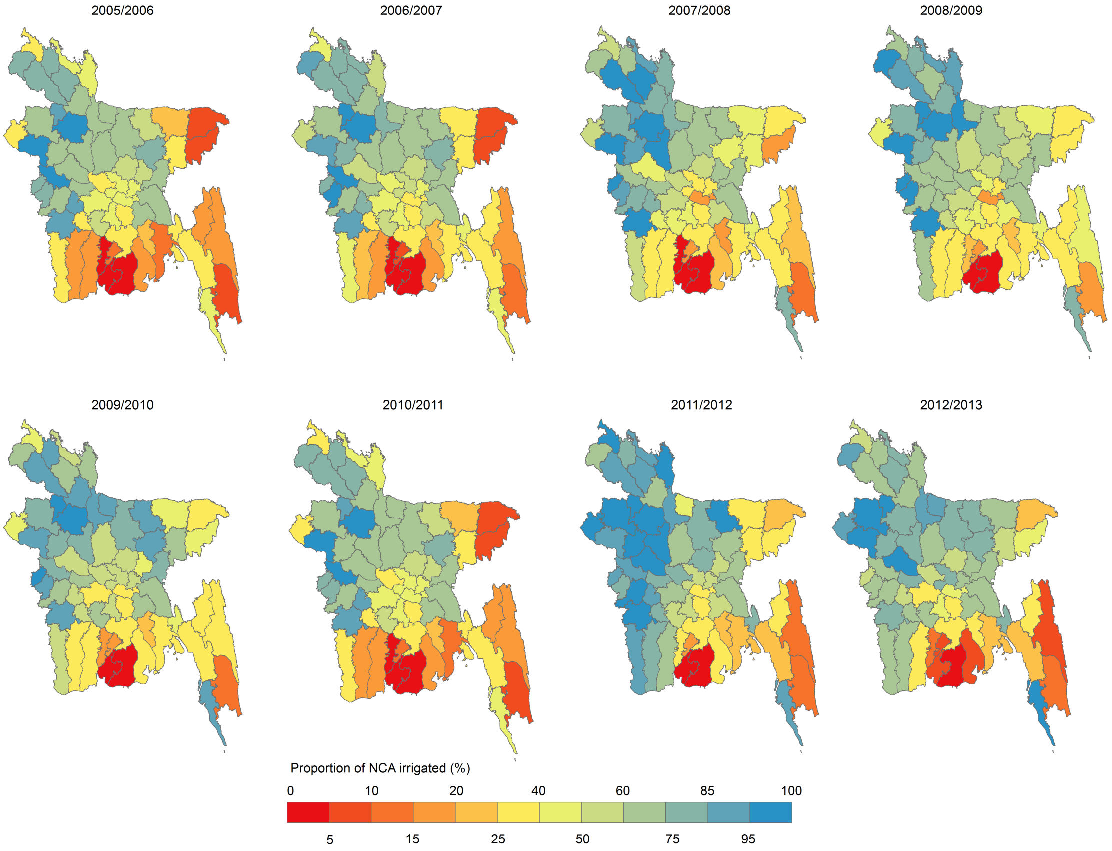


Figure 2.5 Percentage of net cultivable area (NCA) irrigated during 2005–6 to 2012–13 (data source: BADC)

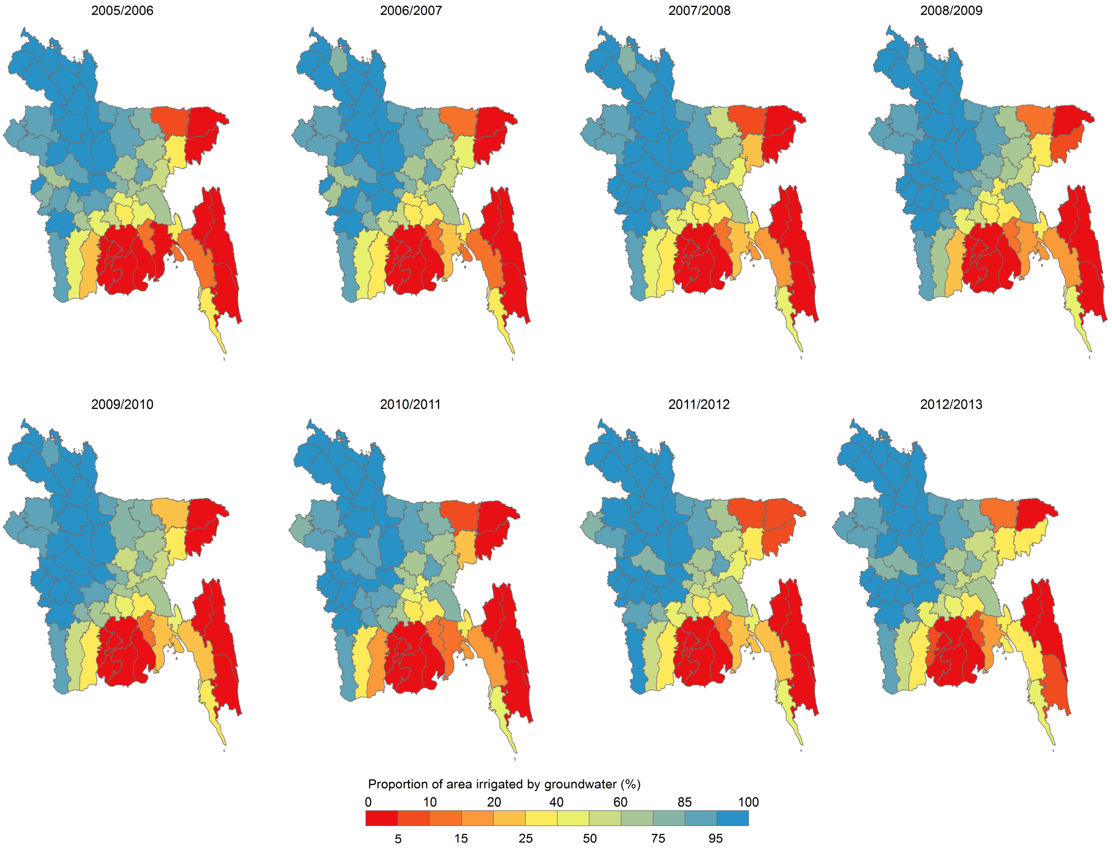


Figure 2.6 Proportion of net cultivable area (NCA) irrigated by groundwater during 2005–6 to 2012–13 (data source: BADC)

2.4 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), and Rahman and Mahbub (2012) all show that groundwater levels are falling in the Barind Tract. 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) conclude that the use of shallow aquifers for irrigation in the area 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 2.7 (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.

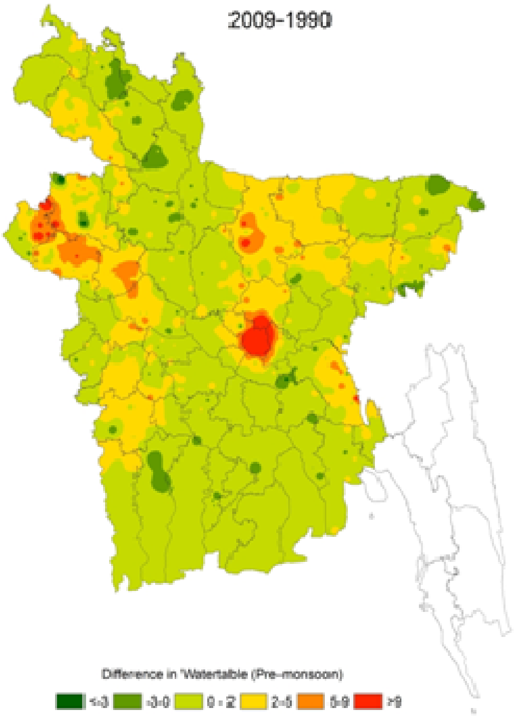


Figure 2.7 Spatial variation (difference in watertable between 2009 and 1990) in pre-monsoon groundwater depth (m) across Bangladesh. The Eastern Hill Tracts in south east Bangladesh were excluded from the analysis (source: CSIRO, 2014)

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 (Figure 2.8). 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 2.8). Other areas, such as the northern part of the northwest region, are dominated by wells with stable groundwater levels.

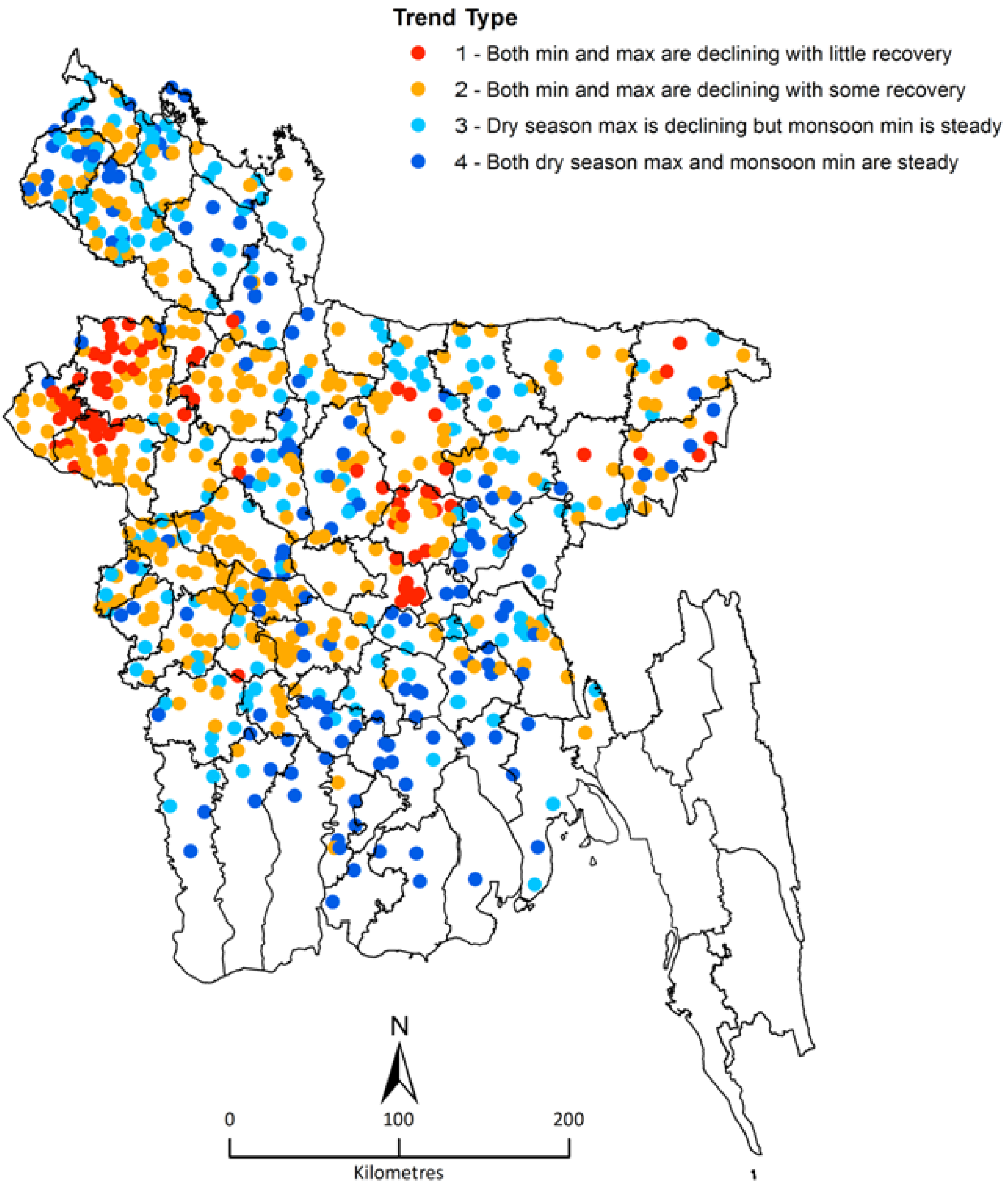


Figure 2.8 Distribution of wells of different trends in groundwater level. The Barind Tract is in the region in the west of Bangladesh dominated by a concentration of declining trend wells (indicated by red points). (source: Hodgson et al., 2014)

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 (shallow tube well) 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 wells in the northwest and north-central regions, but fewer elsewhere where the water tables are generally shallower. This confirms the recent report on the daily newspaper (Haq, 2013) that falling 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.

Nonetheless, the area irrigated by groundwater is rising in the northwest (Figure 2.9) region, but the area irrigated by shallow tubewell has declined (Figure 2.10) 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. The problem in the north-central region is not as prominent as in the northwest region, and the area irrigated by groundwater is still rising (Figure 2.11). However, there are concerns of long-term sustainability of groundwater irrigation in this region as well.

The northwest and north-central regions are at the heart of the current agricultural development of the country and produce the majority of the country's main agricultural products. Table 2.1 compares the basic statistics of these two regions with the country. However, due to the concerns of the sustainability of groundwater use in the northwest region, 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).

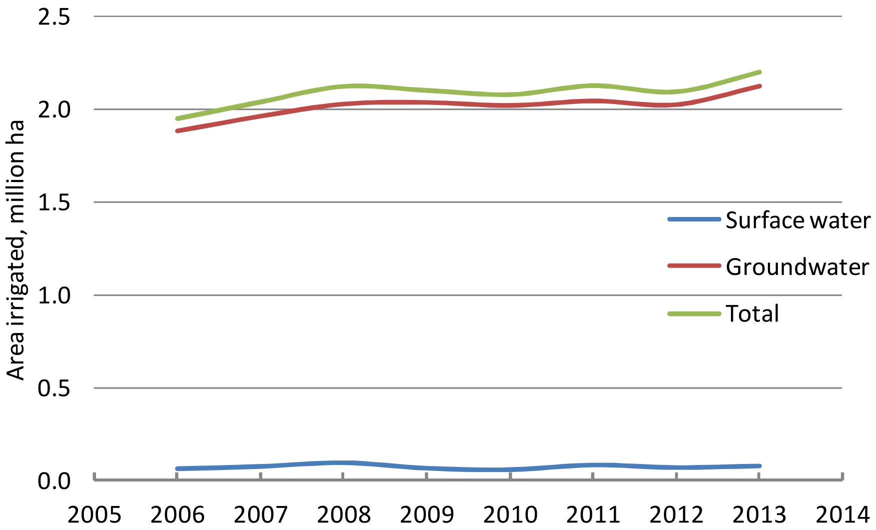


Figure 2.9 Area irrigated by surface water and groundwater in the northwest region for 2006–2013

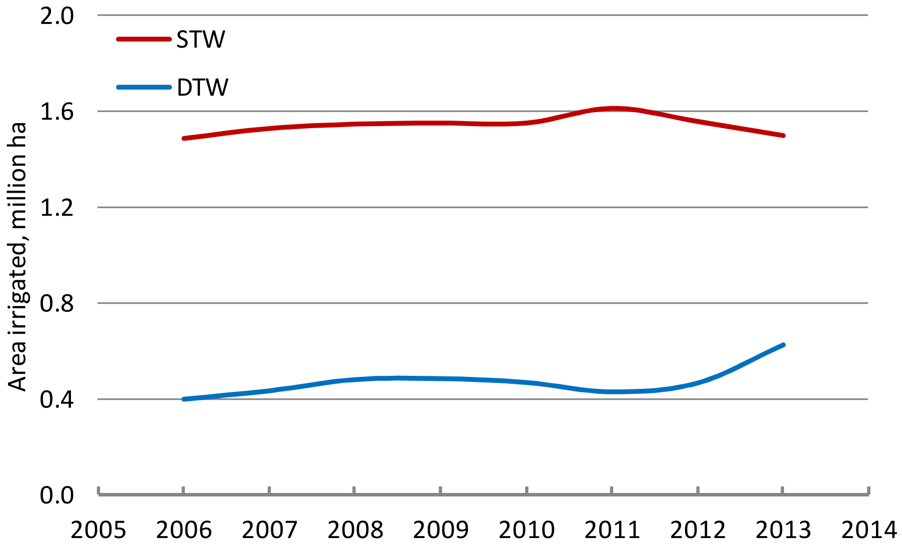


Figure 2.10 Area irrigated by shallow tubewells (STW) and deep tubewells (DTW) in the northwest region for 2006–2013

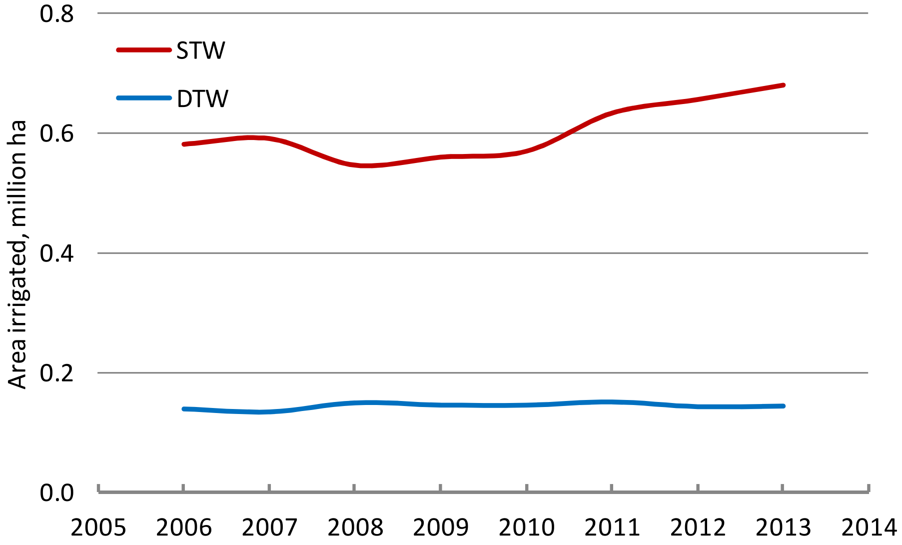


Figure 2.11 Area irrigated by shallow tubewells (STW) and deep tubewells (DTW) in the north-central region for 2006–2013

Table 2.1 Basic statistics of the northwest and north-central regions for 2009–10

ITEM	COUNTRY	NORTHWEST	NORTH-CENTRAL
Total area (Km^2)	146,589	34,515 (23.5%)	18,613 (12.7%)
Net cultivable area (NCA, million ha)	8.268	2.572 (31.1%)	1.257 (15.2%)
Area irrigated (million ha)	5.218	2.079 (39.8%)	0.830 (15.9%)
Area irrigated as % of NCA	63.1%	80.8%	66.0%
Area irrigated by groundwater (million ha)	4.127	2.021 (49.0%)	0.720 (17.4)
Area irrigated by groundwater as % of total irrigated area	79.0%	97.2%	86.7%
Total cultivated rice area (million ha)	11.353	3.542 (31.2%)	1.750 (15.4%)
Aus cultivated area (million ha)	0.984	0.159 (16.2%)	0.062 (6.3%)
Aman cultivated area (million ha)	5.663	1.799 (31.8%)	0.767 (13.6%)
Boro cultivated area (million ha)	4.707	1.585 (33.7%)	0.929 (19.6%)
Wheat cultivated area (thousand ha)	376.2	222.7 (59.2%)	20.2 (5.4%)
Maize cultivated area (thousand ha)	151.7	98.7 (65.1%)	10.3 (6.8%)
Potato cultivated area (thousand ha)	434.6	308.8 (71.1%)	59.6 (13.7%)
Tomato cultivated area (thousand ha)	58.8	18.2 (30.9%)	11.9 (20.2%)
Other rabi crops (thousand ha)	635.8	171.6 (27.0%)	129.1 (20.3%)
Total rice production (million tonnes)	31.974	10.727 (33.5%)	5.087 (15.9%)
Aus rice production (million tonnes)	1.709	0.268 (15.7%)	0.090 (5.3%)
Aman rice production (million tonnes)	12.207	4.145 (34.0%)	1.447 (11.9%)
Boro rice production (million tonnes)	18.058	6.314 (35%)	3.551 (19.7%)
Wheat production (million tonnes)	0.902	0.544 (60.3%)	0.038 (4.2%)

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

Preliminary assessment done under the Bangladesh Integrated Water Resources Assessment project (Kirby et al., 2014; IWM, 2014a) shows that there is considerable exchange between surface water and groundwater. Where two sources of water are intimately linked, changing the location of extraction of water might merely extract the same water via a different route: in other words, the anticipated improvements to groundwater levels might not be realised. Whether this is so or not cannot be properly assessed with our current state of knowledge. Furthermore, while there are concerns about unsustainable groundwater use, our current knowledge is insufficient to determine the sustainable level of use (Kirby et al., 2014). We assess these matters further in Chapters 3 and 4 below.

2.5 Conclusion

Irrigated agriculture is central to the current rapid agricultural development of Bangladesh. 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 2.3. 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 and from the northwest and north-central regions. 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 these two regions.

Groundwater is the main source of irrigation which supplies about 80% of the total irrigation demand of the country. Based on the current trend, it is likely that increased demand due to the increase in irrigated area will further stress the groundwater resources. Dry season river flows (the source of surface water irrigation) on the other hand, are decreasing due to upstream use in India (e.g. Adel, 2001; Mirza, 1997; IWM, 2014b). Thus, water availability for future food security is challenging and will become more challenging if a further increase in irrigated area is expected.

3 Dynamic regional water balance

Contributors: Mac Kirby, Mobin-ud-Din Ahmad, Mohammed Mainuddin, Wahid Palash, Muhammad Enamul Quadir, Sardar M Shah-Newaz

3.1 Introduction

Water balances, or water accounting, is generally regarded as fundamental to the understanding of water availability in a region and hence to the development of sustainable policies and plans for water management (eg Karimi et al., 2013; Molden and Sakthivadivel, 1999). The water accounts of Karimi et al. (2013), Molden and Sakthivadivel (1999) (and others discussed in Kirby et al. 2010) are static water accounts based on a single year, usually an average year. In contrast, Kirby et al. (2010) calculated dynamic monthly water balances which are more suited to assessing dynamic effects such as climate change, land use change and so on.

However, notwithstanding the usefulness, the overall water balance for Bangladesh is not well known. An early water balance for Bangladesh (called East Pakistan at the time) by Khan and Islam (1966) focussed on rainfall and soil moisture. They noted that soil moisture was in deficit in the dry season particularly in the west of Bangladesh, whereas rain exceeded the soil storage capacity in the wet season leading to runoff. The National Water Management Plan (WARPO, 2000; specifically Topic Paper No 7 Land and Water Resources and Draft Development Strategy Annex C Land and Water Resources) is the main source of water balance information to date. However, it does not give a comprehensive water balance: it treats the groundwater and surface water separately, and does not, for example give the exchange between the two; much of the discussion is in terms of demand rather than actual use, and surface water is often given in terms of dependable flows rather than the actual amount of water available and its variation from wet to dry years.

Kirby et al. (2014) described approximate regional water balances for five main regions of Bangladesh, including the northwest and north-central regions of interest in this study. They noted that some terms in the water balance were poorly understood, and relied on simple expressions to provide estimates of such quantities. The exchange of water between groundwater and rivers was one of the poorly known terms. Moreover, the analyses included river flows for only one year (1996, an average year for river flow).

In this chapter, we use a simple, regional averaged modelling approach to assessing the water balance. In it, we extend the water balances of Kirby et al. (2014) for the northwest and north-central regions by adding dynamic river flows. We also modify the water balance models slightly and re-calibrate them, partly to take advantage of the additional dynamic river flow information, and partly to use new information on the exchange between rivers and groundwater, discussed later in Chapter 4.

We use the water balances to assess the relative contributions of groundwater pumping and rainfall variation to the observed variations in regional water balance. This serves as a rough check, at the regional level, of whether observed declines in the groundwater table are due to groundwater pumping for irrigation, or due to rainfall declines in recent years, or both.

3.2 Regional water balance: aggregate model

Kirby et al. (2014) described the water balance model for the regions of Bangladesh. Since we have modified the model slightly, we provide here a complete description. The water balance is calculated monthly, for the 26-year period from 1985 to 2010. The water balances are set in a monthly time-stepping calculation: for brevity, however, we drop time indices from the equations except where it is necessary to show the updating of stores from one time step to the next.

The water balances we regard as approximate in the sense that: 1. the groundwater balance for each region is a partial water balance for the shallow unconfined aquifer alone, and ignores exchanges with deeper aquifers and deep lateral flows of groundwater; 2. the water balances for each region are lumped balances that do not account for within-region spatial variation and so average much detail; 3. some terms (whether at the lumped regional scale or finer spatial scales) have not been fully quantified in any study known to us and so are represented here with simple physically meaningful and plausible expressions. The principal unknown terms are the evapotranspiration drawn from groundwater sources via a capillary fringe and the baseflow to rivers. The evapotranspiration drawn from groundwater sources is known to be significant from the study by Ahmad et al (2014). However, the study was of only a part of the northwest region, and the magnitude of the evapotranspiration from groundwater has not been quantified elsewhere. The baseflow is assessed semi-quantitatively in Chapter 4, and the assessment has allowed us to refine an earlier model of the regional water balance. However, the study is based on assessments of a few locations on a few rivers, and extrapolation to all rivers is somewhat uncertain.

3.2.1 Surface water balance

The surface water balance is calculated separately for each district in the northwest and north-central regions. Within each district, the water balance is calculated separately for irrigated and non-irrigated land. The areas of irrigated and non-irrigated land change throughout the year.

Evapotranspiration from the non-irrigated parts of the landscape is high even in the driest part of the year (Ahmad et al., 2014). The landscape is underlain in most places by shallow groundwater. It is therefore reasonable to assume that the evapotranspiration in the dry season is maintained at high levels by capillary rise from the water table which is accessed by plant roots and consumed as transpiration. Some may also be consumed as evaporation where the groundwater intersects the surface to form shallow wetlands.

Based on these considerations, we assume that the landscape can be modelled as shown in Figure 3.1. The surface water balance for non-irrigated land is assessed in terms of the volumes (not depths) of water, given by:

$$\left(P_v + C_{r,v} - ET_{s,v} - ET_{cf,v} - R_v - D_v + \Delta S_v\right)_{ni} = 0 \tag{3.1}$$

where the subscript *ni* outside the brackets indicates non-irrigated land, P_v is the rainfall (given by PA_{ni}, where P is the depth of rainfall and A_{ni} is the area of the district that is not irrigated in the month being assessed), $C_{r,v}$ is the capillary rise, $ET_{s,v}$ is the evapotranspiration from the soil, $ET_{cf,v}$ is the evapotranspiration from the capillary fringe, R_v is the runoff, D_v is the deep drainage from the soil to the water table and ΔS_v is the change in the water storage in the soil. Evapotranspiration depletes the soil water store in the dry season, and it is replenished by rain in the monsoon. Plant roots also access the capillary fringe, maintaining high transpiration even in the dry season. The evapotranspiration from the soil water storage is governed by a crop coefficient model:

$$ET_s = ET_o \, MIN\left[1, \alpha_1 S / S_{\max}\right] \tag{3.2}$$

where ET_o is the reference evapotranspiration, α_1 is a coefficient (>1), $S_{\max}$ is the maximum depth of water that can be stored in the soil. The evapotranspiration is at the maximum (reference) rate in wet soil and, when drier than a threshold value given by $\alpha_1 S/S_{\max} >= 1$ declines to zero as the soil dries. The store of readily available water is zero in dry soil, though the soil could still contain some residual moisture unavailable to the plants: implicitly, we consider only the readily available water.

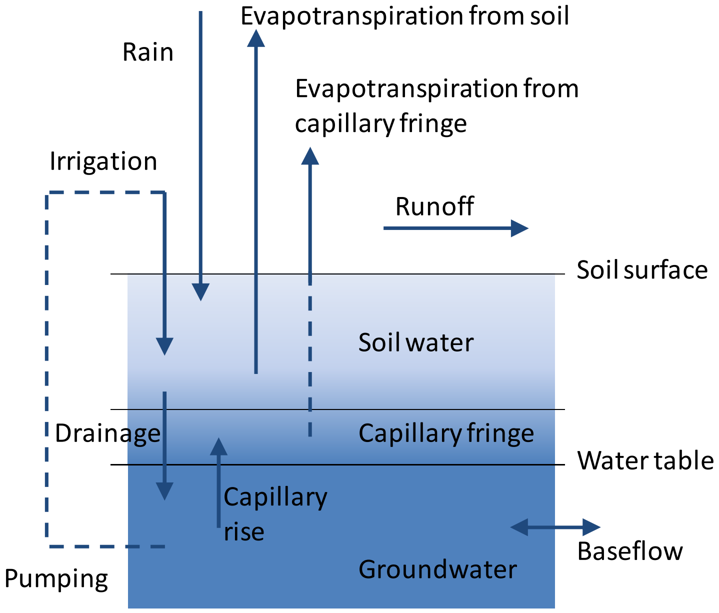


Figure 3.1 Conceptual surface water balance model

The drainage from the soil water storage to groundwater is given by a water content dependent leakage rate:

$$D = \alpha_2 S \tag{3.3}$$

where α_2 is a coefficient (<1).

The runoff is given as a saturation excess:

$$R = MAX\left[0, \left(S^{t-\Delta t} + P - ET_s - D\right) - S_{\max}\right] \qquad (3.4)$$

The expression in the inner brackets sums soil water storage and inflows and outflows; if the sum exceeds the maximum water storage of the soil, the excess is runoff.

The soil water storage is updated as:

$$S = S^{t-\Delta t} + P - ET_s - R - D \qquad (3.5)$$

The evapotranspiration from the capillary fringe is assumed to be a constant fraction of the potential evapotranspiration, limited to the amount of the potential not consumed by the soil evapotranspiration:

$$ET_{cf} = MIN\left[\left(ET_o - ET_s\right), \alpha_3 ET_o\right] \qquad (3.6)$$

where α_3 is a coefficient (<1). The total evapotranspiration is the sum of ET_s and ET_{cf}. The water content of the capillary fringe is assumed to remain constant, with water extracted by roots re-supplied by capillary rise. Therefore, $C_r = ET_{cf}$.

The district volumes of rainfall, evapotranspiration, runoff, drainage and sol water storage are given by multiplying the values derived from Equations

$\left(P_v + C_{r,v} - ET_{s,v} - ET_{cf,v} - R_v - D_v + \Delta S_v\right)_{ni} = 0$

(3.1)

to $ET_{cf} = MIN\left[\left(ET_o - ET_s\right), \alpha_3 ET_o\right]$ (3.6)

by the area of non-irrigated crops, A_{ni}, and the district volumes are then summed to give regional volumes.

The water balance of irrigated land is:

$$\left(P_v + WR_v - ET_{s,v} - R_v - D_v + \Delta S_v\right)_{irr} = 0 \qquad (3.7)$$

where the subscript *irr* outside the brackets indicates irrigated land, and WR_v is the volumetric district water requirement. The water requirement for each crop is given by:

$$WR_j = MAX\left(0, K_{cj} ET_o + D + F_j - P\right) \qquad (3.8)$$

where K_{cj} is the crop coefficient for crop *j*, *D* is drainage assumed to be constant since most of the irrigation is for rice which will drain at a near constant rate from a surface pond through a puddle soil horizon. F_j is the water required to fill the soil on the first irrigation for each crop; since the majority of the area is sown to rice in both the northwest and north-central regions, the soil is assumed to be filled to saturation and maintained there throughout the irrigation season. The evapotranspiration (as a depth of water) of crops under irrigation is thus:

$$ET_j = K_{cj} ET_o \qquad (3.9)$$

The *MAX* function in equation $WR_j = MAX\left(0, K_{cj} ET_o + D + F_j - P\right)$

(3.8) sets the water requirement to zero when rain exceeds the sum of evapotranspiration, drainage and initial filling of the soil (if any). Excess rain, if any, becomes runoff:

$$R_j = MIN\left(0, K_{cj}ET_o + D + F_j - P\right) \tag{3.10}$$

The rain, water requirement, evapotranspiration, runoff and drainage of irrigated crops are multiplied by the areas of each crop, A_j, to give volumes, and the result summed for all crops to give the district volumes in equation (**3.7**). We considered the crops to be *Boro* rice (which is the main irrigated crop, occupying on the order of 86 percent of the area irrigated and, furthermore, growing in the later and warmer part of the dry season and so receiving about 95 percent of the total water applied to irrigation), wheat, potato, *Aus* rice (which receives only supplementary irrigation as its growth extends into the rainy season) and 'other' (which only occupies about 3 percent of the total area).

The overall water balance for the region is the sum of the non-irrigated and the irrigated volumes of water.

3.2.2 Groundwater balance

The groundwater balance comprises drainage inflows from equations (3.1) and (3.7) above, minus baseflow to the rivers, and minus abstractions for irrigation which are equal to the irrigation water requirement in equation (**3.7**). The groundwater balance is calculated in terms of volumes for the whole region – that is, the groundwater aquifer is treated as analogous to a single, large bucket.

In the previous version of the model (Kirby et al., 2014), the baseflow was calculated from an equation that used only the height of the groundwater relative to an arbitrary datum. The resulting calibrated model suggested that there was generally a large net annual baseflow to the rivers. As will be shown in Chapter 4, the baseflow differs in different areas of the northwest region. It is generally net to the rivers in the northern parts of the region where the rivers are more deeply incised, and net away from the rivers (ie a net recharge to groundwater from the rivers) in the southern parts where the landscape is flatter and the rivers are not deeply incised. The overall regional baseflow is not accurately known, but it is probably not a net flow to the rivers of the magnitude calculated with the previous model. This suggests that the previous model should be revised. Furthermore, as part of the current project, monthly river flows have been calculated for the rivers that run through the northwest and north-central regions. (As discussed earlier, only 1996 flows were previously available.)

The rivers rise and fall substantially from the monsoon to the dry season, and the baseflow to or from the groundwater will depend on the height of the groundwater table relative to the height of the water in the river. River height or depth data were not available for this study. We calculated river depth, D_r, from the river inflows, Q_i, and the depth of the river bed below the land surface, D_b, as:

$$D_r = D_b - \alpha_4 Q_i^{\alpha_5} \tag{3.11}$$

Where, the second term on the right hand side is the river height above the bed, and α_4 and α_5 are coefficients. The depth of the river bed below the land surface is unknown, and is treated as an adjustable parameter with the value to be fixed by calibration. The exchange of water between the groundwater and rivers, GR_{ex}, is then calculated from the difference between the depth of the river and the depth of the groundwater below the land surface:

$$GR_{ex} = \alpha_6 \left(D_b - D_g \right) \tag{3.12}$$

where α_6 is a coefficient, and D_g is the depth of the groundwater below the land surface . The change in the volume of groundwater, ΔS_g, is given by:

$$\Delta S_g = \left(D - C_r \right) - F_{Ig} WR - GR_{ex} \tag{3.13}$$

where the term in brackets is net recharge (drainage minus capillary rise) and F_{Ig} is the fraction of the irrigation water requirement supplied by groundwater, the rest being supplied by river water. The regional drainage, D, is the sum of the irrigated area and non-irrigated area drainage in each district (in equations (1) and (7)), summed for all the districts in the region. The depth of the groundwater table is updated as:

$$D_g = MAX\left(D_{g,\min}, D_g^{t-\Delta t} + S_y \Delta S_g / A \right) \tag{3.14}$$

where $D_{g,\min}$ is a minimum groundwater table, S_y is the specific yield and A is the area of the region. The *MAX* function ensures that the groundwater does not become shallower than that observed, which is set by $D_{g,\min}$. If the second term in the *MAX* function is less than $D_{g,\min}$, the excess water is considered to be rejected by the groundwater, and is added to the regional runoff.

Strictly speaking, equation **(3.13)** should include an ‘unaccounted or error’ term. However, we don’t know what the value of the unaccounted / error term will be and in principle we could set it to any value in any time step. We could make it exactly the value required to get perfect calibration *for any value of other terms such as drainage*. What we have implicitly done is to suppose that the unaccounted / error term is zero (ie the unaccounted change in storage is zero), and looked at how well the model then fits; this seems to be a reasonable Ockham’s Razor approach. We have explicitly discussed that there is little or no information on groundwater – river exchanges and that this is an area requiring further work.

3.2.3 River water balance

The inflows of all rivers flowing within a region are taken from separate calculations done by the Institute for Water Modelling. The river outflows (summed for the region), Q_o, are the inflows, Q_i, plus runoff and baseflow, less extraction for irrigation:

$$Q_o = Q_i + R + GR_{ex} - \left(1 - F_{Ig}\right)WR \tag{3.15}$$

Note that the river water balances are those for the rivers that flow within the regions, and do not include the Ganges or Jamuna which mostly bound the regions rather than flowing through them.

3.2.4 Data and calibration

The rainfall was taken direct from the Bangladesh Meteorological Department, and potential evapotranspiration was calculated from district temperature and other climate data from the Bangladesh Meteorological Department. The crop coefficients are standard crop coefficients from the FAO. The crop areas were taken from the Ministry of Agriculture (http://www.moa.gov.bd/statistics/statistics.htm), from where the proportion of irrigation supplied by groundwater was also sourced. For scenario exploration, the areas are taken as the 2009–10 areas unless otherwise stated. The river flows were obtained from modelling by the Institute of Water Modelling as part of this project.

For calibration, the areas of irrigated crops were assumed to increase threefold from 1985 to 2010, which is the approximate increase of irrigated crops in Bangladesh over that period (Section 2.3). The regional evapotranspiration for the northwest region was calibrated by comparing the total regional evapotranspiration divided by the area of the region with the evapotranspiration modelled from remote sensing (satellite) observations, as described by Ahmad et al. (2014). The remotely sensed observations are for January to April of the dry season of 2009, and the calibrated modelled evapotranspiration is for those months only. The remotely sensed modelled evapotranspiration is for about half the total area of the northwest region but, since the fractions of cropped areas and the potential evapotranspiration are similar in the remotely sensed part and the whole region, we think the comparison is likely to be reasonable. The match shown in Figure 3.2 was obtained by manually adjusting $S_{\max}$, α_1, α_2 and α_3 to obtain the best visual match. Values of the fitted parameters for each region are shown in Table 3.1 Values of the fitted model parameters for the northwest and north-central region. The model is fairly sensitive to all the parameters except for α_4 and α_5, to which it is less sensitive.

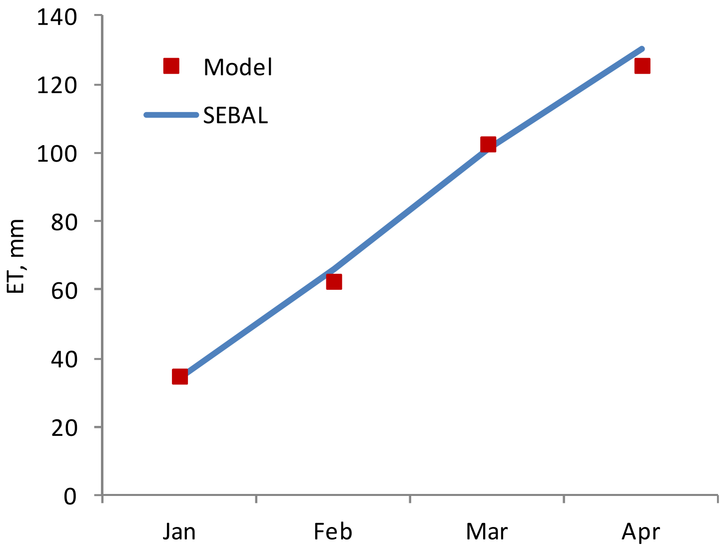


Figure 3.2 Comparison of the 2009 January to April regional water balance model (red squares) and a remotely sensed model (SEBAL) estimate of evapotranspiration for the same period for the northwest region of Bangladesh. The SEBAL results were estimated by Ahmad et al. (2014)

Table 3.1 Values of the fitted model parameters for the northwest and north-central regions

REGION	S_{MAX}	α_1	α_2	α_3	α_4	α_5	α_6
Northwest	0.2	2	0.55	0.48	1	0.5	0.0005
North-central	0.2	2	0.50	0.50	0.1	0.5	0.085

Ahmad et al. (2014) estimated the regional average groundwater depths for the main regions in Bangladesh, based on water levels observed in boreholes. The regional average depths were calculated for three times at each of five periods at five year intervals. We adjusted the coefficients in Table 3.1 to obtain the best fit. We assumed a specific yield of 0.1. The resulting fit for the northwest and north-central regions is shown in Figure 3.3. The R^2 of the fit is 0.97 and 0.82, and the Nash-Sutcliffe Efficiency (NSE) is 0.92 and 0.77, for the northwest and north-central regions respectively.

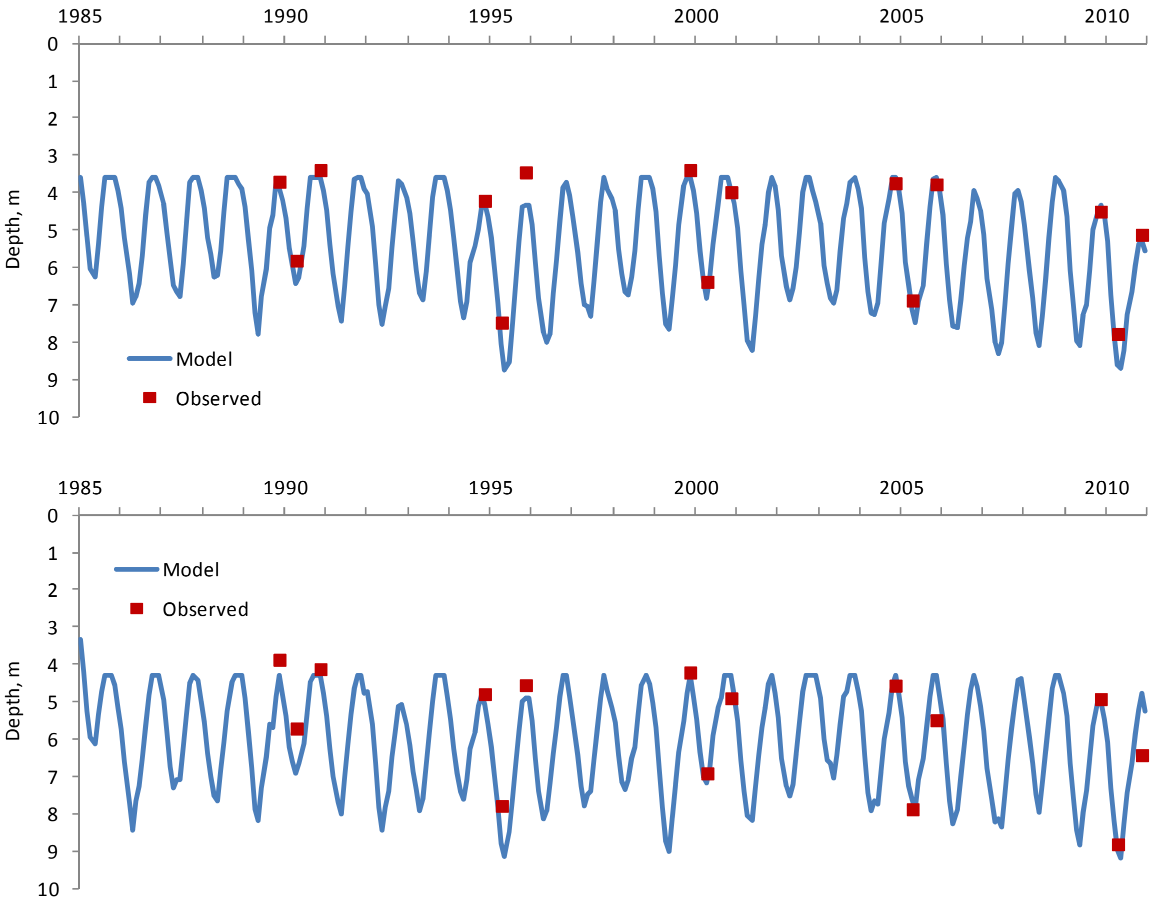


Figure 3.3 Comparison of the observed regional average water table heights and modelled monthly water table heights (each above an arbitrary datum) for the northwest region (top) and north-central region (bottom). The observed results are regional average water table depths estimated from borehole records by Ahmad et al. (2014)

3.2.5 Scenarios

The water balance from 1985 to 2010 for the two regions was modelled for three scenarios. All scenarios use the historical rainfall and potential evapotranspiration, as was used in the calibration. The first is the calibration scenario, already discussed, which represents the historical climate with the historical trend of increasing irrigation area. In the second scenario, we assume that irrigation is at the 2010 level of development. This contrasts with the historical experience, where the area irrigated has increased about threefold since 1985; the historical experience will not necessarily be a good guide to how currently developed irrigation will impact groundwater levels during a dry year such as 1994. The second scenario is based on the 2010 level of irrigation development, which allows an approximate assessment of the likely impact on the groundwater level and other aspects of water resources with the current (2010) level of development. The second scenario is likely to be a better guide to future impacts of droughts or other changes to water availability.

In the first two scenarios, a declining water level could be a response to pumping water for irrigation, or dry periods, or both. We cannot separate them in the scenarios. In the third scenario, we assume that there is no irrigation. The scenario, by comparison with the current (2010 development) irrigation scenario, separates out the rainfall effect and allows assessment of whether the rainfall or pumping effect is the more important.

We emphasise that the assessments using the scenarios are approximate. The water balance, as discussed above in section 3.2, is an approximate, regional-average water balance. It does not give accurate simulations, and does not give information of variation within a region.

3.3 Regional water balances – results and discussion

3.3.1 Regional rainfall and potential evapotranspiration

The average annual rainfall from 1985/6 to 2009/10 was 1927 mm in the northwest region and 2133 mm in the north-central region. The corresponding figures for potential evapotranspiration are 1309 and 1275 mm. The monthly distribution of rainfall and potential evapotranspiration (Figure 3.4) shows the strong monsoon peak of rainfall from May to September or October, with very little rainfall in December and January. The potential evapotranspiration is more evenly distributed, though it is generally higher towards the end of the dry season from March to May.

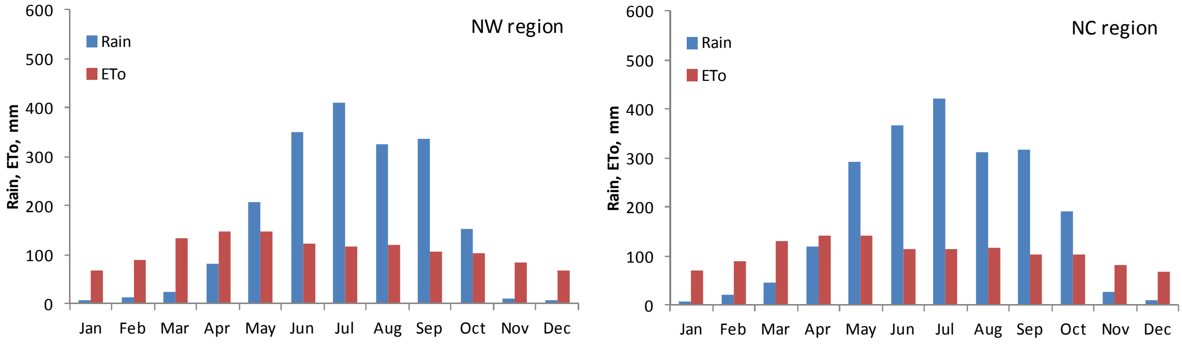


Figure 3.4 Monthly distribution of rainfall and potential evapotranspiration in northwest and north-central regions of Bangladesh. The monthly totals are the average monthly totals from 1985/86 to 2009/10

The annual rainfall from 1985/86 to 2009/10 (Figure 3.5) shows the rainfall for water years (July to June) for comparison with later figures of irrigation water use and other water balance terms. The annual rainfall was lowest in both regions in 1994/95. The annual rainfall totals show a slight decline on average from 1985 to 2010; the decline is equivalent to a 13 mm/year decrease in rainfall for the northwest region and 12 mm/year for the north-central region.

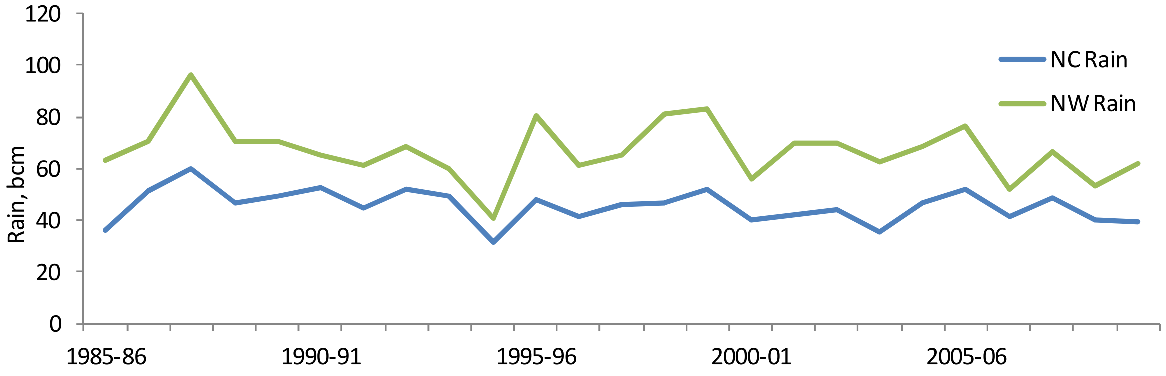


Figure 3.5 Annual rainfall volume totals for the northwest and north-central regions for the water years 1985/86 to 2009/10

3.3.2 Main elements of the water balance

We assessed the main elements of the water balance using the current (2010 development) scenario, this being relevant to the understanding of current conditions. The main elements of the water balance for the two regions are shown in Figure 3.6 as annual, wet season and dry season averages. Figure 3.6 shows that the main inflows are rainfall and river inflows. The main outflows from the land surface are evapotranspiration and runoff, followed by drainage (which is an inflow into the groundwater). The volume of water for irrigation use is smaller than those terms. However, as shown in the bottom plot in Figure 3.6, irrigation water use is almost all in the dry season, when it is one of the larger terms in the water balance. Irrigation and direct evapotranspiration from groundwater are the main evapotranspiration terms in the dry season. The low rainfall and river flows in the dry season explain the large use of groundwater for irrigation. There is a small baseflow from groundwater to the rivers, primarily in the dry season; this is consistent with the findings of Chapter 4. The recalibrated water balances in this report have smaller baseflow to the rivers than the previous model in the Bangladesh Integrated Water Resources Assessment, and are more consistent with the findings of Chapter 4.

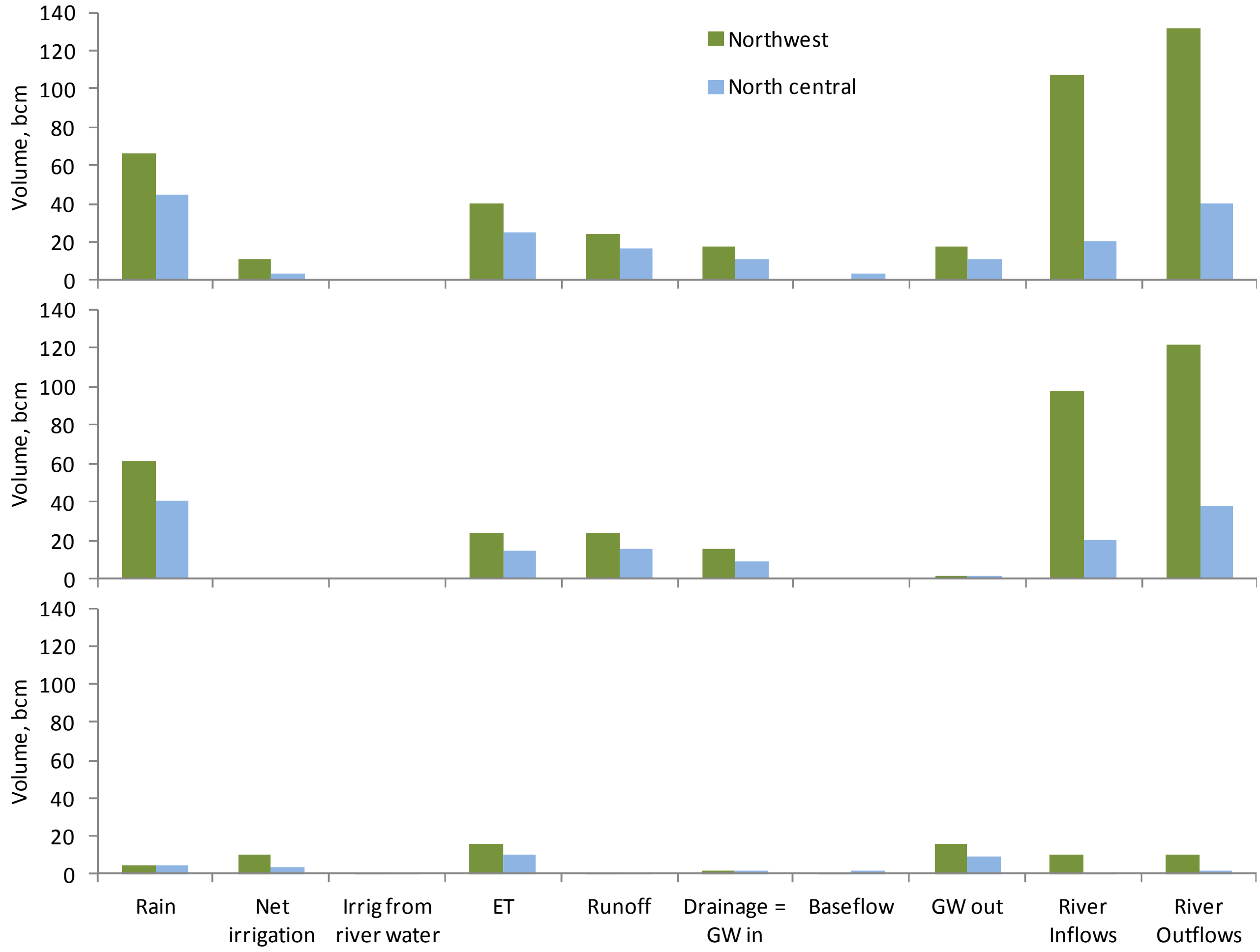


Figure 3.6 Main elements of the water balance (in billion cubic meters) for the northwest and north-central regions in the current (2010 development) scenario. The top plot is annual averages, the middle plot is wet season averages, and the bottom plot is dry season averages

3.3.3 Irrigation water use

The annual irrigation water use was calculated for the current scenario (2010 development) from 1985/86 to 2009/10 is shown in Figure 3.7. The irrigation water use shows some response to rainfall; thus the dry year of 1994/95 has the greatest calculated water use in the northwest region. However, the irrigation water use also depended on the distribution of rain throughout the year; some years that were dry overall had low wet season rainfalls but were not drier than normal during the irrigation season and so do not show greater irrigation water use. Thus, the correlations between overall water use and rainfall are weak. Figure 3.7 also shows that most irrigation water in both regions comes from groundwater. However, the proportion of river water is greater in the north-central (where 83 percent of the area irrigated uses groundwater) than the northwest region (96 percent).

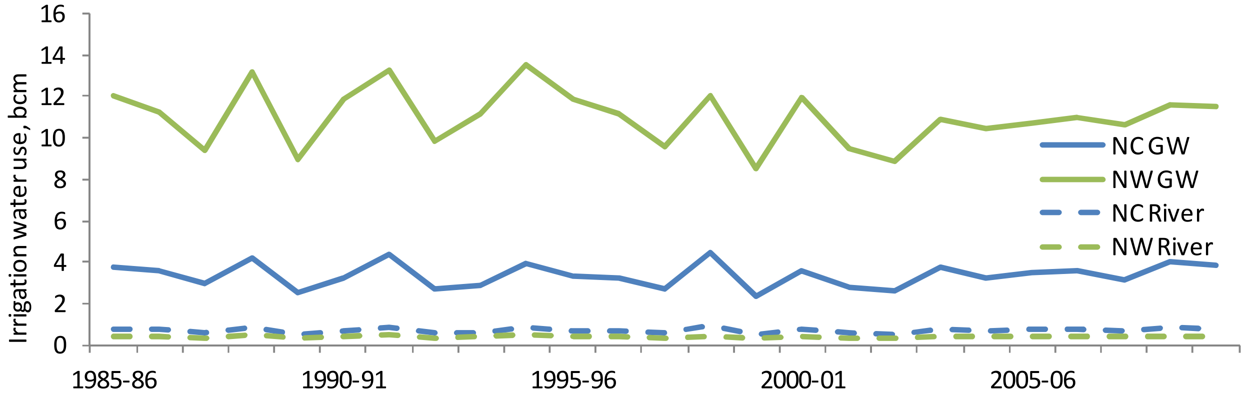


Figure 3.7 Annual irrigation groundwater (GW) and river water use for the northwest and north-central regions for the water years 1985/86 to 2009/10

3.3.4 The impact of pumping and rainfall variability on groundwater levels

The pre-monsoon minimum (deepest) calculated groundwater level and the post-monsoon maximum (shallowest) calculated groundwater level are shown for the two regions in

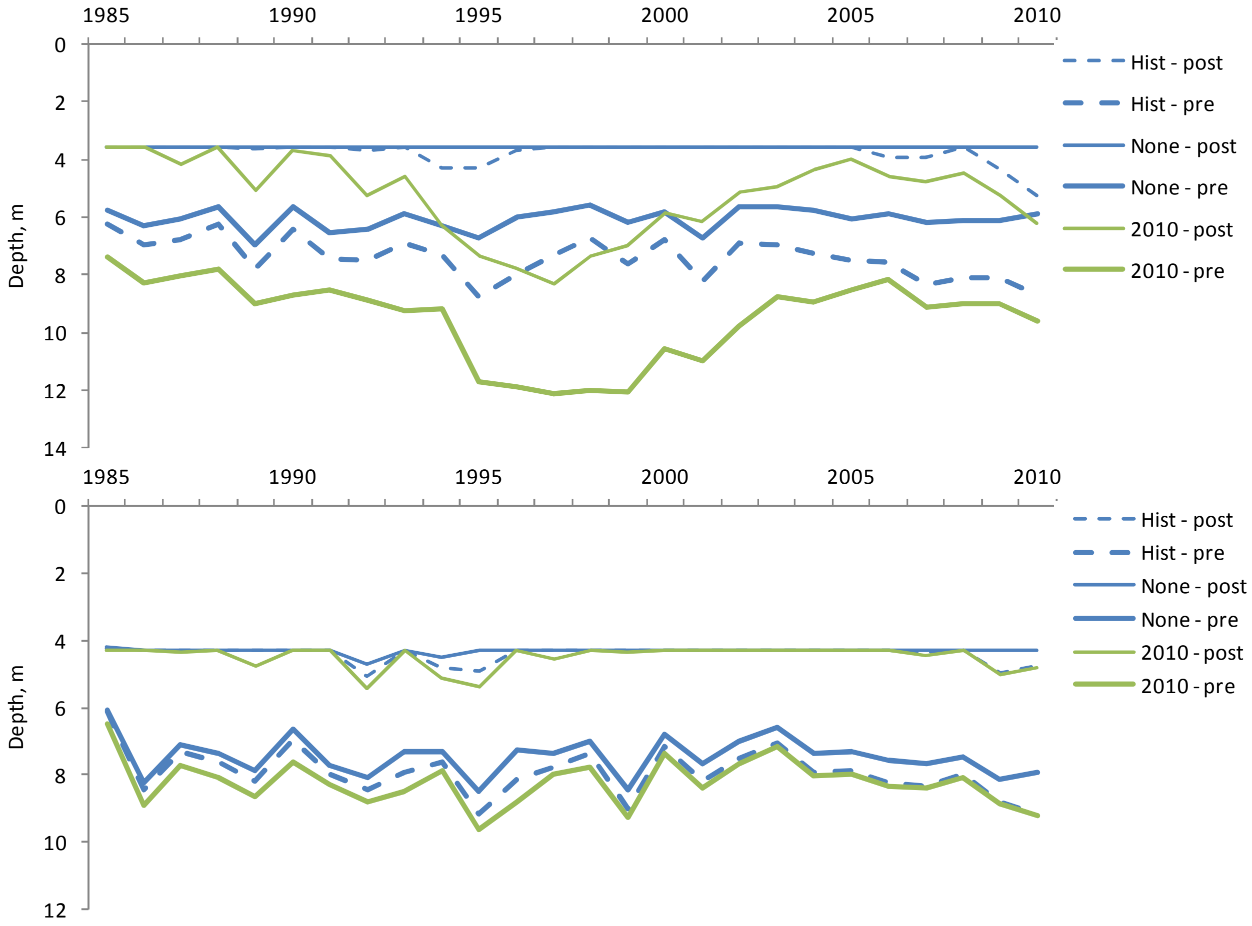


Figure 3.8. The levels were calculated for the calibration, current (2010 irrigation development) and non-irrigated scenarios.

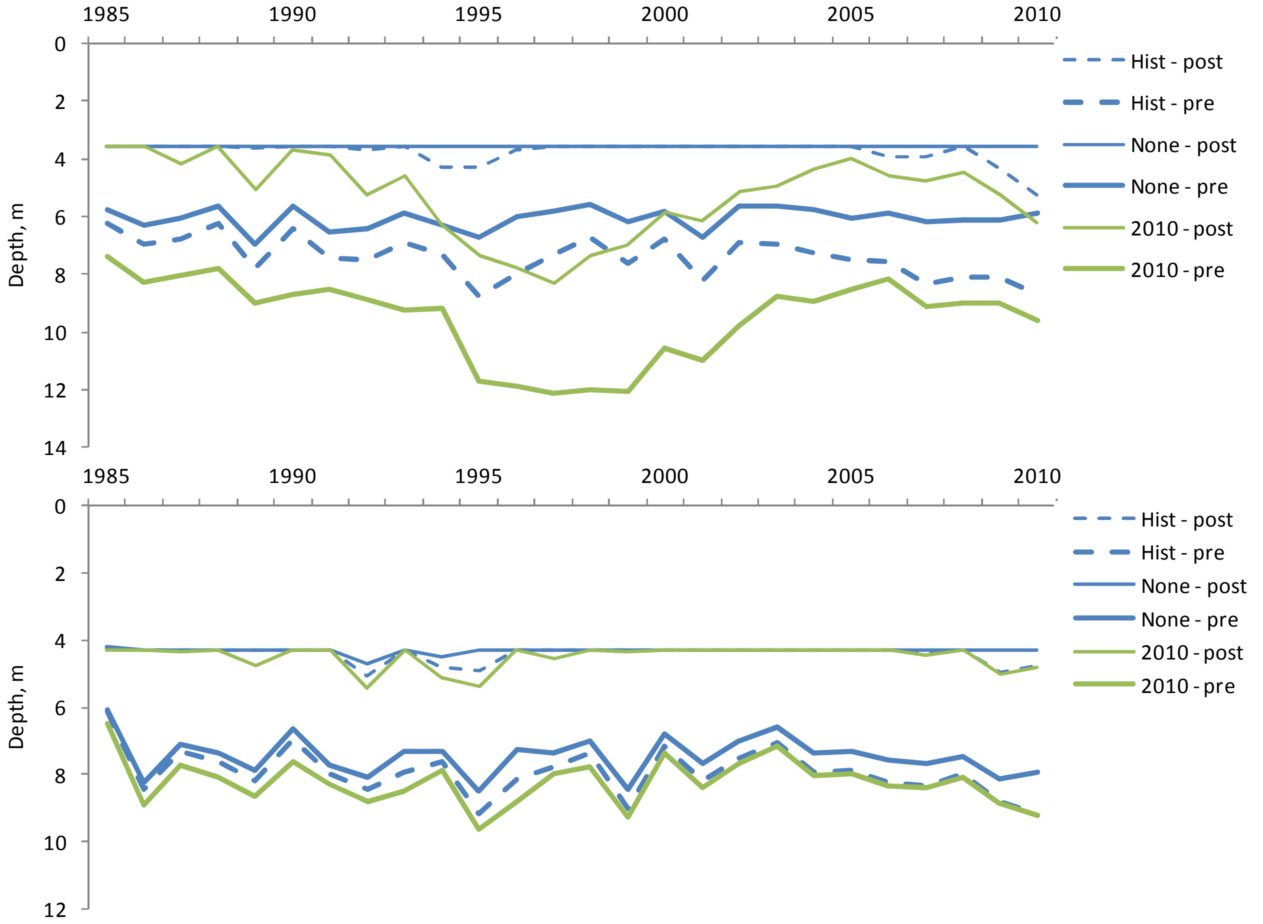
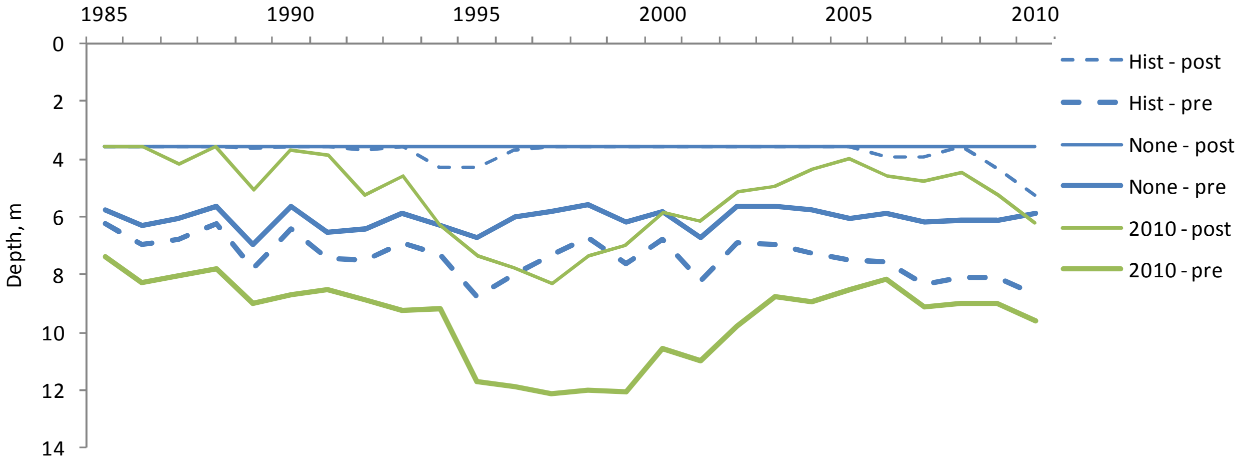


Figure 3.8 shows that during the low rainfall year of 1994, pre-and post-monsoon water levels are calculated to have dropped in both regions. This is consistent with observations (Figure 3.5, and Ahmad et al., 2014) and with the calculated greater irrigation water use in the dry year (Figure 3.7).



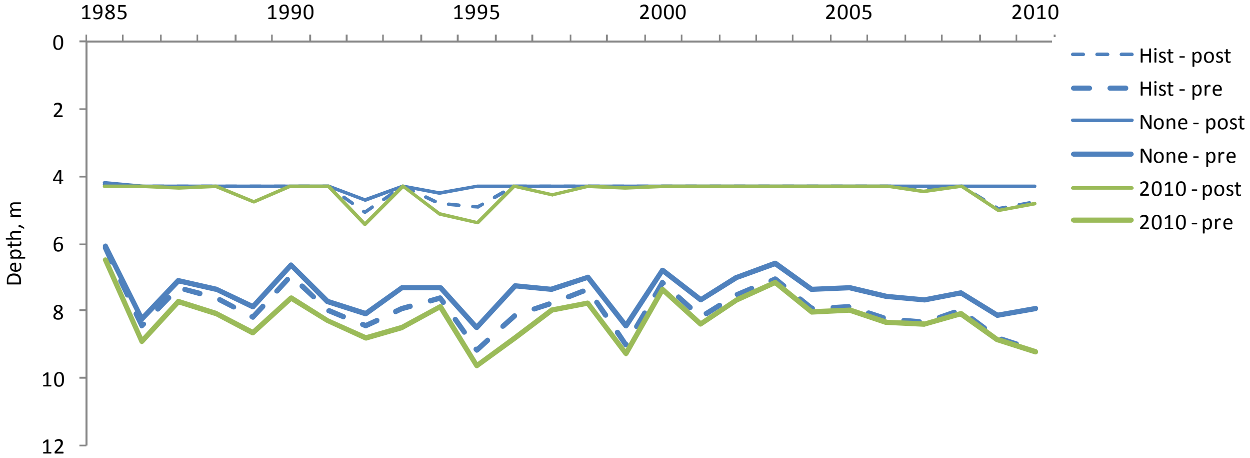
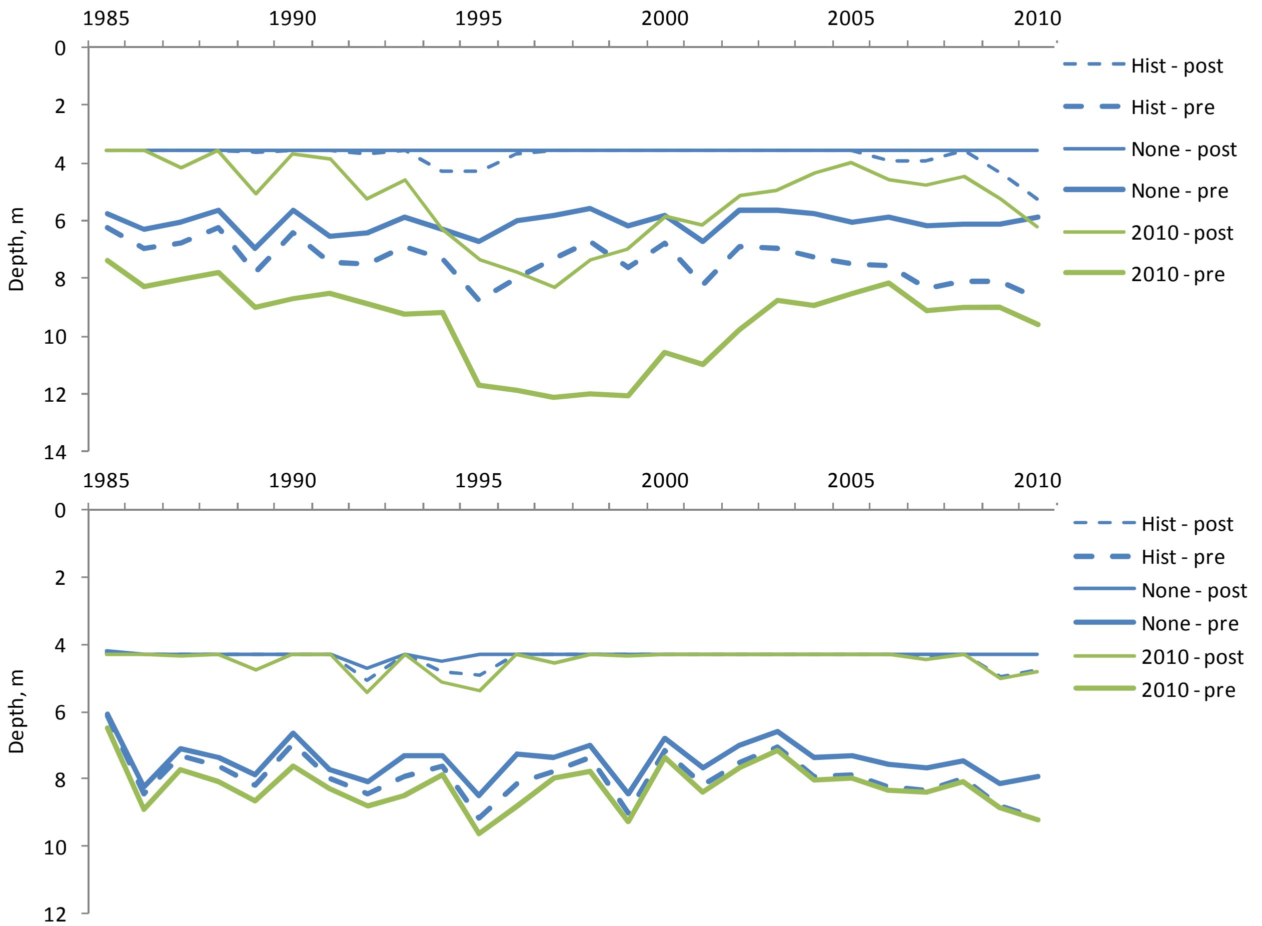


Figure 3.8 also shows that there is calculated to be a large difference between the fully irrigated and the non-irrigated scenarios in the case of the northwest region, and a small difference in the north-central region. Within the limitations of an approximate model, this suggests that groundwater pumping has less of an impact in the north-central region than in the northwest. This may be partly because the higher rainfall in the north-central region, partly because of the slightly lower potential evapotranspiration (leading to a slightly lower crop water demand) and partly because of the somewhat greater proportion of the area irrigated by river water. However, the most important factor is the fraction of the area covered by irrigation. In the northwest region, the area of irrigated crops is 68 percent of the total area (but some areas might be double cropped, so the actual area covered is a little less), with *Boro* rice (the largest water user) covering 46 percent of the total area. The corresponding figures in the north-central region are 42 and 35 percent. The groundwater levels in both the fully irrigated and the non-irrigated cases are calculated to respond to variations in rainfall and baseflow in both regions. Thus, within the limitations of an approximate model, this suggests variations in recharge do affect observed groundwater levels.



Most of the lines in Figure 3.8 show no statistically significant trend, the exceptions being those for the calibration scenario post- and pre-monsoon levels in the northwest and the calibration scenario post-monsoon levels in the north-central region. This suggests that with no irrigation, or with a constant (2010) level of irrigation, there is no continuing decline or rise in groundwater levels, whether pre-monsoon maxima or post-monsoon minima. Thus, the modest trend to less rainfall (as discussed in section 3.2.1) appears not to have resulted in a trend in groundwater levels. However, as shown in the upper plot in

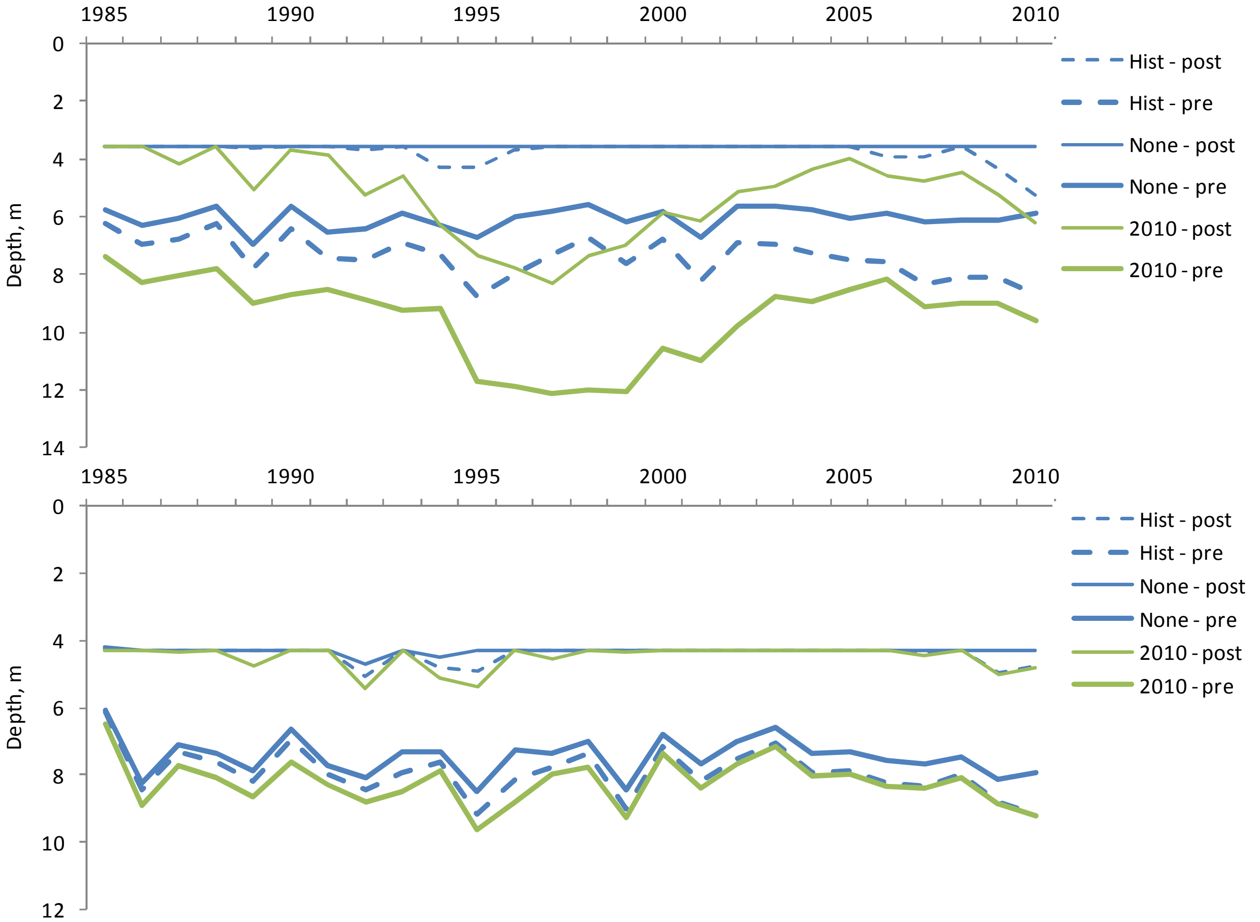


Figure 3.8, the historical increase in irrigation area does result in a trend of groundwater levels. The trend is more obvious for the pre-monsoon maximum depth in groundwater, which was calculated to be near the non-irrigated groundwater depth in 1985, and to have fallen nearly to the fully irrigated depth in 2010. The trend is statistically significant. The trend in the post-monsoon minima is less marked, but also statistically significant. The trend for the north-central region pre-monsoon minimum groundwater levels is also less marked but is statistically significant. Thus, within the limitations of an approximate model, the results suggest that the trends in regional groundwater levels observed in the northwest region (as reported by Ahmad et al., 2014) may be at least partly a result of the increase in area irrigated. With a halt to the increase in area irrigated (which may have happened recently, as reported by Mainuddin et al., 2014), the declining groundwater trend may be reduced. We emphasise that the result is for the regional average groundwater level. Within the northwest region the Barind Tract is an area of clear declining groundwater levels that result from overuse, not from a trend due to a trend of increasing area or decreasing rainfall (Section 2.4 and Kirby et al., 2013, 2014). The result reported here was calculated using an approximate model with the limitations already discussed. The result should be tested with further research.

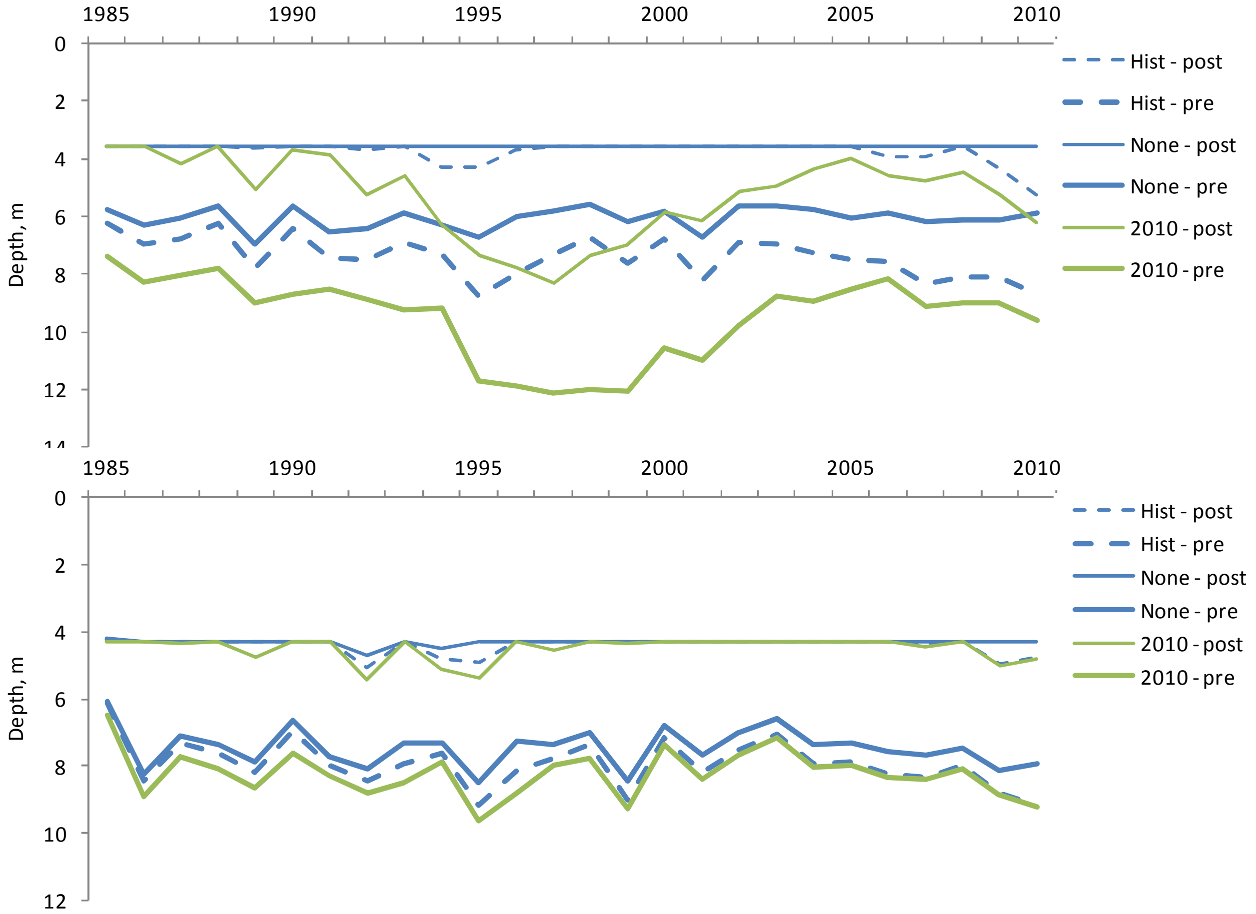


Figure 3.8 Maximum (deepest) annual pre-monsoon groundwater and minimum (shallowest) annual post-monsoon calculated groundwater depths for the northwest (top) and north-central (bottom) regions over the period 1985 to 2010

The increasing irrigation water use from 1985 to 2010 has led not only to a calculated trend of declining groundwater levels, but also to other changes. The regional runoff and baseflow to rivers are calculated to have declined over the period, and the evapotranspiration to have increased.

3.4 Conclusions

We calculated the regional water balances from a simple water balance model which indicates the approximate volumes of water available from rainfall and river inflows within the northwest and north-central regions. The overall volumes of water available annually greatly exceed the volume used in irrigation, but in the dry season the irrigation water use is nearly as large as the combined rainfall and river flows and is therefore dependent on groundwater. Rainfall varies from year to year, and the dry year of 1994 resulted in reduced recharge and greater than average irrigation water use, and hence a significant fall in groundwater levels both pre- and post-monsoon.

Groundwater pumping has led to declines in groundwater levels over the period from 1985 to 2010. However, some of the decline is due to the continually increasing irrigation areas and the consequently greater water use and pumping from groundwater. If the increase in irrigation area and hence water use were to stop at the 2010 level, the trend in groundwater decline is calculated to slow appreciably, albeit with groundwater at a lower level especially in the pre-monsoon minimum. The reduction in pre-monsoon water levels is problematic for drinking and irrigation water access. The increase in irrigation water use and groundwater decline is calculated to be accompanied by a decline in runoff and baseflow to rivers.

The results are based on an approximate model and should be verified by more detailed study.

4 Surface water and groundwater interaction

Contributors: Glen Walker, Tarikul Islam, Jakir Hossain, Geoff Hodgson, Mobin Ahmad

4.1 Introduction

About 78% of the total irrigated area of the country uses water derived from groundwater (Section 2.3). The growth of groundwater use has meant the shift of management effort from developing its resource to maintaining sustainability of the resource. This is especially true of the northwest and north-central regions, which are the focus of this study. The predominance of groundwater use results from the lack of available surface water in the dry season (Section 3.3.2).

In a country where water tables are so close to the surface, the differentiation between groundwater and surface water is somewhat difficult, especially as water tables rise to the surface in the monsoon season, as land is covered by floods and in areas adjacent to rivers, where groundwater extraction affects surface water and vice-versa.

As groundwater use approaches limits of sustainability, it becomes increasing important to fully understand the water balance and the key processes affecting the water balance.

Previous studies (Shamsudduha et al. 2009, Shamsudduha et al., 2011) have shown that groundwater balance, similar to the total water balance, is dominated by vertical processes. Monsoonal rains cause most water tables to rise near the surface and then drop due to evapotranspiration, groundwater pumping and other discharge processes. As more groundwater is extracted, water table levels prior to the monsoon become lower with each passing year. This creates storage above the water table, allowing more water to infiltrate during the monsoons. This water would have otherwise been part of the local run-off. However, as groundwater extraction increases further, there does reach a limit to the amount of water infiltrating. This limit is a factor of the rainfall and the permeability of the surface soils. As this limit is reached, post-monsoon water levels drop below the land surface. This creates a situation where both pre- and post-monsoon water table levels may be falling (Hodgson et al., 2014).

While vertical processes dominate, lateral processes (even not including run-off of surface water) can make an impact. In particular, it has been shown (Rahman and Jackson, 2006) that lateral groundwater movement can modify a groundwater balance locally by up to 20%. While this would appear to be a small fraction of the water balance, it could be enough to affect falling trends in water tables. While lateral groundwater fluxes can redistribute diffuse recharge through the land surface, they also can redistribute water to and from streams. In this way, additional water can be accessed for irrigation and other uses.

The previous Bangladesh Integrated Water Resources Assessment study had mixed estimates with respect to groundwater–surface water exchange fluxes. The regional water balance study (Kirby et al., 2014) suggests that the combined runoff (overland flow direct to rivers) and baseflow (discharge into rivers from groundwater) is about 144 billion cubic meters (BCM), of which baseflow may be as high as about 31 BCM. An aquifer exchange pilot study, conducted under the Bangladesh Integrated Water Resources Assessment (BIWRA) Project (IWM, 2014a) on a 23 kilometre section of the Jamuna and several tributaries and distributaries that join or leave the Jamuna in this reach, showed that for one reach, the flux from river to groundwater was more than .01 BCM/km, but most other sites were about a magnitude lower and varied as to whether the net flux was to or from the river. This baseflow estimate from the regional water study (Kirby et al., 2014) is higher than would be presumed from the Jamuna – aquifer exchange pilot study, but the study cannot rule the estimate out.

One of the responses to groundwater use reaching sustainable limits is to increase irrigation from surface water. Some new schemes are planned. However, such schemes are almost certainly going to influence groundwater availability and may be ultimately deriving the water from groundwater. Before such schemes are developed, it is important to understand the nature of groundwater-surface water interactions (Hoque and Islam, undated).

Apart from sustaining irrigation, surface-groundwater exchange fluxes can also be important by supporting ecosystems such as wetlands or in-stream systems and also to maintain water quality for both groundwater and surface water (Adhikary et al., 2012).

Flooding is another way in which water transfers from surface water to groundwater. As river levels rise higher than the banks, water moves overland and then potentially recharges groundwater system. This has been previously recognised as potentially important recharge mechanism (Shamsudduha et al., 2009), but is also not well-studied.

Overall, we conclude that the volumes of water exchanged between the surface water and groundwater are not well known, and should be examined in greater detail. This study is another step towards understanding these fluxes; it aims to analyse the historical data of groundwater water level and the river flow to understanding the surface water and groundwater interaction (vertical recharge, lateral movement, their significance on overall water balance) and its trends.

This study does this by:

1. analysing transects of groundwater bores about surface water gauges in various rivers to determine seasonal, annual and mean estimates of groundwater-surface water fluxes
2. developing a conceptual model of drivers for groundwater-surface water fluxes that explains the varying magnitudes and characteristics of these fluxes
3. compare this conceptual model to existing geochemical data
4. running an existing MIKE-SHE model for the northwest province.

4.2 Conceptual groundwater model

4.2.1 Hydrogeological settings

The groundwater systems of the northwest and north-central regions are part of the larger groundwater system that underlies nearly all of Bangladesh. The geology and hydrogeology of this groundwater system have been described elsewhere. The groundwater system acts as a connected single system, although it may be divided into a number of aquifers and aquitards. As mentioned previously, water tables in most of Bangladesh are near the land surface and so the groundwater system is topographically constrained. This means that the groundwater system does not change significantly over time in thickness and the hydraulic gradients that drive the groundwater systems are similar to the topographic gradients. This leads to a range of nested groundwater systems. At the largest scale, there is a southerly groundwater flow to the Bay of Bengal. At the smallest scale, there are the vertical processes described earlier. In between are a range of intermediate and regional groundwater systems that flow from higher land to lower land.

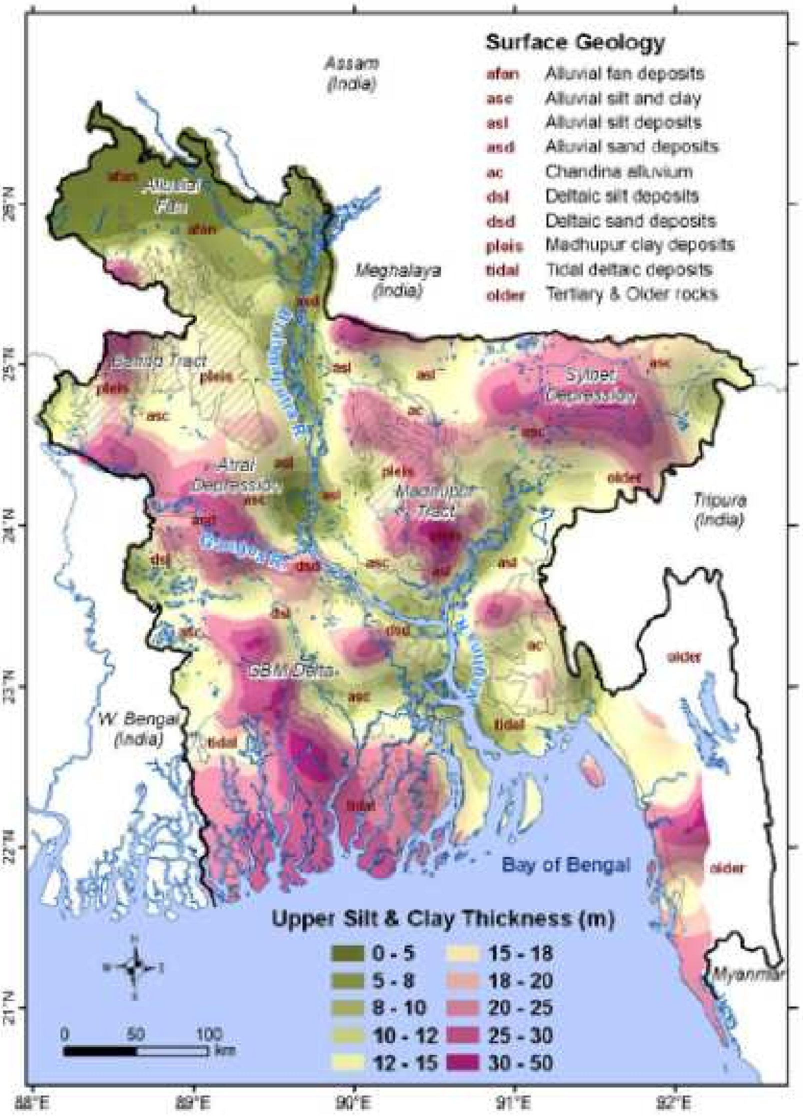


Figure 4.1 Physiographic units and thickness of clay at the surface of Bangladesh (after Shamsudduha et al., 2011)

Generally, four major physiographic units exist at the surface of Bangladesh (Figure 4.1). These are: (a) Tertiary sediments in the northern and eastern hills; (b) Pleistocene Terraces in the Madhupur and Barind Tracts; (c) Recent (Holocene) floodplains of the Ganges, the Brahmaputra and the Meghna rivers and (d) the Delta covering the rest of the country. Most of the present land surface of the country is covered by the Holocene floodplains deposited by the Ganges-Brahmaputra-Meghna river systems. For the topic of groundwater-surface interactions, this will be of most interest. Of the four physiographic regions, all but the delta exist in the northwest and north-central regions. Some authors have sub-divided the physiographic regions, especially the

Holocene floodplains e.g. Teesta, Little Jamuna, Middle Atrai, Lower Atrai, Lower Mahananda, Ganges, Brahmaputra-Jamuna, and Old Brahmaputra.

Conceptually, the hydrostratigraphic system for the northwest and north-central Alluvium is usually divided into Top Soil, Upper Aquitard, Composite Aquifer, Lower Aquitard and Main Aquifer. The Lower Aquitard is not continuous, so the Composite Aquifer, Lower Aquitard and Main Aquifer may be considered as a single layer as aquifer, leaving Top Soil, Aquitard and Main Aquifer. The Composite Aquifer unit exists just beneath the semi-confining silty clay layer. The semi-confining silty clay layer acts as an upper aquitard. The Composite Aquifer is composed of grey and light brown coloured very fine-to-fine sand with lenses of fine to medium grained sand and occasionally with clay, silt and trace mica lenses. The Main Aquifer is considered as principal source of groundwater production in the study area. This aquifer unit has a thickness in the northwest region of 35-50 m and is composed of medium to coarse-grained sand with occasional fine sediment lenses. Lithological logs have been used to collate information on these layers. Some example cross-sections are illustrated in Figure 4.2, Figure 4.3 and Figure 4.4. The data for all of the cross sections have been used for the modelling described later.

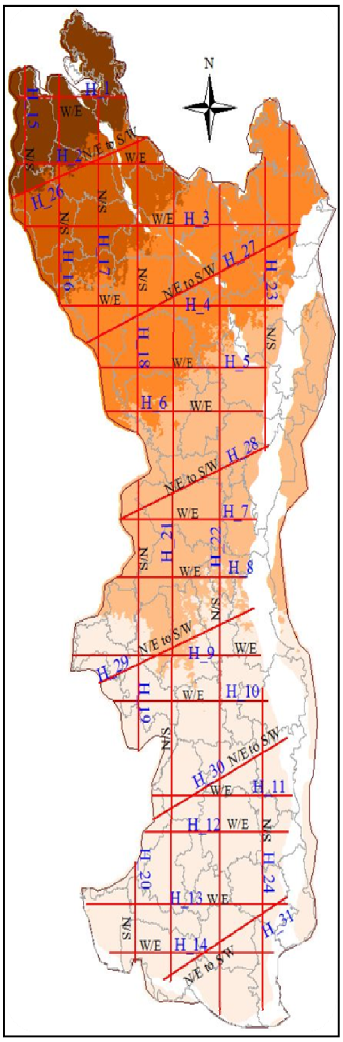


Figure 4.2 Layout and sample plot hydrostratigraphic sections

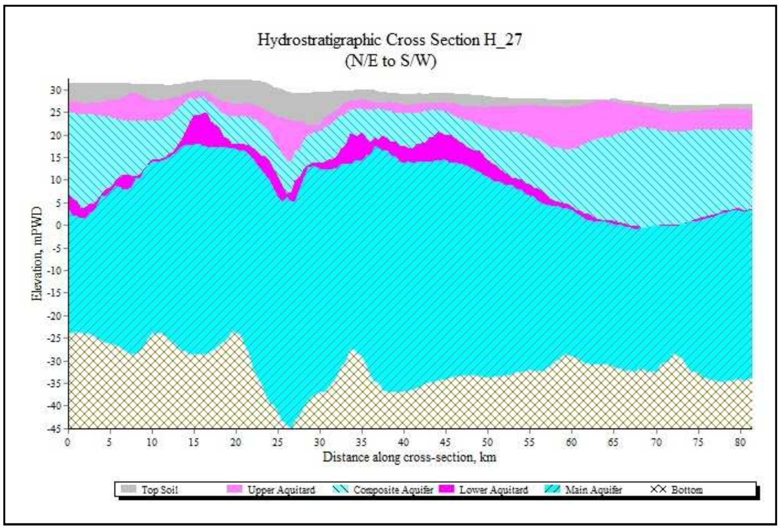


Figure 4.3 Hydrostratigraphic cross-section (N/E to S/W, section H_27 in Figure 4.2) showing the thickness of overlying clay

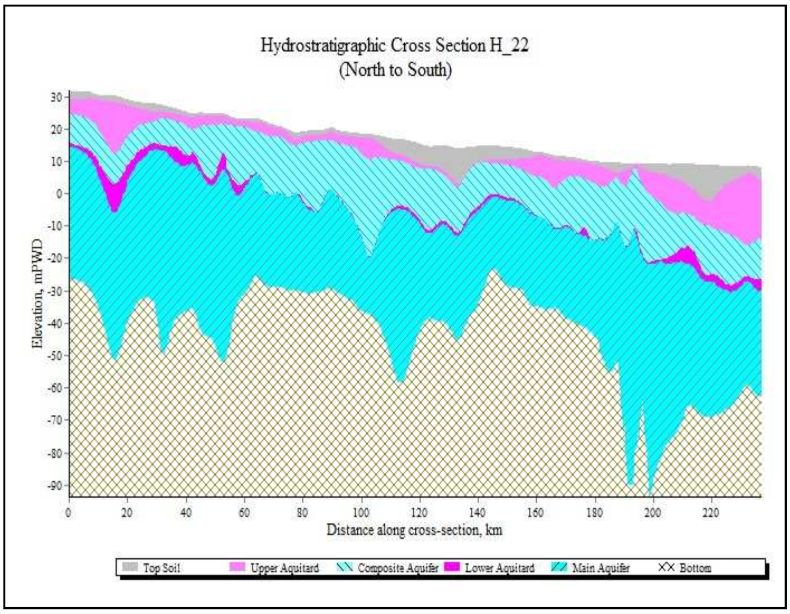


Figure 4.4 Hydrostratigraphic cross-section (N to S, section H_22 in Figure 4.2) showing the thickness of overlying clay

The main regional groundwater gradients can be seen in Figure 4.5 and Figure 4.6, which shows both pre-monsoon and post-monsoon groundwater elevations for the northwest and north-central regions, as well as the Digital Elevation Model. As expected, these groundwater gradients follow the topographic gradients. In the northwest region, there are two main features relevant to this study. The first is a south-easterly flow along the Teesta towards the Brahmaputra. The estimate of this flow is 0.3-0.5 million cubic meters(MCM)/yr/km width or approximately .02 BCM/year and continues beyond the Brahmaputra-Jamuna rivers parallel to the Old Brahmaputra in the north-central region at about the same flux. The second is the flow to the Lower Atrai Basin from the north and west. The Lower Atrai Basin is a very flat low-lying area. Groundwater pumping and other discharge creates a groundwater depression, which induces flows west from the Jamuna and north from the Ganges during the dry season. The flow west from the Jamuna is 0.1–0.3 BCM/yr/km pre-monsoon and 0.0–0.1 BCM/yr/km post-monsoon.

The red-dashed line in Figure 4.6 shows the divide between the south-easterly flow and southerly flow. The black arrows show the directions of groundwater flow. The red arrows show directions apparent in pre-monsoon groundwater, which are not apparent in post-monsoon groundwater contours.

For the north-central region, the general regional flow follows the Old Brahmaputra in a south-easterly fashion. There is a westerly flow from the Madhupur Tract towards the Jamuna and to the south, there is an easterly flow from the Jamuna.

Ahmad et al. (2014) estimated the net groundwater use (rainfall – evapotranspiration) for part of the northwest region (Figure 4.7). The areas in blue and green show high groundwater extraction and/or lateral groundwater inflow, which would lead to higher net groundwater use. This is partially consistent with the groundwater flow directions and inter-seasonal fluctuation.

The major rivers (Brahmaputra-Jamuna, Ganges and Teesta) and most of their flow originate from outside of Bangladesh and are expected to have cut more deeply into the sediments. A number of local rivers have most of their flow occurring in Bangladesh. For example, many of these flow into the right hand bank of the Jamuna. We will be considering groundwater-surface water exchanges with both the major rivers and some of the local rivers. All of these rivers have much greater flows resulting from the monsoons and in wetter years most flood. The rivers to the north of the northwest region are more incised into the landscape. This will lead to a local groundwater flow system from the adjacent groundwater system discharging to the river. In the south, the accumulation of sediments has led to less pronounced incision. The amount of surface water-groundwater interaction is influenced by the aquitard, and the degree to which streams have cut through the aquitard.

Figure 4.1, Figure 4.3 and Figure 4.4 show the thickness of the overlying clay. This shows that the Teesta, Brahmaputra and Jamuna go through areas of thinner clay. Figure 4.3 and Figure 4.4 show a more recent collation of the stratigraphy of the northwest region. The pink region shows the Upper Aquitard, while the purple region shows the Lower Aquitard. The blue region shows the Composite and Main Aquifers. The hashed area shows the basement. Similar transects are available for all of the areas shown on the map.

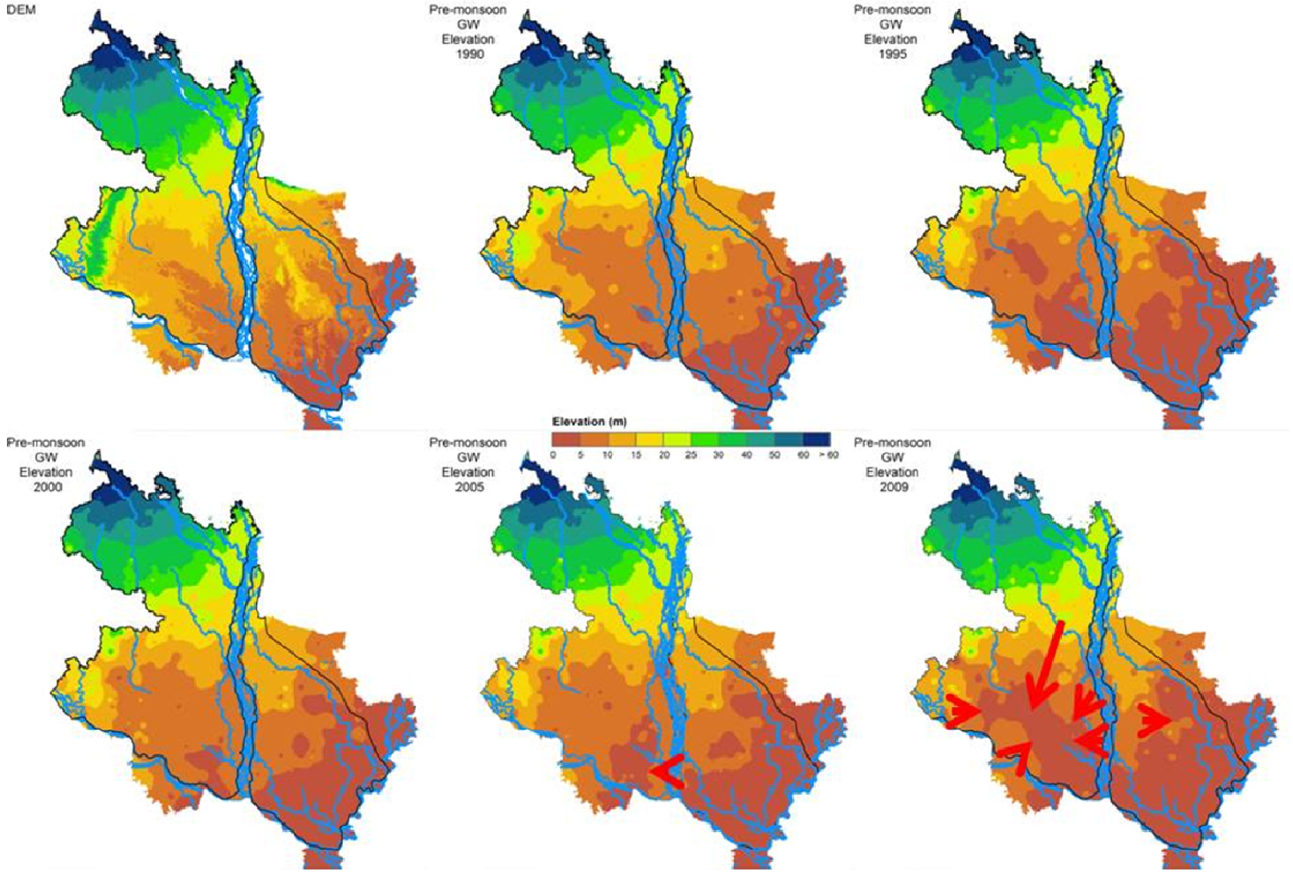


Figure 4.5 Pre-monsoon groundwater elevation of the northwest and north-central regions for the years 2000, 2005, and 2009

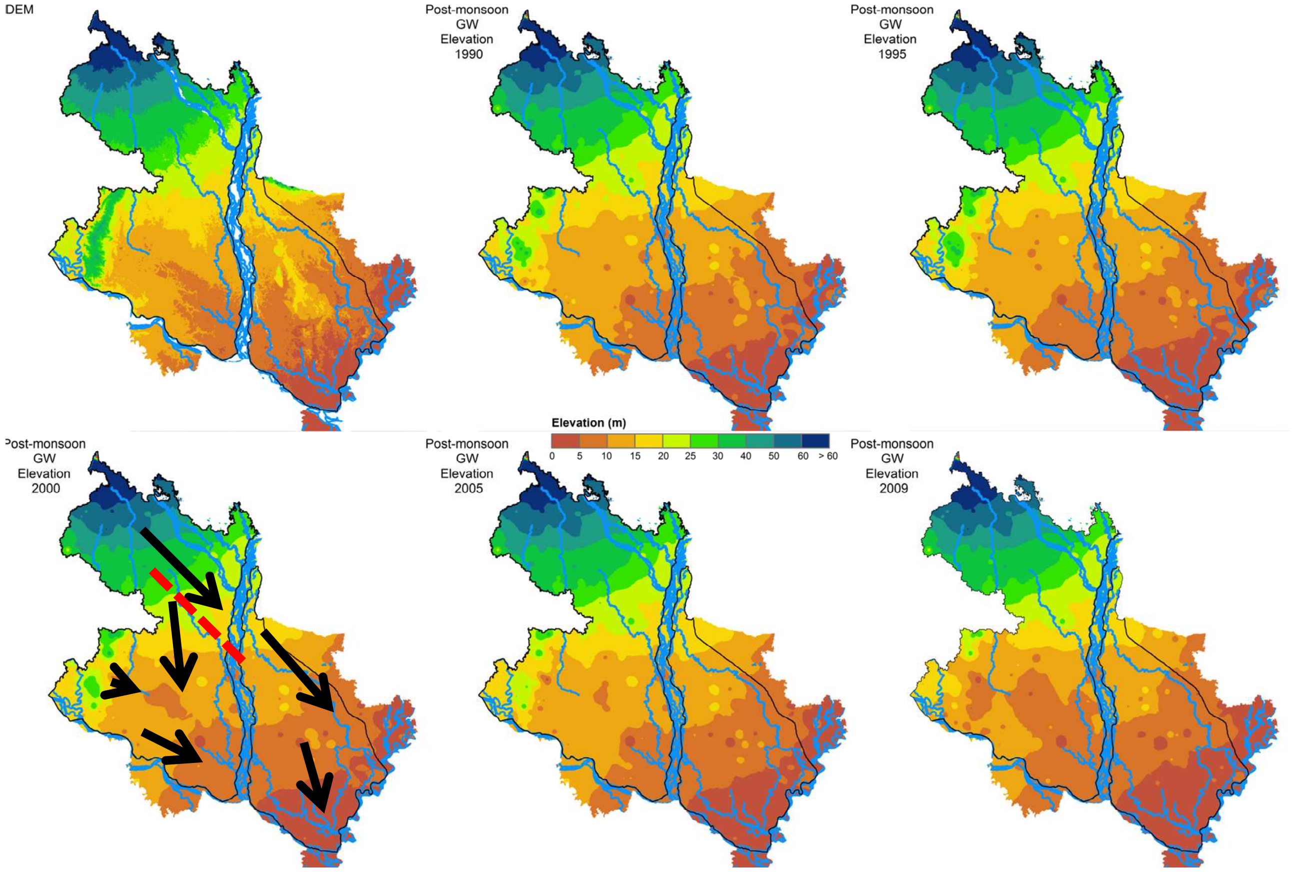


Figure 4.6 Post-monsoon groundwater elevation of the northwest and north-central regions for the years 2000, 2005, and 2009

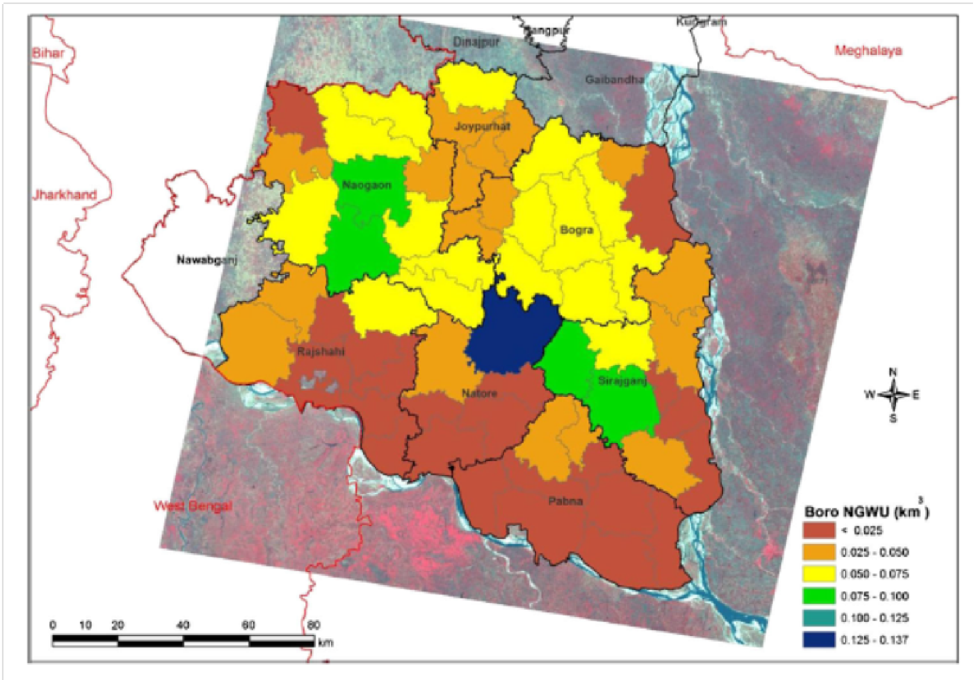


Figure 4.7 Volume of net groundwater use for *Boro* rice production in the northwest part of Bangladesh (grey and black colour lines represent *Upazilla* and Districts boundaries)

4.2.2 Groundwater responses to various recharge processes

The previous section described a number of groundwater processes.

The first of these is the vertical process of recharge during the monsoon season, and then losses due to groundwater extraction and evapotranspiration (Figure 4.8). This process has been previously modelled in BIWRA (Hodgson et al., 2014).

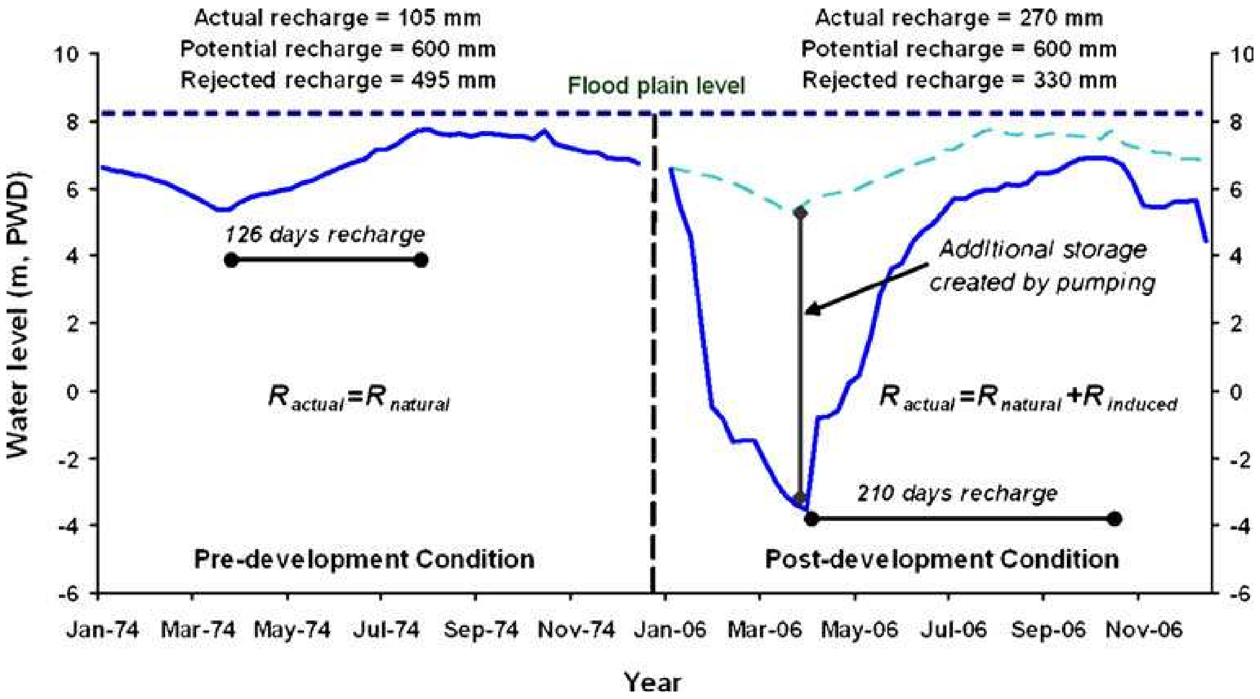


Figure 4.8 Diagram showing the effect of induced recharge from lowering the groundwater table and hence increasing the storage capacity through abstraction for irrigation (after Shamsudduha et al., 2011)

The groundwater is also affected by lateral processes that may lead to recharge and discharge to the area. For example, the Lower Atrai region receives lateral groundwater flow from the surrounding areas. This is formally the equivalent of decreased groundwater extraction. Similarly, if groundwater moves from the area, this is formally equivalent to a reduction in groundwater extraction.

One of the important lateral movements is that to and from streams. In most cases, the stream bed will be lower than the surrounding land surface. This will lead to a mean stream water level being lower than the mean elevation different of ambient groundwater, which is closer to that of the ambient land surface. This means generally that there will be a flux towards the river in addition to any regional groundwater flux. If we suppose that the monsoon rainfall keeps water table near the land surface, the flux between river and the aquifer is given by Darcy’s Law using the mean groundwater elevation (near land surface) and stage height as respective heads. In many cases, the rivers act as drains to the groundwater system. It is not clear without observation what separation distance should be used in Darcy’s Law. There clearly should be a threshold flux, which drops the mean groundwater elevation below the surface despite the monsoon rains. In depositional environments, the stream bed may not be that much lower than the surrounding areas. In such cases, the groundwater extraction can cause the groundwater level to be lower than the stream for much of the year, leading to a situation where the aquifer is gaining from the stream or there is a variable losing/gaining situation.

In addition to the mean gradients, the rivers rise above and fall below the mean stage height in response to monsoonal rainfall. Figure 4.9 shows the groundwater response at various distances from the stream for typical parameters in Bangladesh (Transmissivity = 1600 m^2/day, Specific yield = 0.1, no bank impedance and actual stream hydrograph for Jamuna). This has been estimated using the method of Jolly et al. (1994). This shows that for distances much more than 1 km from the stream, response is muted and delayed.

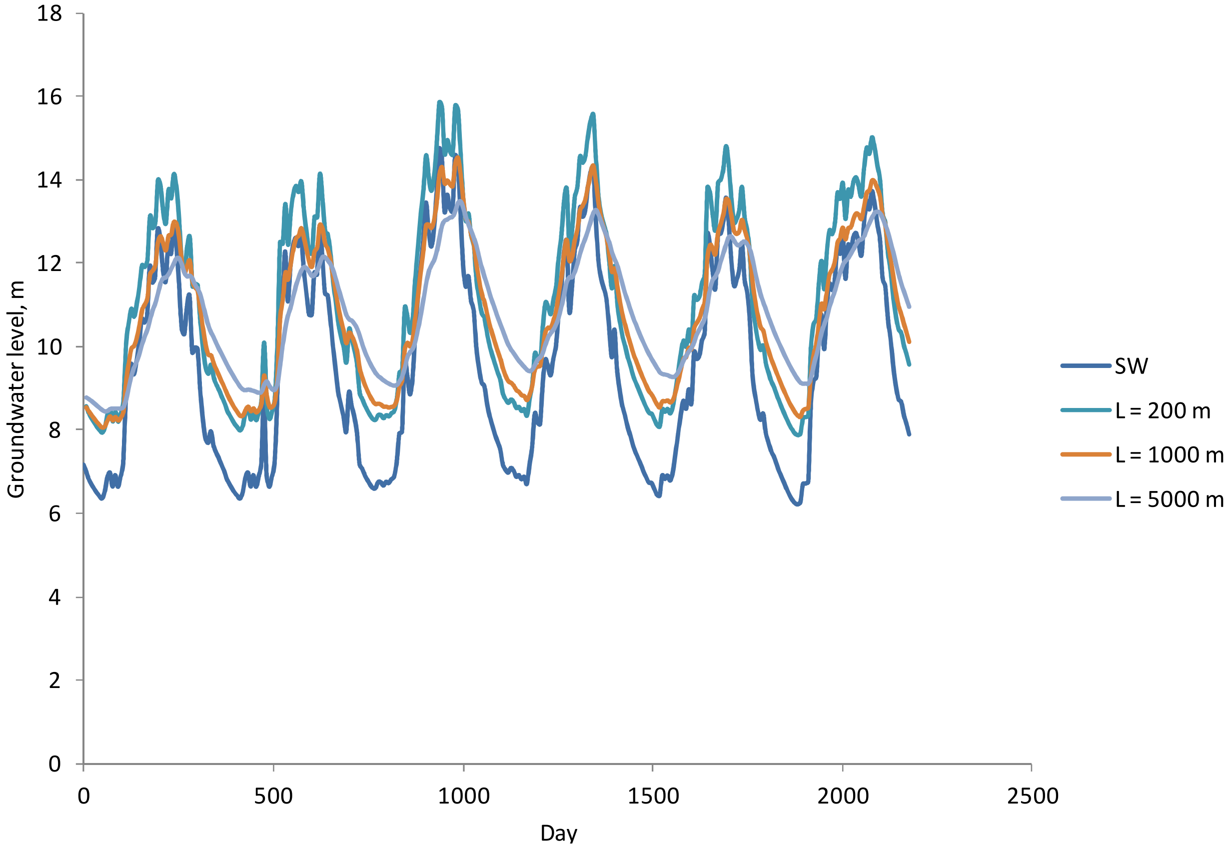


Figure 4.9 Groundwater response (level) at various distances from the stream for typical parameters in Bangladesh

However, it should be noted that many groundwater bores show good correlation with stage hydrographs despite being several kilometres from major streams. There may be different reasons for this 1) both groundwater and streams are responding to same rainfall events. Hence rises in groundwater may have nothing to do with nearby streams 2) the diffusivity (T/S) is up to two orders of magnitude higher. This might be the case if the aquifer is more confined and 3) that streams go overbank, so that distances between bores and stream is shorter.

The effect of floods is to potentially cover the land surface more quickly and then infiltrate towards the groundwater system.

The groundwater response at any point is a superposition of the above effects. The superposition breaks down when water tables reach the land surface. The effect of lateral groundwater movement is the same as reducing or increasing groundwater extraction. The characteristics of responses to other processes in part depend on their timing. It could be that initial response is due to early diffuse recharge. Then in the vicinity of streams, bank storage effects may add to this.

Later in the season, the area floods and causes a sharper rise in groundwater until the land is saturated.

4.3 Previous Bangladesh studies on groundwater-surface water interactions

A number of studies on river-aquifer interaction have been carried out from early sixties till to date. The available study reports, project documents, published scientific articles have been collected and reviewed to get an overall idea of the study area and its aquifer properties. Some of the important studies are briefly described below.

Besbes et al. (1978) estimated the recharge from ephemeral streams in arid regions in Tunisia. Assuming that the transmissivity does not vary with time, the equations of flow in the saturated aquifer are linear. The recharge from the stream was determined using the fluctuations of the piezometers in the vicinity of the stream. The empirical runoff-recharge relationship was then determined to extend the estimation of recharge to a 23-year period.

Nobi and Gupta (1997) carried out studies on numerical model for simulations of the regional flow in an integrated stream-aquifer in the coastal region of Bangladesh, considering the dynamic interaction between stream and the aquifer. The interactions between the stream and aquifer significantly influenced the flow in the aquifer and the river network. The stream-aquifer flow exchange of the system fluctuated seasonally. In the wet season, as the river level drops below the groundwater levels, the flow condition reverses. The river and aquifer system was analysed interactively. The rate of flow exchange between the stream and the aquifer was considered linearly on the head difference between the aquifer and the stream (Morel-Seytoux, 1975). The study found that the rate of flow exchange was highest immediately after the wet season as the river level goes down fast and after that the rate of exchange reduced gradually as the river and the groundwater levels become closer.

Bangladesh Water Development Board (1987) carried out a study on the Ganges for the year of 1983. In this study the groundwater levels obtained from piezometric observation wells were compared with the river stage, and based on this it was determined whether the slope of water table was towards the river or away from the river. The study shows that the river Ganges gains from surrounding groundwater aquifer for a very longer period of the year while it contributes horizontal recharge to groundwater aquifer only for two and a half months.

Bangladesh Water Development Board (1990) carried out a study using existing data, reports and primary data of test-drillings and aquifer tests in Rajshahi, Noagaon and Nowabganj districts. Contour maps of ground water depth and of average maximum fluctuation of groundwater level were prepared to show area-wise maximum depth and flow directions. Contour maps of specific yield were prepared using data from aquifer tests. Field surveys were conducted to determine *upazilla* wise irrigation equipments and their use. The *upazilla* wise actual and available groundwater recharge was assessed, which varied from 322 to 567 mm and from 243 to 411 mm respectively. The balance of available recharge after existing uses was determined assuming all DTW of 2 cfs (0.057 m^3/s) capacity ran 13 hrs /day for 120 irrigation days and all STW of capacity 0.40 cfs (0.011 m^3/s) for the same periods.

Karim (1972) studied the aquifer-stream interaction for the river Teesta, Tangon, Karatoya, Charalkata and Ghagot River using analytical method. In this study the groundwater level were compared with the river stage. Using the groundwater level data a contour was generated and from this contour hydraulic gradient was computed. Using Darcy's law groundwater flow due to interaction was determined. The study shows that the loss of surface water occurs in some parts of the river reach and gains occur in other parts.

MacDonald (1977) conducted a study on the relationship between Ganges river stages and hydrographs of groundwater levels in the vicinity of the river in Pabna and Rajshahi Districts. Study results show that the groundwater levels correlate with the river stage, suggesting lateral inflow from the river during the monsoon. The analysis indicates that the quantity of water recharged to the aquifer adjacent to the Ganges in this particular section is small, averaging only 140 m^3/m (0.14 MCM/yr/km) length of the river bank.

Chowdhury (1998) carried out a study on a reach of lower part of Ganges River for the period of 1974 to 1994. In his study he selected some suitable transect lines within the study reach. Then he selected some groundwater observation wells on the selected transect line. Using Darcy's Law, he used hydraulic gradient from river stage and groundwater level and specific yield of the aquifer to investigate the river-aquifer interaction. In this study, he found that there is a considerable amount of groundwater discharge from the surrounding aquifers to the Ganges. For the entire period of the record, the minimum recharge from the river is seen to vary from 11 m^3/day/m (4 MCM/yr/km) to a maximum of 640 m^3/day/m (230 MCM /yr/km) whereas discharge of groundwater towards the river Ganges ranges from 117 m^3/day/m (43 MCM /yr/km) to 1519 m^3/day/m (554 MCM /yr/km).

Mridha (2005) carried out a study for Groundwater-Surface Water Interaction for the river Tangon and Karatoya. In this study MODFLOW modelling software were used. In this study, it was found that the exchange of flow between aquifer and river varies throughout the year. The quantity of groundwater flow varies also for different reach of the river.

IWM (2006) carried out a study on Deep Tubewell Installation Project in Barind Area. The main objective of this project was *upazilla*-wise groundwater resources assessment. Under this study the exchange rate of groundwater and the rivers Punarbhaba, Mahananda and Ganges were also investigated using mathematical modeling for the year 2001 (average year condition). In this study it was found that for the reach of Godagari to Charghat, annual groundwater loss per kilometer was about 0.33 MCM. From the study in Barind area (IWM, 2006), it has been found that 13.45 MCM /yr (.013 BCM/yr) groundwater is moving to the nearby River Ganges, and 7.24 MCM /yr (.007 BCM/yr) to India. The losses to the Ganges are respectively -7.05, 11.9, 3.0 and 5.6 MCM /yr (-.007, .012, .003 and .006 BCM/yr) for the different segments. The study recommended further investigation on the interaction between the Ganges river and Barind aquifer.

Rahman and Roehig (2006) investigated the flow exchange at 13 different locations between the Atrai River and aquifers in the in the Rajshahi and Naogaon districts in the northwest region. The aquifer has an average inflow rate of 0.009 m^3 /sec (0.0003 BCM/yr) and the average outflow rate is 0.0007 m^3/sec (.0002 BCM/yr). The aquifer fed the river during dry seasons which starts in November. During wet seasons the gradients reverse with water flows from the river to the aquifer.

Islam (2009) carried out a study for Barind Aquifer – Ganges River Interaction. In this study analytical approach were used. In this study, it was found that the exchange of flow between aquifer and river varies throughout the year. It was found that during monsoon, the aquifer gains only for a short time but it loses most of the time and the annual out flow from aquifer to Ganges was about 13 MCM (0.013 BCM/yr) for the reach from Godagari to Charghat Regulator.

Haque et al. (2012) found that net inflow (inflow – outflow) from the Ganges to the Rajshahi City aquifer was about 25 % of the inflow; comparable to the recharge to the aquifer in the study area and about 10% of the total groundwater inflow to the study area.

A previous Bangladesh Integrated Water Resources Assessment project report, IWM (2014a), investigated groundwater-surface water exchanges for 5 river stretches (15 km of Dharla River up to Dharla –Jamuna confluence; 21 km of Teesta River up to Teesta –Jamuna confluence; 23 km of Jamuna River between the confluence with Dharla and Teesta, 35 km of Old-Brahmaputra river from off-take; and 27 km of Ghagot River up to Ghagot-Jamuna confluence). They found that the net fluxes to the groundwater to the rivers were .18, .38, 9.9, -1.4 and -.29 MCM /km/yr respectively showing a nearly 50-fold variation. There was also a range of the ratios of left bank fluxes to right bank fluxes being respectively .08, 3.3, .94, .98 and .21 representing a 400-fold range. There was also a range of ratios for inflows to river relative to outflows being 0.80, 0.70, .20, 4.9, and 2.5 respectively representing nearly a 50-fold range. The magnitudes of some of these fluxes, especially for the Jamuna, are large enough to be significant for the regional water balance of the northwest region, but the range of behaviour and the causes need to be understood before interpretation.

4.4 Analysis of transects: implications for groundwater–surface water interactions

4.4.1 Introduction and objectives

The main objective of this activity is to investigate river-aquifer interaction at 12 sites of varying conditions using historical observations of both river stage height and nearby groundwater levels.

The specific objectives of the present study are:

- to identify the periods of lateral discharge and recharge of the aquifer to or from the river
- to assess the annual and mean groundwater-surface water exchange fluxes
- to understand the drivers for the range of responses with respect to groundwater-surface water recommendations.

The approach we use is Darcy’s Law.

4.4.2 Description of data and transects

The location for investigation of interaction is shown in Figure 4.10. The study area is situated in the Northwest part of Bangladesh. The assessment of interaction was carried out for the river Jamuna, Brahmaputra, Teesta, Dharala, Karatoya and Bangali. The groundwater monitoring wells and gauge stations used for this study are given in Table 4.1 and Table 4.2 respectively. Apart from information on location, there is a range of other information: 1) distance of the piezometer from the nearest gauging station 2) approximate elevation of the land surface as established from a coarse Digital Elevation Model, used to aid interpretation and 3) the segment of river to which the measurement is thought to be relevant. The sites represent a range of sites on major and secondary river and both in upper and downstream reaches. Also, some sites in the Old Brahmaputra in the north-central region have been investigated. These studies are reported in Appendix B.

4.4.3 Methodology

This study has been carried out using Darcy's Law directly on the observations. Hydrographs of groundwater and river water level were prepared and analysed to estimate the mean flux between the piezometer and the stream over a period of time. If the piezometer is some distance from the river, it is possible that the flux will vary over the length of the transect, reflecting recharge and discharge processes. The main groundwater flow may be at an angle to the river or even parallel to it. The groundwater-surface water exchange flux is defined as the perpendicular flux at the river's edge. As mentioned previously, irrigation has a marked effect on the groundwater balance and it is likely that the effect of the river may only extend for a few kilometres, and the gradient changes significantly at that distance from the river. Thus, Darcy's law will represent a combination of the groundwater-surface water exchange flux and the groundwater flux in the groundwater system. The longer the distance, the more the flux is weighted towards the latter. Nonetheless, it will indicate the period of gain and loss of groundwater of the aquifer from or to the river.

This means groundwater flow was computed using Darcy's law (1856), which is expressed as

$$Q = TiW$$

where,

Q = rate of groundwater flow in m^3/day

T = transmissivity of the aquifer in m^2/day

i = hydraulic gradient

W= width of the aquifer along the river in m.

The required groundwater level and surface water level data were collected for the period of 2005 to 2010 from hydrology circle, Bangladesh Water Development Board (BWDB). The lithology data were obtained from Barind Multipurpose Development Authority (BMDA) and used to define aquifer characteristics, such as type and thickness. The values of horizontal hydraulic conductivity were obtained from the Institute of Water Modelling (IWM) and were obtained from studies that collected pump test information, but also information from calibration from models. The value of T (transmissivity) is assumed to be the product of the horizontal hydraulic conductivity and the aquifer thickness.

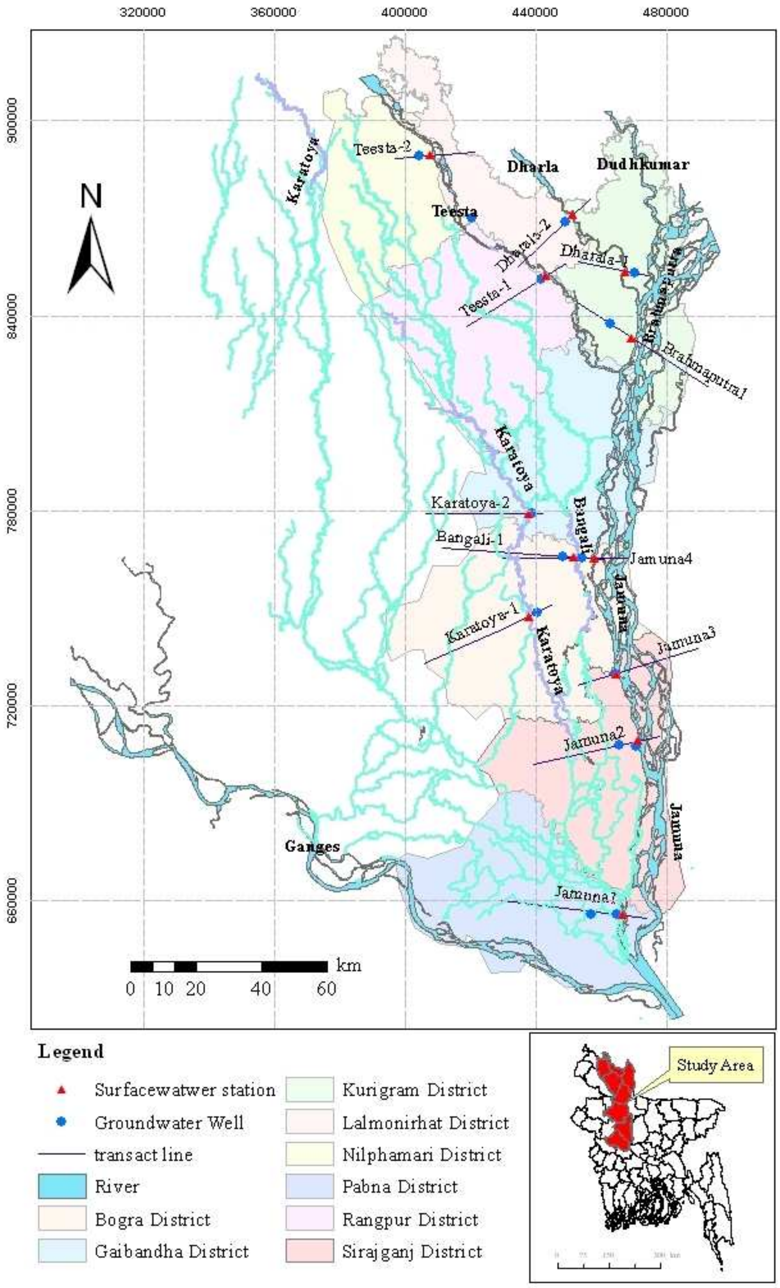


Figure 4.10 Location of groundwater—surface water interaction investigation in the northwest region

The use of Darcy's Law assumes that 1) the groundwater gradient is relatively even between the observation points, 2) the bank impedance is low, and 3) there is saturated connectivity between the observation points.

Some of the uncertainties include:

1. Specific location and hence separation of the observation wells, and specific elevation of the groundwater and surface water levels. Streams can expand significantly with higher flow, affecting the separation. Much of this data comes from other sources and its accuracy is unknown. However, these uncertainties are thought to be relatively small.
2. The representativeness of the bores and gauges for the surrounding area. Groundwater bores are often located on higher ground and/or in villages. Groundwater behaviour is often influenced by local pumping and local hydraulic properties. Groundwater-surface fluxes can

vary along the stream over small distances, reflecting stream shape, incision, impediments to groundwater flow, local topography, etc. In the study area, stream networks are complicated and one groundwater observation bore may be influenced by more than one stream.

3. Transmissivity. The error in the estimate in flux is directly proportional to the error in the estimate of transmissivity, the uncertainty of which can be large. In particular, near the stream there can be sometimes impeding layers, reflecting clay deposition or more conductive conditions related to stream meandering.

Provided transmissivity does not vary in time, Darcy's Law is linear and hence any time interval can be used. For example, it can apply at a point in time, over a month, a year or the long-term mean, as long as the associated means of the heads are also used.

Table 4.1 Groundwater wells used in groundwater–surface water interaction investigation

Well_ID	Associated transect	Easting (m)	Northing (m)	District	Thana	Village	Distance from SW Station (m)	Approximate elevation of vicinity (m) (from DEM)
GT5255009	Dharala-u	448778	869123	Lalmonirhat	Lalmonirhat Sadar	Lalmonirhat	3400	30
GT4952003	Dharala-d	469881	853350	Kurigram	Kurigram Sadar	Kurigram	3500	24
GT3230004	Karatoya-2	438749	779451	Gaibandha	Gobindaganj	Gobindagonj	750	19
GT1020007	Karatoya-1	440265	748822	Bogra	Bogra Sadar	Malotinagar	3000	17
GT7312005	Teesta-u	404039	889268	Nilphamari	Dimla	North Jhunagac	3700	48
GT8542004	Teesta-d	441196	851404	Rangpur	Kaunia	Hariswar	2740	29
GT1095026	Jamuna 4	448154	765808	Bogra	Sonatola	Sukkanpukur	9500	15
GT1095027	Jamuna 4	453955	765626	Bogra	Sonatola	Sonatala	3700	15
GT1095027	Bangali	453955	765626	Bogra	Sonatola	Sonatala	2800	15
GT4994008	Brahmaputra	462536	837641	Kurigram	Ulipur	Ulipur	7700	24
GT4994009	Brahmaputra	458572	840609	Kurigram	Ulipur	Durgapur	12700	25
GT7616009	Jamuna 1	464379	655862	Pabna	Bera	Bijoygonj	2100	8
GT7672029	Jamuna 1	456669	655768	Pabna	Santhia	Santhia	9600	8
GT8861011	Jamuna 2	458914	705638	Sirajganj	Royganj	Chandikona	12700	-
GT8878014	Jamuna 2	470401	707681	Sirajganj	Sirajganj Sadar	Sirajganj	1100	12
GT8878016	Jamuna 2	465274	707983	Sirajganj	Sirajganj Sadar	New Bogara	6000	12
GT8850006	Jamuna 3	464018	729799	Sirajganj	Kazipur	Khadbaudi	1000	-

Table 4.2 River gauging stations used in groundwater–surface water interaction investigation

Transact No	Station name	Easting (m)	Northing (m)	District	Thana	Union	Relevant segment length (km)
Jamuna1	Mathura	466509	655797	Pabna	Bera	Nutan Bharenga	49
Jamuna2	Sirajgonj	471106	709372	Sirajganj	Sirajganj Sadar	Kaoakola	38
Jamuna3	Kazipur	464581	729991	Sirajganj	Kazipur	Maijbari	29
Jamuna4	Mathurapara	457645	765593	Bogra	Sonatola	Tekani Chukainagar	55
Brahmaputra1	Chilmari	469218	833426	Kurigram	Chilmari	Raniganj	84
Dharala-1	Kurigram	467366	853915	Kurigram	Kurigram Sadar	Punchgachhi	28
Dharala-2	Taluk-Simulbari	451247	871483	Kurigram	Phulbari	Shimulbari	23
Teesta-1	Kaunia	442878	852495	Rangpur	Kaunia	Kaunia bala para	10.6
Teesta-2	Dalia	407600	889589	Nilphamari	Dimla	Jhunagachh Chapani	10.6
Bangali-1	Simulbari	451386	765780	Bogra	Sonatola	Sonatala	98
Karatoya-1	Bogra	437671	747538	Bogra	Bogra Sadar	Shabgram	106.8
Karatoya-2	Chak-Rahimpur	437961	779461	Gaibandha	Gobindaganj	Gobindaganj	95.7

4.4.4 Results

From Table 4.3, it can be seen that there are only a few transects where first bore is within 2 km of the stream gauge. These include Karatoya-2 (750m), Jamuna-3 (1000m), Jamuna-2 (1100m) and Jamuna-1 (2100m). These are the ones that we would expect closer correlation between surface water and the nearest groundwater bore. They would also provide a hydraulic gradient truer to the estimate of groundwater-surface water exchange, rather than the regional gradient.

Table 4.3 shows the long-term mean of the stage heights of gauges and piezometric heads. The difference between the mean river elevation and the mean groundwater elevation at the first piezometer is used to denote the characteristic of the connectivity. If the head difference is large, the gauge-piezometer combination is denoted gaining or losing, depending on the sign of the difference. It is expected that with such a large difference, there would be infrequent occasions where the difference changes sign. For those, where the difference is less and sign changes frequently as stream flow rises and falls. The following groups emerge from this analysis (where losing and gaining refer to the loss or gain of water in the aquifer):

1. Losing group 1: The gauges along the Brahmaputra-Jamuna: Jamuna2, Jamuna3 and Brahmaputra.
2. Losing group 2: The upper gauges of the Dharala(-2) and Karatoya(2).
3. Gaining group 1: The downstream gauges of the Karatoya(-1) and Jamuna(-1) and the Bangali.

4. Gaining group 2: Teesta-2 is sited above the barrage. The surface water is held artificially high to supply an irrigation district and is necessarily high with respect to the land surface and hence the groundwater.
5. Variable sites: Jamuna-4, Teesta-1, Dharala-1.

Table 4.3 Distance of the groundwater bores within the transect from the stream gauge

TRANSECT NAME	SURFACE WATER MEAN ELEVATION	GROUNDWATER 1 MEAN ELEVATION (M)	GROUNDWATER 1 DISTANCE (M)	GROUNDWATER 2 MEAN ELEVATION (M)	GROUNDWATER 2 DISTANCE (M)	GROUNDWATER 3 MEAN ELEVATION (M)	GROUNDWATER 3 DISTANCE (M)	CONNECTIVITY STATUS - AQUIFER
Jamuna-1	5.92	4.89	2100	5.63	9600			Gaining
Jamuna-2	9.54	10.45	1100	10.38	6000	8.00	12700	Losing
Jamuna-3	10.71	12.67	1000					Losing
Jamuna-4	12.88	12.87	3700	13.54	9500			Variable
Brahmaputra	19.91	23.26	7700	23.48	12700			Losing
Dharala-1	23.59	23.64	3500					Variable
Dharala-2	28.51	30.56	3400					Losing
Karatoya-1	11.98	10.99	3000					Gaining
Karatoya-2	16.98	17.73	750					Losing
Bangali	14.61	12.87	2800					Gaining
Teesta-1	27.14	27.72	2200					Variable
Teesta-2	50.62	47.48	3700					Gaining

Dharala-2 and Karatoya-2 are the responses expected of streams incised into a landscape. With groundwater levels near the surface and with regional flow following the general topographic surface, the groundwater direction will follow the general direction of the streams. he deeper incised streams in the higher ground cause local groundwater gradients transverse to this. Any lateral movement of the streams with respect to the main topographic gradient, will cause streams to cut across the regional groundwater gradients and intercept some of the regional flow. The Brahmaputra is somewhat different. The more recent cutting of the Brahmaputra is at an angle to the main regional south-easterly topographic gradient. The river is incised relative to surrounding areas and so intercepts the regional groundwater flow plus some additional local flow due to the river elevation.

The Jamuna-2 and Jamuna-3 transects appear also to be incised relative to nearby countryside, but do not intercept regional flow. As can be seen with Transect 2, there is a groundwater divide within less than 10 km of the right bank of the river. On the easterly side, groundwater drains to the Jamuna River. On the westerly side, groundwater flows away to the Atrai depression. The creation of a groundwater divide could be in part due to 1) drainage from irrigation in the vicinity of the groundwater mound contributing to both lateral flow to the east and the west and also could be in part due to 2) the southerly groundwater flow dividing with some moving to the Jamuna River and some to the west. The flownet supports this latter hypothesis, with the southerly groundwater flow near Jamuna-4 changing to a south-westerly flow. It is, however, likely to be a combination of both these processes, noting that there are changes in flow directions over the year, with the groundwater discharge in the Atrai depression accentuating the westerly flow.

In contrast to the aquifer losing at Jamuna-2 and -3, the aquifer is gaining near Jamuna-1. This is mostly due to the junction of the Ganges and the Jamuna being just downstream and the Atrai sediments between causing a large flat area, with a high evaporation rate. The fluctuating water tables mean that the flow directions change during the year.

The Jamuna-4 transect also differs from the Brahmaputra transect upstream and the Jamuna-3 downstream. The groundwater direction has changed from the Brahmaputra gauge from a south-easterly flow to a southerly flow, running parallel to the river (see red-dashed line in Figure 4.6). Also between the gauging stations, the Brahmaputra has bifurcated into the old Brahmaputra and the Jamuna. A number of streams are entering on the right bank.

The other two gauging stations, for which the aquifers gain, are the Karatoya-1 and Bangali. The Bangali is close to the Jamuna-4 site and the interaction with groundwater is strongly influenced by the Jamuna (noting the piezometer occurs between the two rivers. The Karatoya-1 gauge is on a flat area west of the Jamuna River. The groundwater discharge causes groundwater levels to drop below the stream for much of the year.

Besides Jamuna-4, there other two stream gauges, which are variably gaining and losing (Teesta-1 and Dharala-1). Both have almost the same mean for groundwater and surface water. The Dharala-1 gauge is just upstream of the Brahmaputra with the piezometer between the two streams. The Teesta-1 gauge is on a short steeper river reach between two flatter areas.

Estimation of mean stream recharge or aquifer discharge

Stream recharge or aquifer discharge has been estimated for the period of 2005 to 2010 for different rivers. The estimated mean groundwater flow is shown in Table 4.4. The positive quantity of flow represents that the aquifer is gaining i.e. lateral inflow of groundwater from river to aquifer occurs and the negative quantity indicates that the aquifer is losing i.e. lateral outflow of groundwater from aquifer to river occurs.

Darcy’s law is applied in two ways. The first is to use just the nearest piezometer to calculate the gradient. The second is to use all of the piezometers in the transect, and take an average of the gradients. However, as noted earlier, the gradients can change sign for times of the year and if so, the average reverts back to the first. The latter method generally produces smaller estimates of fluxes.

The piezometers closest to the river (Karatoya-2 (750m), Jamuna-3 (1000m), Jamuna-2 (1100m) and Jamuna-1 (2100m)) generally give relatively higher fluxes with -0.36, -1.14, -0.75, 0.32 Mm/yr/km respectively. This suggests that piezometers further away from the stream may be giving more weight to the regional gradient, which is often smaller than that of the stream-groundwater exchange flux. This suggests that we are underestimating the latter.

The last column in Table 4.4 shows a comparison with outputs of a previous Mike-SHE study (IWM, 2006). This study is described in Appendix A. It should be noted that the study was directed to the evaluation of groundwater resources rather than groundwater-surface water interactions. This means that the calibration process was not necessary right for this purpose. On the other hand, Mike-SHE captures more of the processes and is less susceptible to issues of representability of piezometers. It also should be noted that due to the boundary conditions applied, fluxes to and from the Jamuna and Brahmaputra cannot be estimated. The comparisons with the Mike-SHE model are mixed, with those for Dharali-2, Karatoya-2, Teesta-1 comparing well, while those for the Karatoya-1 and Bangali being of the opposite sign. This suggests that where the gauges are on upper reaches of rivers, comparisons are good, while those on the lower reaches, and where the aquifer is gaining, the comparisons are extremely poor.

For the pilot study last year, the Mike-SHE model was calibrated for the purpose of estimating groundwater-surface water interactions for a small part of the northwest and north-central region. The results from the Teesta-1, Jamuna-4, and Dharala-1 could be compared directly to the left-side of Dharala, right-side of Teesta and right-side of the Jamuna respectively, noting that Teesta-1 sits outside of the pilot study area. The estimate for both the Dharala and Teesta is a similar magnitude despite wrong sign for the net flux (Table 4.5). However, the major flux in the Mike-SHE modelling is that of the Jamuna, which is 5-10 times of the estimates for the Jamuna-3 and Brahmaputra respectively, but at least another order of magnitude for the Jamuna-4. We will return to this discrepancy later.

Table 4.4 The groundwater gradients, flux and exchange fluxes, using one or more piezometers (averaged)

Transact name	Gradient (x1.e-4)		Flux estimate using default transmissivity, MCM/yr/km		Volume estimate for segment (BCM/yr) (x1.e-4)		IWM MIKE SHE
	First point only	average	First point only	average	First point	Average	
Jamuna-1	4.88	4.88	0.32	0.32	0.016	0.016	
Jamuna-2	-8.25	-3.21	-0.75	-0.29	-0.029	-0.011	
Jamuna-3	-19.60		-1.14		-0.033		
		-1.14		-0.033			
Jamuna-4	0.04	0.01	0.00	0.00	0.000	0.000	
Brahmaputra	-4.39	-2.74	-0.40	-0.33	-0.034	-0.027	
Dharali-1	-0.12		-0.01		0.000		-0.002
Dharali-2	-6.03		-0.33		-0.008		-0.007
Karatoya-1	3.30		0.12		0.013		-0.008
Karatoya-2	-9.90		-0.36		-0.035		-0.004
Bangali	6.20		0.23		0.022		-0.001
Teesta-1	-2.64		-0.12		-0.001		-0.001

Table 4.5 Results from previous BIWRA pilot study using MIKE-SHE annual flux (MCM/yr/km)

RIVER NAME	LEFT-SIDE		RIGHT-SIDE		TOTAL		NET
	River-Aquifer	Aquifer-River	River-Aquifer	Aquifer-River	River-Aquifer	Aquifer-River	Aquifer-River
Dharala	0.36	0.34	0.55	0.39	0.91	0.73	-0.18
Teesta	0.74	0.45	0.50	0.42	1.24	0.87	-0.38
Jamuna	5.86	1.08	6.43	1.34	12.29	2.42	-9.87
Old Brahmaputra	0.16	0.84	0.20	0.89	0.35	1.73	1.38
Ghagot	0.08	0.13	0.11	0.35	0.19	0.49	0.29

Weekly estimates of groundwater-surface water fluxes

The hydrographs of groundwater and surface water level for different stations used for groundwater-surface water interactions are shown in Figure 4.11. As can be seen, there is a high degree of correlation between surface water hydrographs and groundwater hydrographs. Also, it can be seen that the previous categorisation of Losing, Gaining and Variable appears to be correct in distinguishing those sites where the direction of the flux only changes infrequently and those where the change is annual. In describing the following, we will be focussing on the amplitude of the fluctuations, the timing of the fluctuations (using the 50th percentile between minimum and maximum) and the asymmetry of the fluctuation. By doing this, we hope to see what real connection there is between the hydrographs apart from the same rainfall events causing both, the extent to which the baseflow in the rivers can be attributed to groundwater discharge and whether flooding plays a significant role.

For the losing sites on the Jamuna-Brahmaputra (Jamuna-2, -3 and Brahmaputra), we would expect the surface water hydrograph to be most strongly influenced by rainfall outside of Bangladesh. Hence, the baseflow and amplitude should have little to do with the northern regions. For Jamuna-2, the surface water peak of 14.3-14.7 m occurred in the years of 2007-8, whereas in 2005/6, it was about 12.9 m. For the years 2007/8, the nearby piezometers peaked at 15.1 and 13.8 respectively, while for 2005/6, the peaks were 14.4 and 11.6 m respectively. The timing of the surface water peaks was mostly late August or early September, although one year appeared at end of July. The timing for the groundwater peak was very similar. The lowest point for the surface water was generally between 6.4 and 6.9 and occurred from mid-February to early march while that for groundwater was between 7.9 and 8.8 m and generally occurred late march to mid-April. The rise in surface water occurred mainly from mid-May to mid-June while that for groundwater occurred about two weeks later. The fall in surface water occurred late October to mid-November while that for groundwater occurred a few weeks later with one exception, where it occurred fractionally earlier. The timing of the second piezometer appears to be more muted and generally later. This does suggest that the surface water might be driving the groundwater rises and falls. The matching of the peaks of the first piezometer could relate to flooding. A diffusivity of 30 times the default value provides good, but not perfect, matching with both piezometers, even ignoring groundwater processes, other than the general groundwater gradient.

Jamuna-3 shows less correlation between groundwater and surface water hydrographs. In some years, the groundwater hydrograph appears to rise quickly in line with the surface water, but falls more slowly, but in some years, the rise is also slow. This suggests some influence, but not strong. For the Brahmaputra, the rise again seems to coincide with the rise in surface water but fall is much more subdued.

The other losing streams (Dharala-2 and Karatoya-2) have slightly different patterns. The amplitude of the surface water hydrograph at Dharala-2 is smaller than for the Jamuna, being about 2.8-3.4m with the rise occurring in June. The amplitude of the groundwater hydrograph is more variable, ranging from 1.8 to 4m, with the rise occurring also in June, sometimes just before the surface water rise. The fall, however, is somewhat different with the fall in the surface water occurring generally in September, but with the groundwater fall occurring anytime from November until January. For Karatoya-2, the surface water amplitude ranges from 5.4 to 5.8 m, while the groundwater amplitude is 2.3 to 3.7 m. The rise of the surface water occurs in June, however, the groundwater rise occurs in July. The surface water fall occurs in October, while groundwater fall is much slower, occurring in December. The surface water hydrograph has a more obvious baseflow tail than does the Dharala, perhaps suggesting a slightly higher transmissivity.

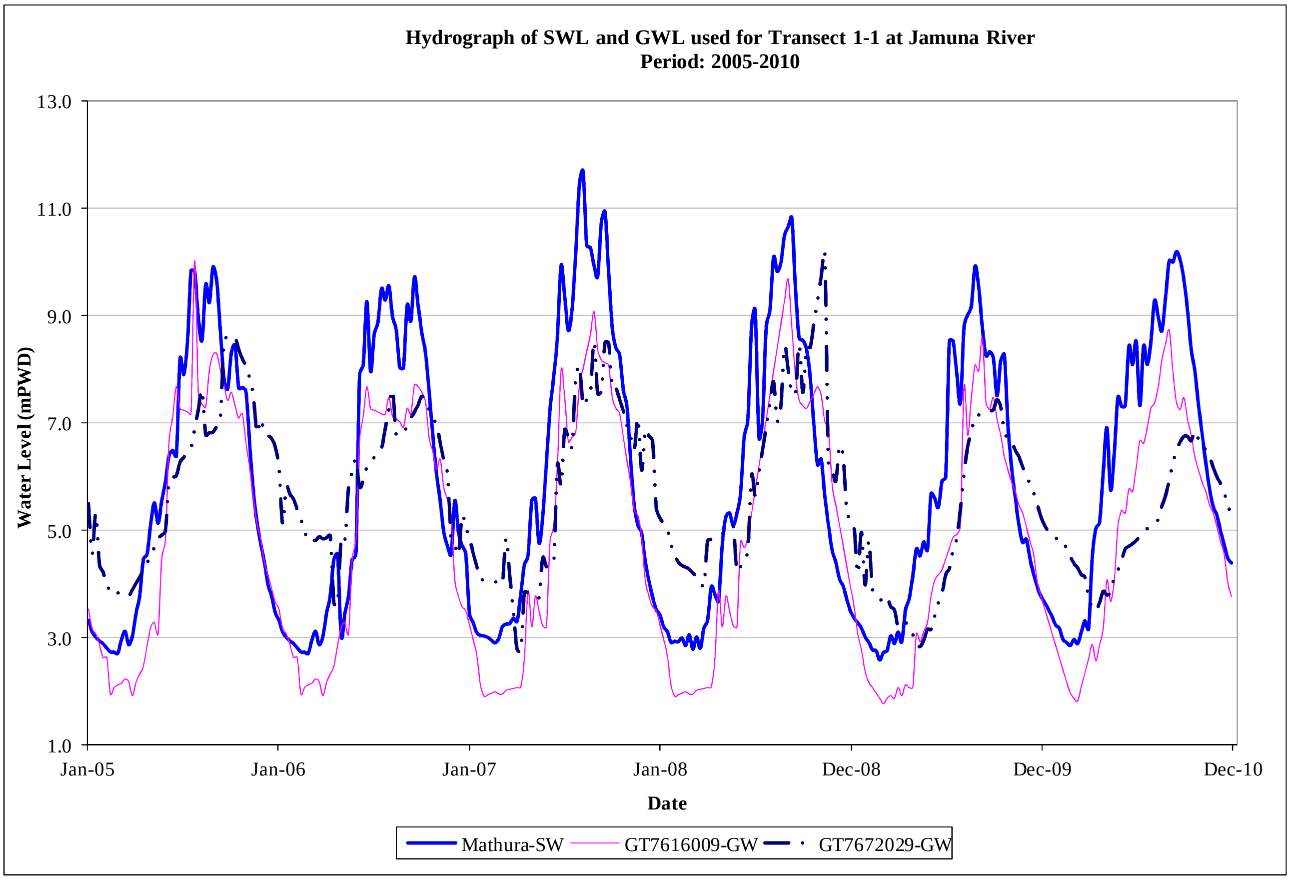
Jamuna-1 shows highly correlated surface and groundwater hydrographs. Assuming surface-water driven processes, a good fit can be obtained for a diffusivity of 50-100 times the default values.

The Teesta-2 gauging station shows little correlation between surface and groundwater hydrographs. The groundwater hydrograph rises in February, well before the surface water rise in May, with an amplitude approximately half that of the surface water. While the hydrographs suggest the sites could be disconnected, another explanation is that the barrage holds the surface water higher than the land surface and the groundwater hydrograph is rising to the land surface. Why it is rising in February before other areas is unclear.

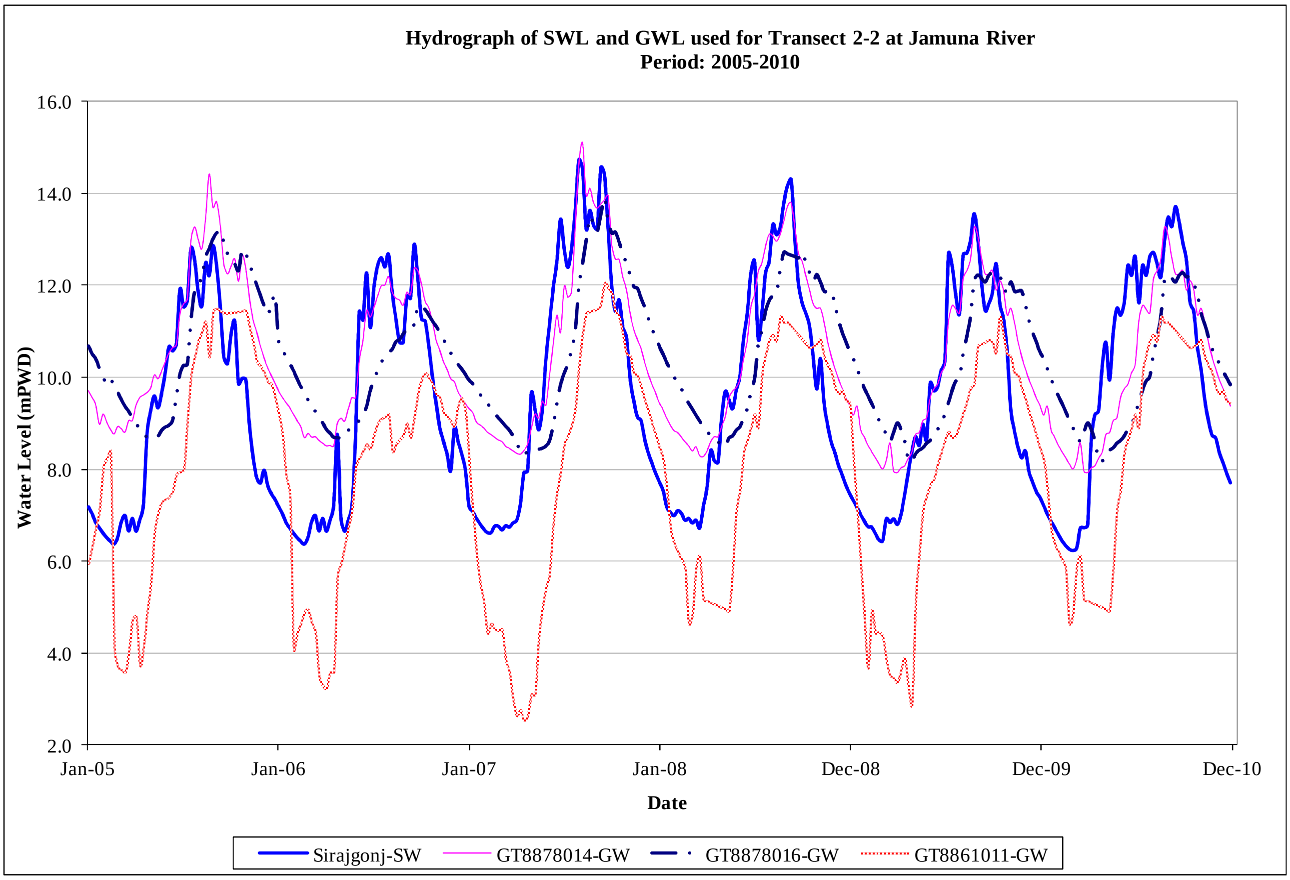
The other gaining sites, namely Bangali and Karatoya-2, show similar behaviour in that groundwater extraction appears to lower water tables into January, February and March. This is then followed by rapid rises in the June period in synchronicity with surface water rises.

The variably gaining-losing sites, namely Jamuna-4, Dharala-1 and Teesta-1 all show correlation between surface water and groundwater. Jamuna-4 can be modelled as surface-driven with a diffusivity ten times that of the default parameters.

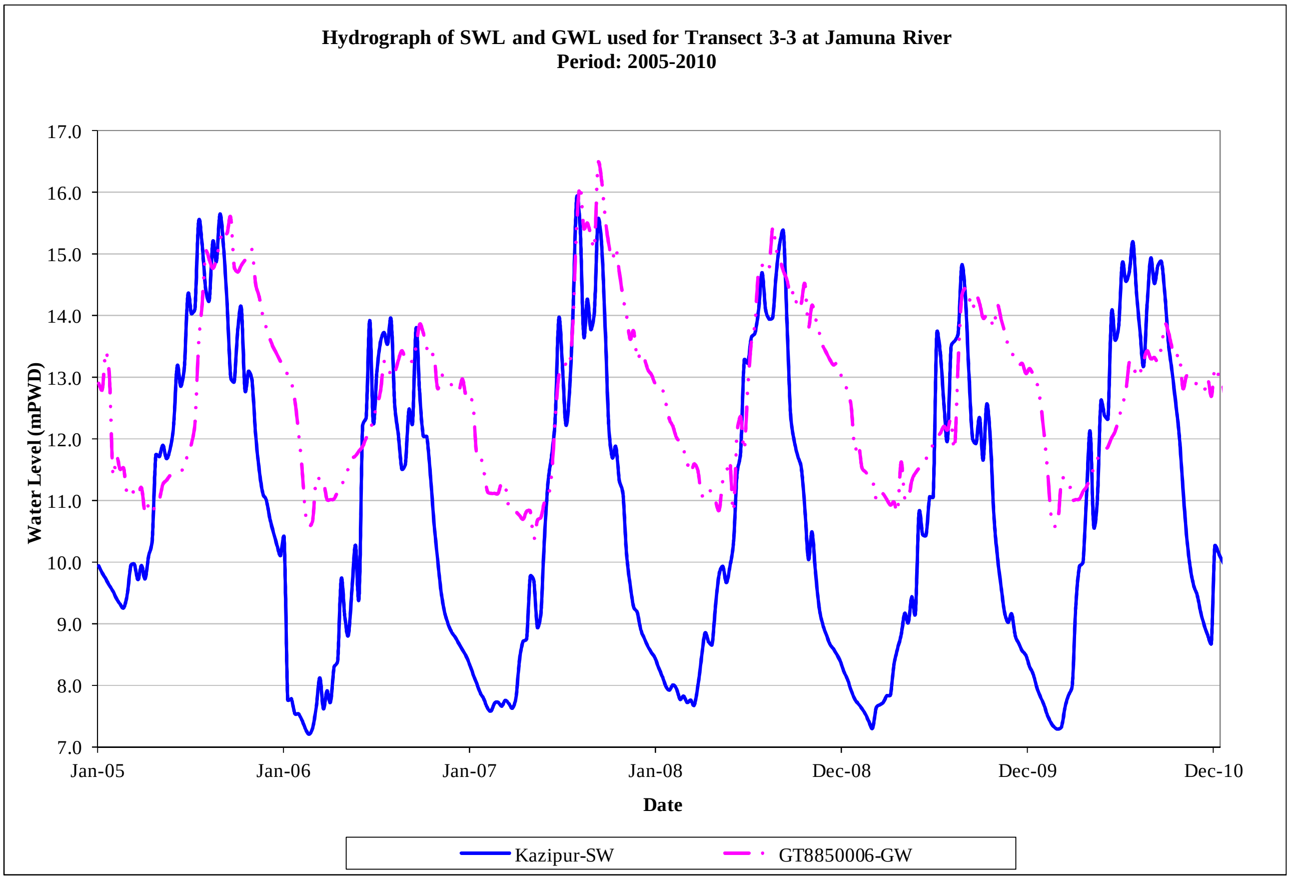
The monthly fluxes largely reflect the hydrographs. However, it should be noted that the fluxes are not always self-evident due to both the groundwater and surface water rising and falling at the same time or perhaps with a slight time difference. The annual fluxes appear to show some trends but there is no overall trend across the region, or even along the same rivers.


Hydrograph of SWL and GWL used for Transect 1-1 at Jamuna River
Period: 2005-2010
Water Level (mPWD)
13.0
11.0
9.0
7.0
5.0
3.0
1.0
Jan-05
Jan-06
Jan-07
Jan-08
Dec-08
Dec-09
Dec-10
Date
Mathura-SW
GT7616009-GW
GT7672029-GW

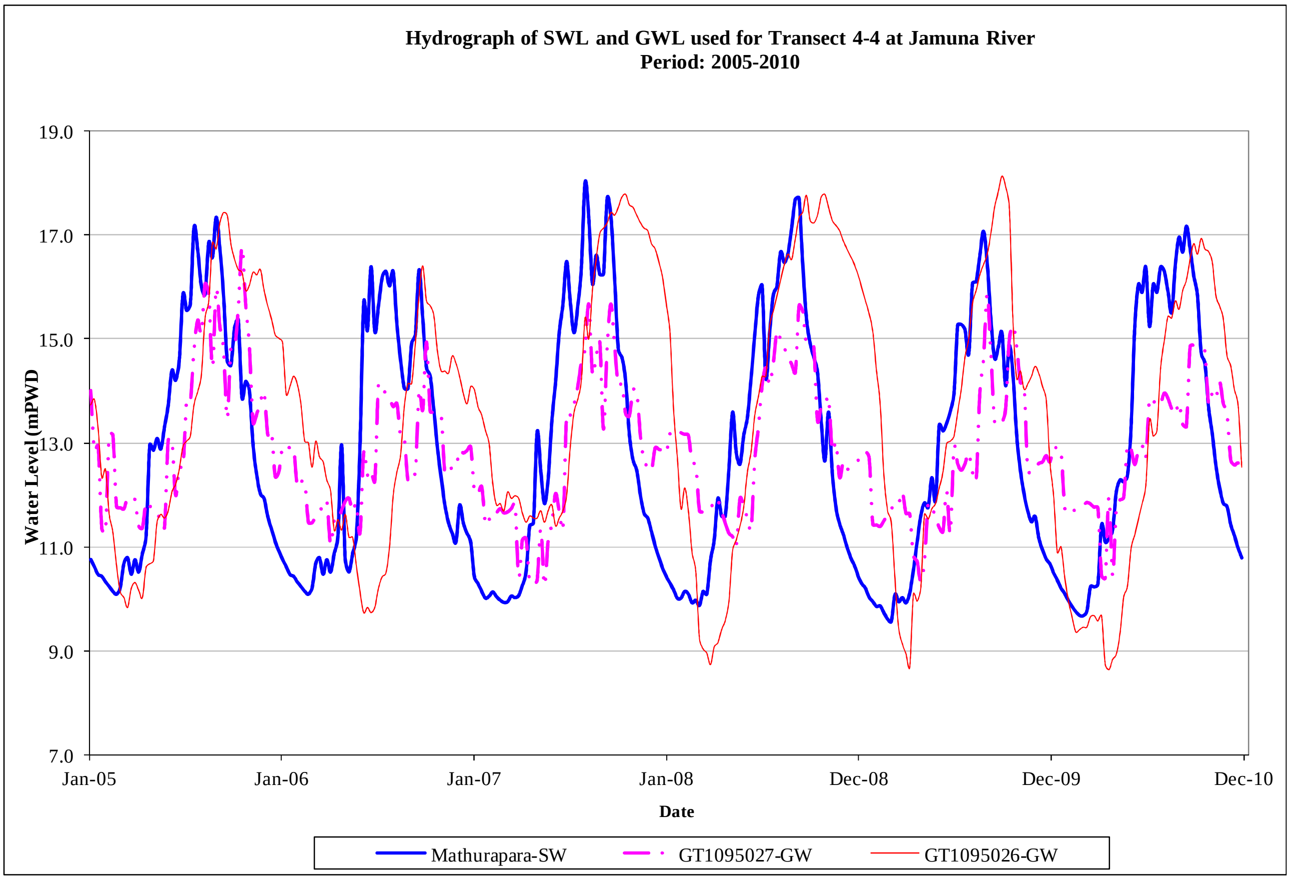
(a)


Hydrograph of SWL and GWL used for Transect 2-2 at Jamuna River
Period: 2005-2010
Water Level (mPWD)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
Jan-05
Jan-06
Jan-07
Jan-08
Dec-08
Dec-09
Dec-10
Date
Sirajgonj-SW
GT8878014-GW
GT8878016-GW
GT8861011-GW

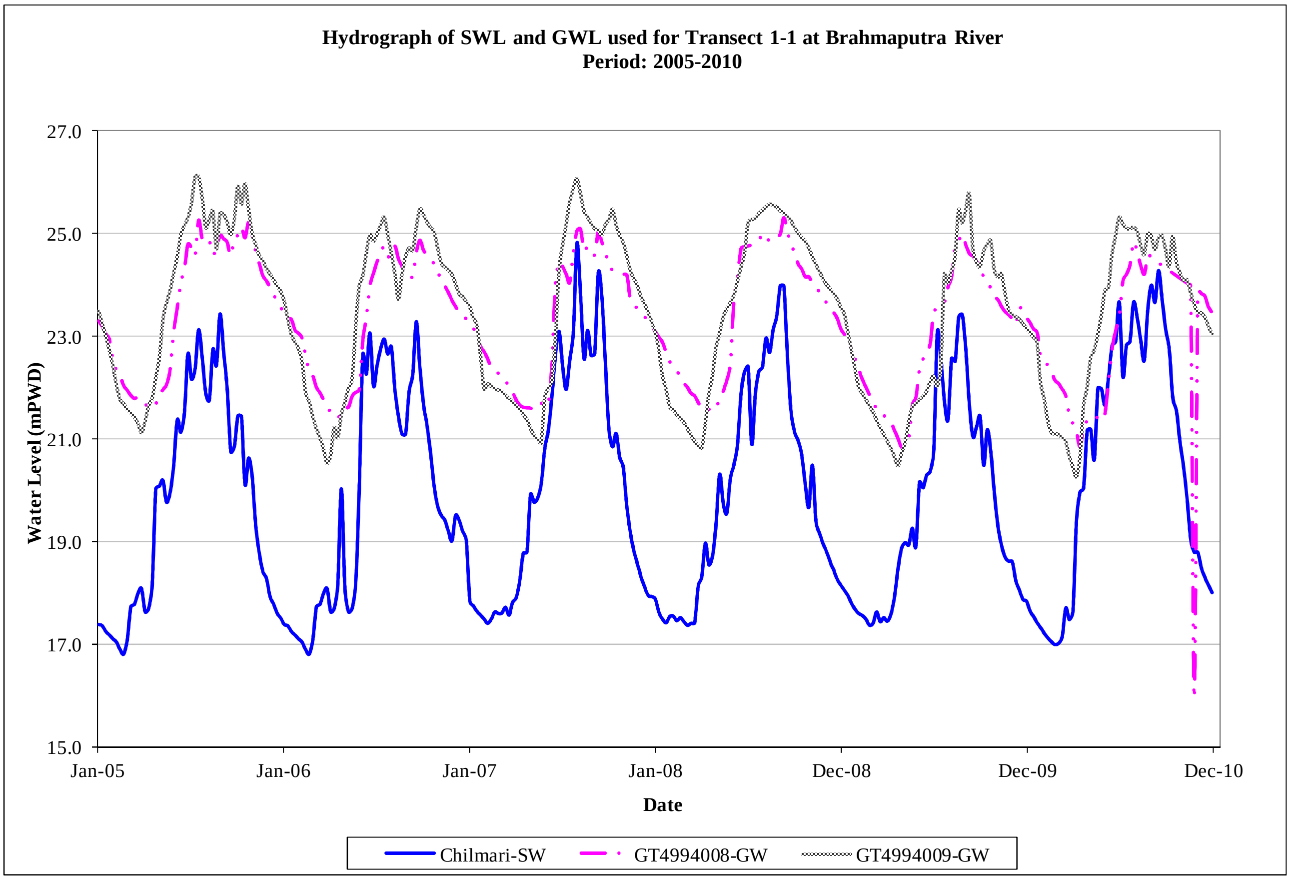
(b)


Hydrograph of SWL and GWL used for Transect 3-3 at Jamuna River
Period: 2005-2010
Water Level (mPWD)
17.0
16.0
15.0
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
Jan-05
Jan-06
Jan-07
Jan-08
Dec-08
Dec-09
Dec-10
Date
Kazipur-SW
GT8850006-GW

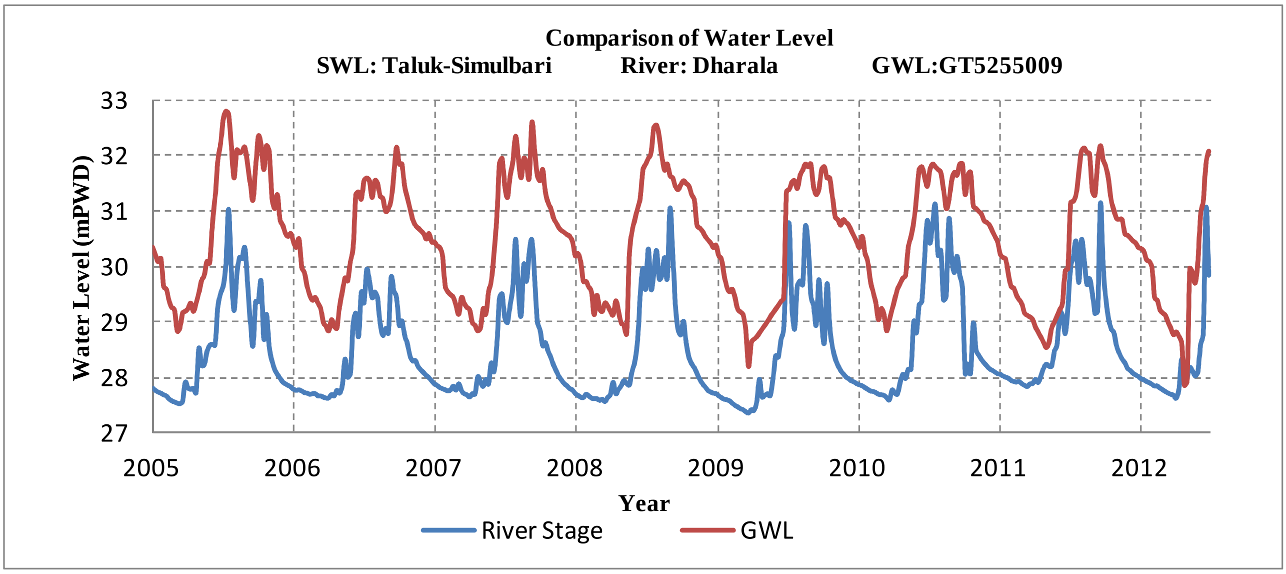
(c)


Hydrograph of SWL and GWL used for Transect 4-4 at Jamuna River
Period: 2005-2010
Water Level (mPWD
19.0
17.0
15.0
13.0
11.0
9.0
7.0
Jan-05
Jan-06
Jan-07
Jan-08
Dec-08
Dec-09
Dec-10
Date
Mathurapara-SW
GT1095027-GW
GT1095026-GW

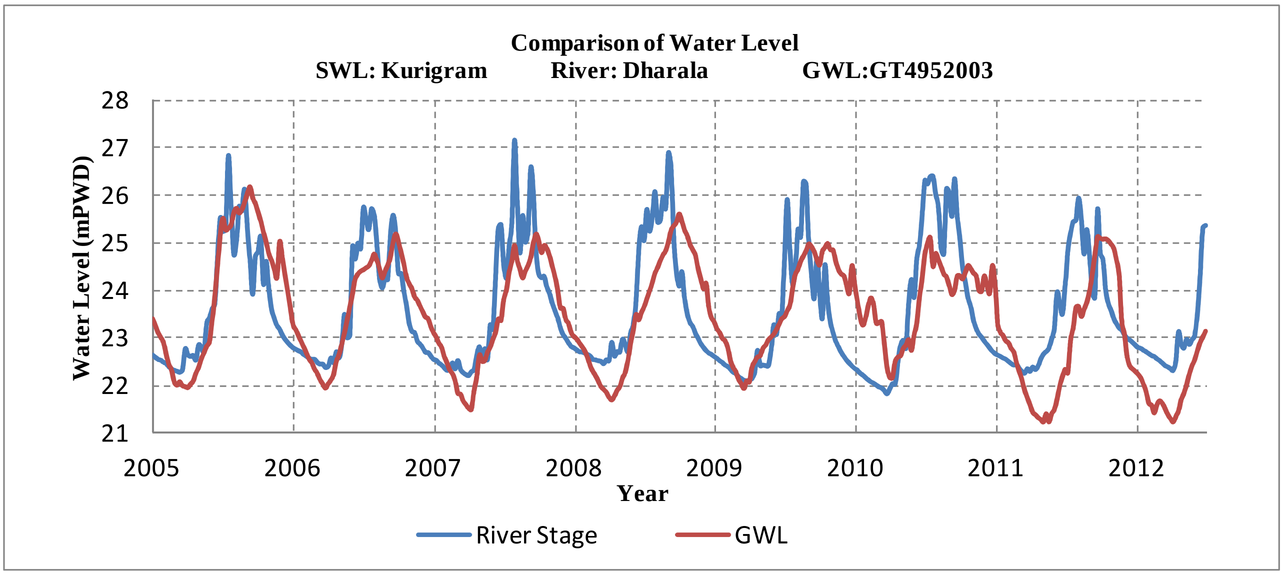
(d)


Hydrograph of SWL and GWL used for Transect 1-1 at Brahmaputra River
Period: 2005-2010
27.0
25.0
23.0
21.0
19.0
17.0
15.0
Water Level (mPWD)
Jan-05
Jan-06
Jan-07
Jan-08
Dec-08
Dec-09
Dec-10
Date
Chilmari-SW
GT4994008-GW
GT4994009-GW

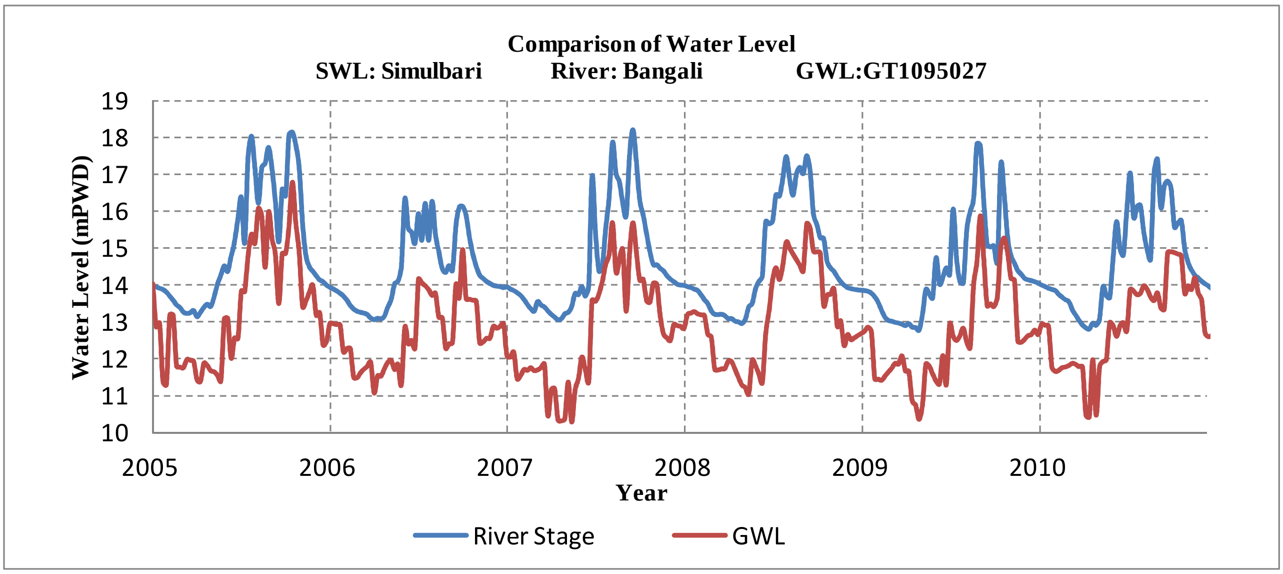
(e)


Comparison of Water Level
SWL: Taluk-Simulbari
River: Dharala
GWL:GT5255009
33
32
31
30
29
28
27
Water Level (mPWD)
2005
2006
2007
2008
2009
2010
2011
2012
Year
River Stage
GWL

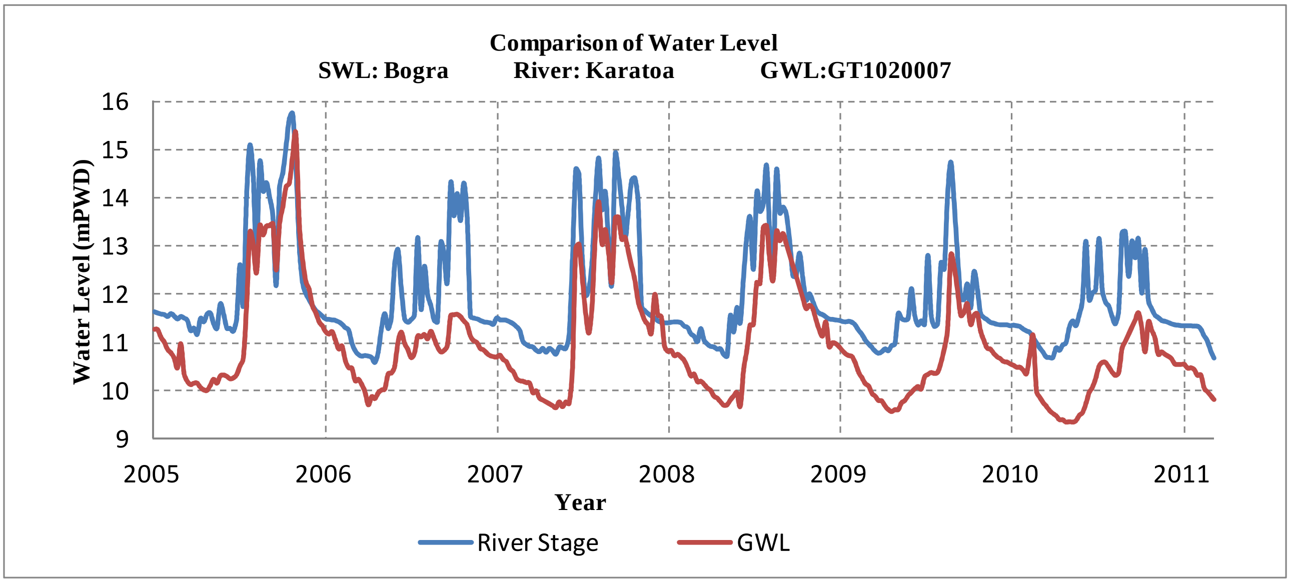
(f)


Comparison of Water Level
SWL: Kurigram
River: Dharala
GWL:GT4952003
Water Level (mPWD)
28
27
26
25
24
23
22
21
2005
2006
2007
2008
2009
2010
2011
2012
Year
River Stage
GWL

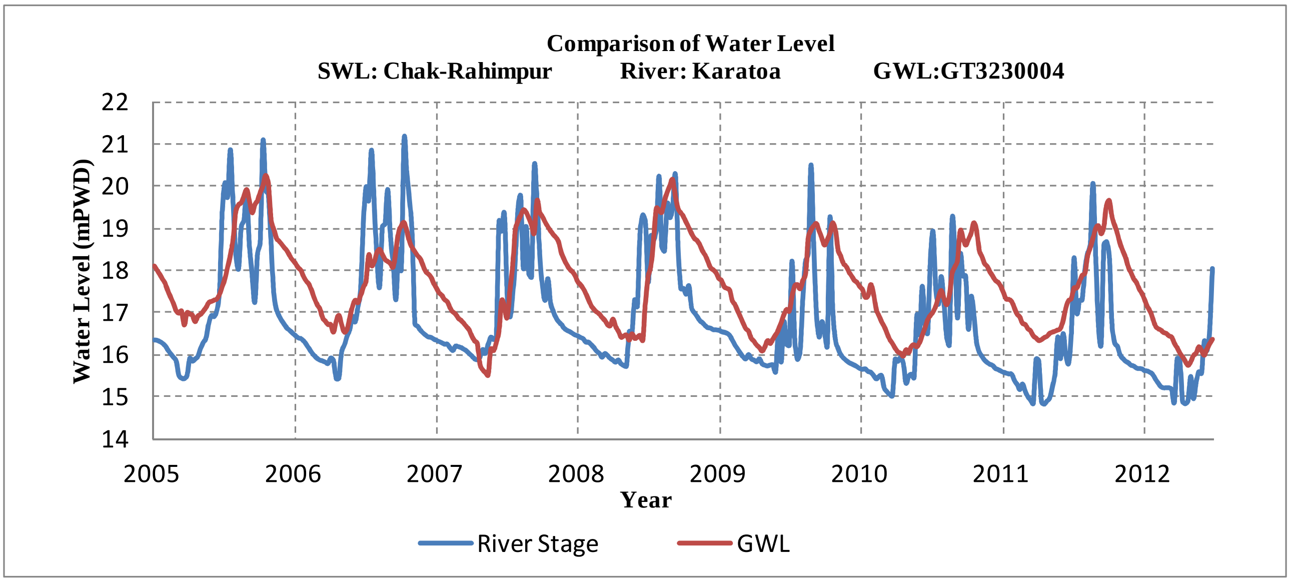
(g)


Comparison of Water Level
SWL: Simulbari
River: Bangali
GWL:GT1095027
Water Level (mPWD)
19
18
17
16
15
14
13
12
11
10
2005
2006
2007
2008
2009
2010
Year
River Stage
GWL

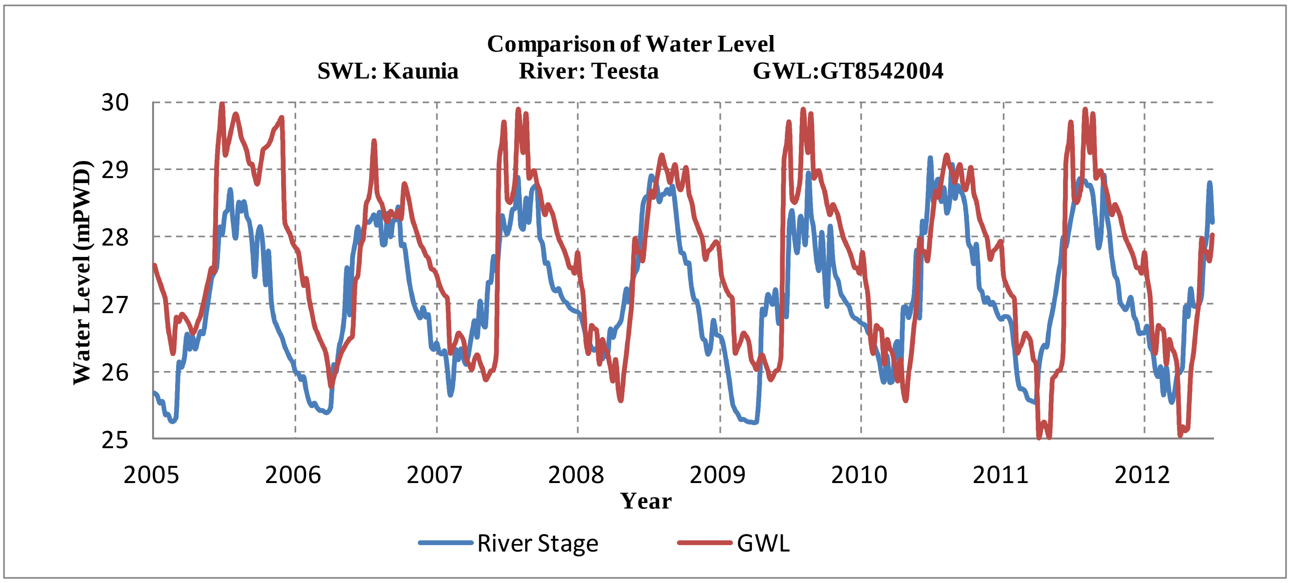
(h)


Comparison of Water Level
SWL: Bogra
River: Karatoa
GWL:GT1020007
Water Level (mPWD)
16
15
14
13
12
11
10
9
2005
2006
2007
2008
2009
2010
2011
Year
River Stage
GWL

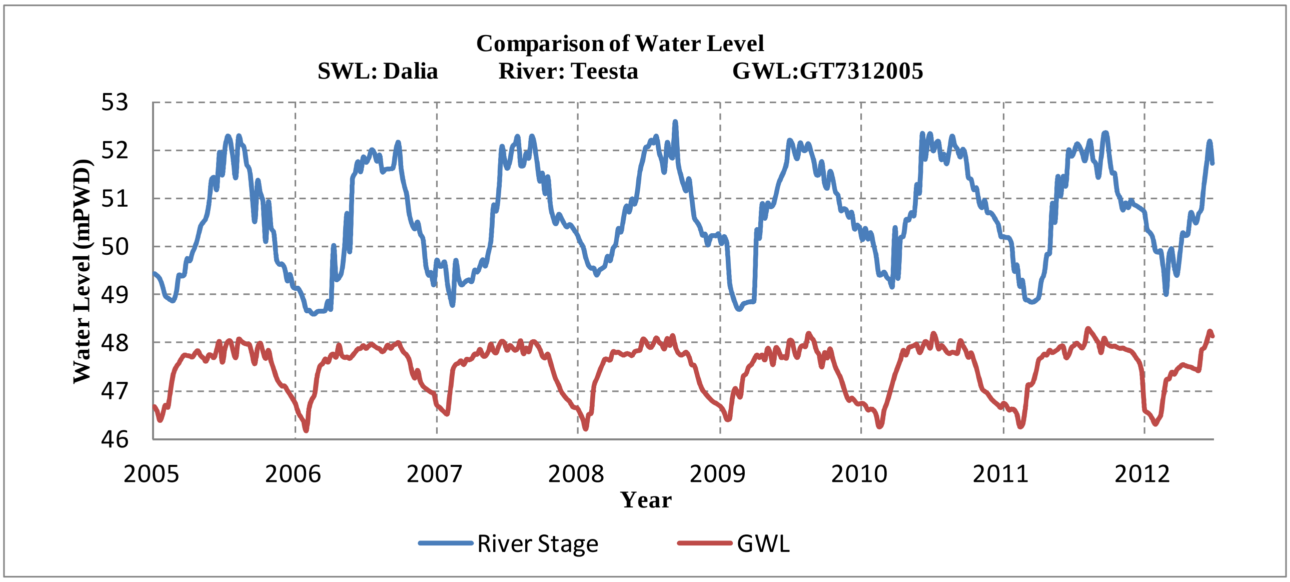
(i)


Comparison of Water Level
SWL: Chak-Rahimpur
River: Karatoa
GWL:GT3230004
Water Level (mPWD)
22
21
20
19
18
17
16
15
14
2005
2006
2007
2008
2009
2010
2011
2012
Year
River Stage
GWL

(j)


Comparison of Water Level
SWL: Kaunia
River: Teesta
GWL:GT8542004
Water Level (mPWD)
30
29
28
27
26
25
2005
2006
2007
2008
2009
2010
2011
2012
Year
River Stage
GWL

(k)



(l)

Figure 4.11 (a)-(l): Groundwater level and river stage for various transects: (a) Jamuna-1 (b) Jamuna-2 (c) Jamuna-3 (d) Jamuna-4 (e) Brahmaputra (f) Dharala-1 (g) Dharala-2 (h) Bangali (i) Karatoya-1 (j) Karatoya-2 (k) Teesta-1 (l) Teesta-2

4.5 Geochemical analysis

4.5.1 Introduction

The objective of this section is to conduct a preliminary analysis of existing geochemical data in the context of groundwater surface-water interactions. Geochemical analysis is important considering the impact of water quality on social, agricultural and drinking purposes. The analyses collated here were collected for other purposes under a range of projects for the Government of Bangladesh. Chemical analyses were done in the laboratory of Department of Public Health Engineering (DPHE) and BUET and included a wide range of analyses of major cations, anion, minor ions and trace elements conducted on the Inductively Coupled Plasma Spectroscopy (ICP) & Ion Chromatograph (IC). Only, the distributions of total dissolved solid and electrical conductivity are investigated here. Samples were collected in Rangpur, Bogra and Pabna. It is unclear what the depth of screening was for the samples, but thought to be 30-40m. An interpretation of analyses for consumptive uses can be found in (Hossain et al., 2010).

4.5.2 Conceptual model

As mentioned before, there are a number of nested groundwater flow systems operating in the northwest region. The deeper groundwater flow system goes from north to south. The mean residence time is likely to be thousands of years and hence the chemistry of the deeper system will reflect pre-development conditions. Given the high recharge rates, the expectation would be that the groundwater would be fresh. As water moves along the flowpath, there would be interactions with the matrix and also recharge of water to the deeper system. More often than not, this means that flow becomes more concentrated. Some of the deeper flow system will be sampled in the analyses described here.

At the opposite end of the spectrum, groundwater irrigation will lead to recycling of salts. These salts would have come from rainfall and interactions with the soil. As water is lost to evapotranspiration, salts will be concentrated. When the system is recharged by monsoonal rain, the salts are diluted. Some of the salts will shift from this recycling as it recharges the deeper, intermediate or local flow systems or moves to streams. Along the local and intermediate systems, there is the opportunity for this water (and salt) to be intercepted by tube wells and recycled again and then at the end of the flowpath to be concentrated by evapotranspiration. The shallow systems therefore represent more recent post-developmental conditions. Local and intermediate flow systems are affected by groundwater extraction and recharge rates may be decreased. Some of this shallow water will also be sampled in the analyses described here.

The impact of groundwater- surface water interactions will be mostly on the shallow systems. For many of the areas, groundwater moves mostly to streams and the chemistry may not change significantly, except to reflect the shorter residence times. However, as seen earlier, the groundwater extraction has meant that for parts of the landscape that water moves from streams to groundwater. Also, flooding can have a major role in recharge. One of the major features of the northwest region is the movement of both groundwater and surface water to the Atrai Depression and the regular flooding there.

4.5.3 Results

The data for both total dissolved solids (TDS) and electrical conductivity (EC) were collected for Rangpur, Bogra and Pabna districts by IWM for different projects. The distribution maps for TDS and EC are shown for these districts in Figure 4.12 and Figure 4.13 respectively. In broad terms, it can be seen that both TDS and EC are increasing from north to south, e.g the value in Bogra is higher than Rangpur and the value in Pabna is higher than in Bogra.

The Rangpur district contains the Teesta-1 site with the Karatoya-2 site slightly downstream. The Teesta forms the northern boundary and the various branches of the Karatoya cover the western region. It would be expected that the rivers drain the groundwater system from this region. However, we did note that the Teesta-1 site is variably gaining-losing and this may be related to changes in topographic gradient, with the Teesta-1 site being on a steeper part for the landscape not far above some flatter land.

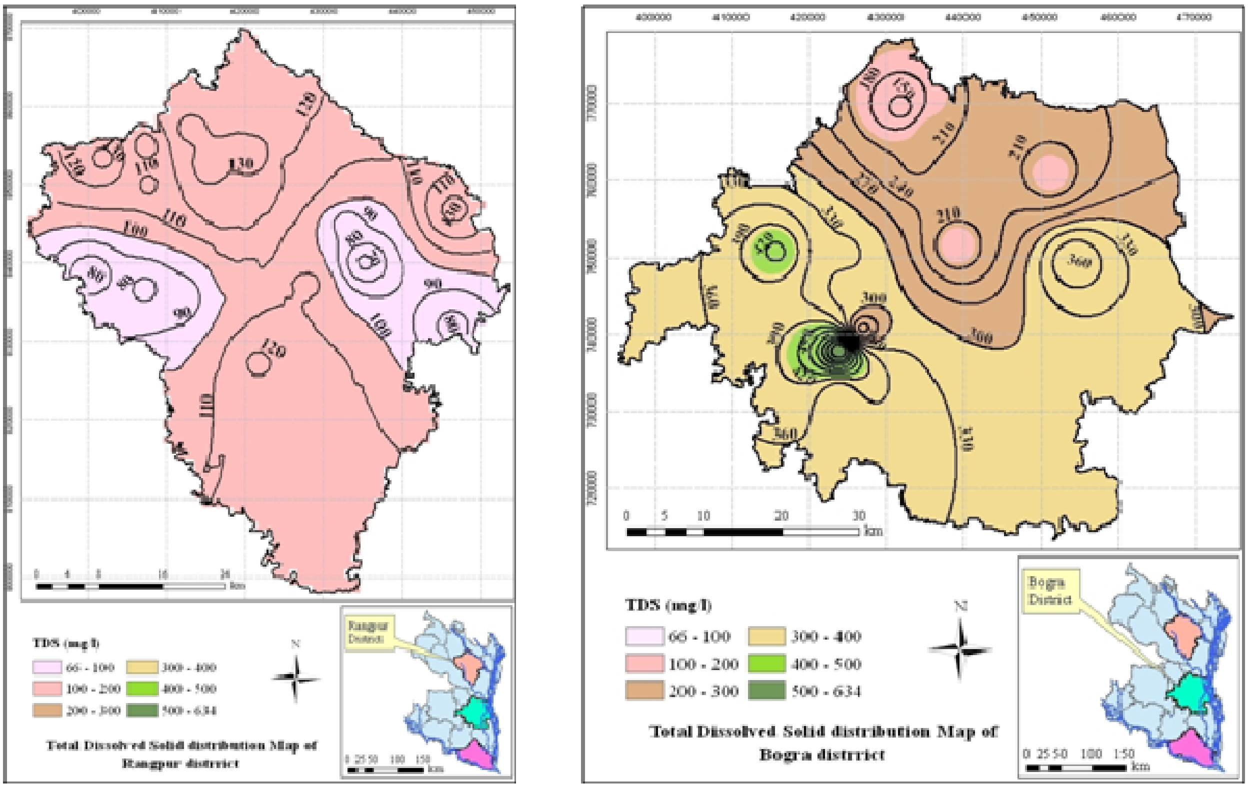
The map shows very fresh water generally throughout the district. The variation is relatively smaller, with perhaps the fresher areas being over-emphasised by the choice of colour range. The fresher water does not appear to coincide with the Teeesta-1 site, but appears to be related to the upper reaches of the Bangali and Karatoya Rivers. They may be coincident with changes in topography.

The Bogra district includes the Bangali and Karatoya-1 sites to the north and the centre of the region respectively. Both of these sites are sites where water flows from the surface water to the aquifer. The northern part of the district represents the interface between the sloping and flat land. The distribution map does show a trend from north to south with higher concentrations in the south. The fresher areas do appear to coincide with river water recharging aquifers, but this effect could also reflect changes in groundwater gradients. There is an increase in the EC towards the south-west, which could reflect higher net groundwater use (Figure 4.7).

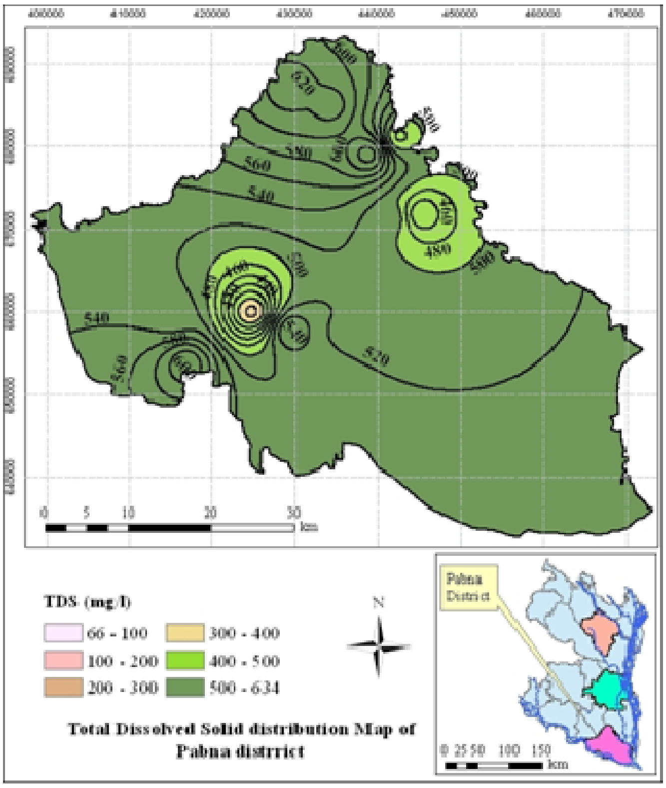
The Pabna district includes the Jamuna-1 site to the south-east. The region is covered by rivers and is regularly flooded. There are no obvious trends across the region, except for higher concentrations to the northwest. This may be associated with higher net groundwater use to the northwest (Figure 4.7). The lack of trends probably reflects the deep sampling and the relatively recent development of groundwater depressions in the dry season.

Overall, there is limited evidence of groundwater-surface water interactions. Perhaps, this should not have been expected given that many of the rivers drain the groundwater and any evidence would be in the river. The north of the Bogra region shows trends that would be consistent with aquifers gaining from streams. However, further sampling would be required to relate cause and effect. This would entail more care with depth of screens in any sampling and if possible, taking samples at more shallow depths. Because of the groundwater extraction, effects would be increasing with time and this may not be very evident in the current sampling.

Perhaps, more problematic is the salt balance for the southern districts such as Pabna. Clearly water is moving to these areas in the Atrai and if anything, the salt concentration should be higher than it is currently. Floods and monsoonal rains may provide some dilution and floods may remove some salt. Some better understanding of the salt balance of this region would seem worthwhile to project the future condition of this region.

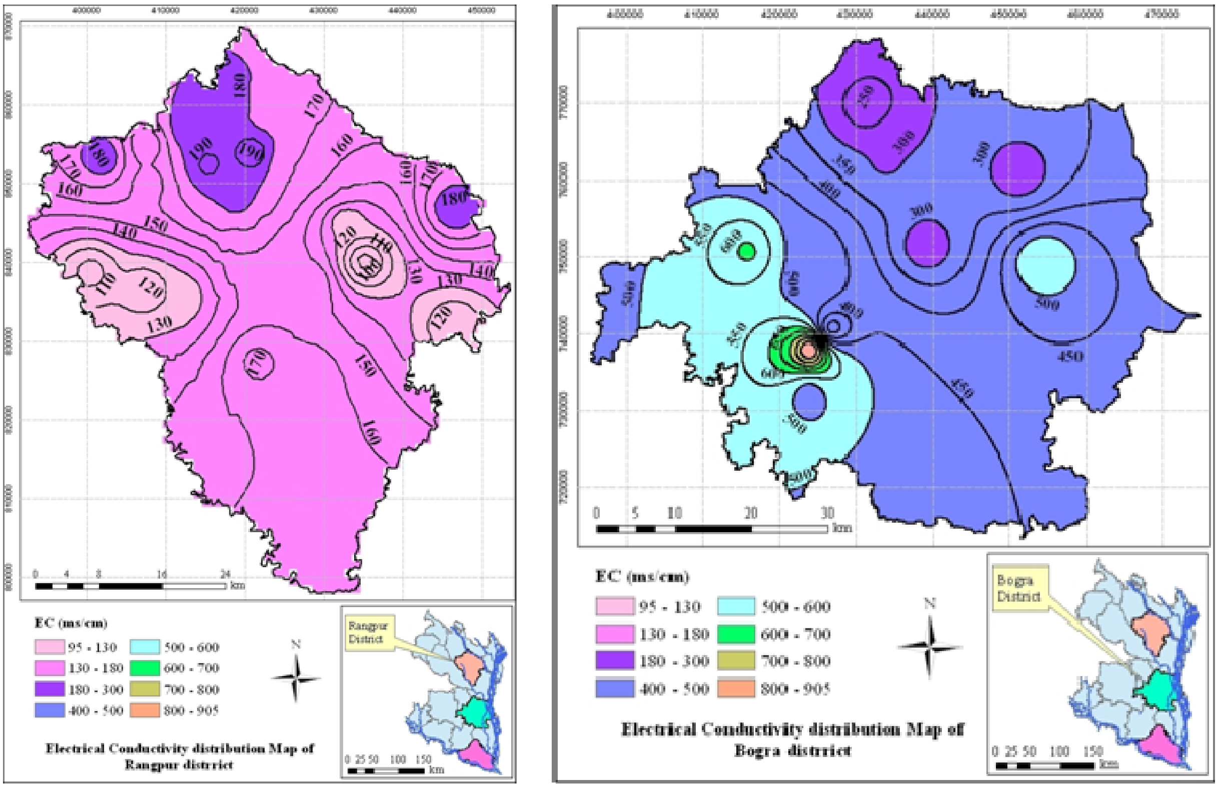


(a) (b)



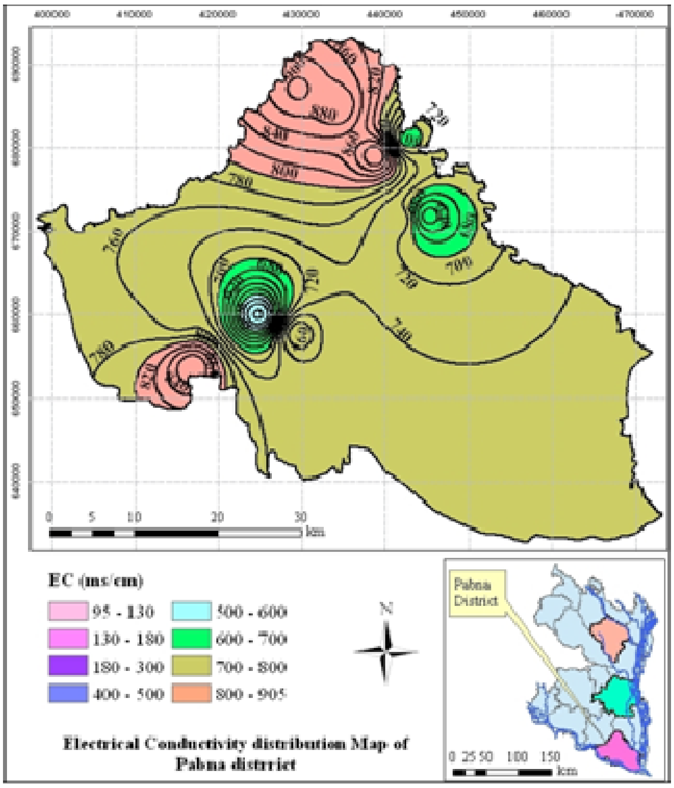
(c)

Figure 4.12 Total Dissolved Solid distribution in the (a) Rangpur, (b) Bogra and (c) Pabna Districts



(a)

(b)



(c)

Figure 4.13 Electrical Conductivity distribution in the (a) Rangpur, (b) Bogra and (c) Pabna Districts

4.6 Discussion

It is very easy to over-interpret results which come from a large region. There are often a range of influences, so that each site may in some ways be unique.

Nonetheless, it is clear that for most of the region and for most of the year, groundwater follows topographic gradients. Towards the beginning of the monsoon season groundwater pumping modified this behaviour in the Atrai Basin. It is likely that under natural conditions, most rivers will drain the groundwater i.e. the aquifers are losing. The effect of pumping has been to lower water tables so that in flatter areas, water flows from rivers to the aquifers i.e. rivers have become losers.

Apart from Teesta-2, which supplies a surface water irrigation district, the surface water and groundwater rise at about the same time, and in many cases, fall at the same time. There are also many sites in which the groundwater falls more slowly than the surface water. There are likely to many influences of which the surface water is just one. It is known that vertical processes, rainfall, extraction and irrigation dominate groundwater systems. In the vicinity of streams, water tables are likely to be influenced by both processes. Where piezometers are close to the river, and transmissivity is high, the surface water fluctuations are likely to have a greater effect on water tables. Where rivers meet, the groundwater near the junction will reflect the river levels, leading to a situation in which there will be variably losing and gaining, or if there is also groundwater extraction, a gaining aquifer.

The influence of the river is likely to extend to a few kilometres. For the Jamuna, the groundwater divide is between 2 and 6 kilometres from the river, with the groundwater draining to the river, but further away moving away from the river.

The estimates of groundwater-surface water exchange fluxes are somewhat smaller than estimates from the regional water balance and some Mike-SHE modelling from the Bangladesh Integrated Water Resources Assessment project. However, it is consistent with other modelling results, and the re-calibrated regional water balance in this project (Chapter 3) is also more consistent with the results described here. It is feasible that for many of the sites, the estimated flux is representative of the regional groundwater flow rather than the exchange with the river. Also, the estimated transmissivity represents regional values and that in the vicinity of major rivers such as the Brahmaputra and Jamuna it may be higher. This is supported from some modelling of the surface and groundwater fluxes. It is also feasible that the flux has been under-estimated because only the bigger rivers were considered. Finally, the impact of extraction on surface water fluxes has not been estimated in this analysis. Nonetheless, when taken with all of the studies done, the total exchange with surface water for the region is likely to be dwarfed by other fluxes.

4.7 Conclusions

1. Historically, the rivers have acted as drains for the groundwater systems of the northwest region, with water moving from the groundwater systems to the rivers.
2. As groundwater extraction has increased, this has resulted in the following changes:
   - Groundwater levels have fallen in the pre-monsoon period and this has meant a shift towards less groundwater moving to streams and more water moving from streams back into aquifers, for irrigation;
   - More water infiltrating groundwater systems through the land surface, with a probable reduction in surface run-off and reduced return flow to streams.
3. Even so, aquifers are losing water to most major streams. The exceptions appear to be above junctions of major rivers and/or in areas where landscape is flattening.
4. The influence of the streams on the groundwater appears to be constrained to within a few kilometres of the stream. For the Jamuna, this means that there is a groundwater divide, from which the groundwater flows to the west towards the Atrai Basin and to the east towards the Jamuna. Just above the junction with the Ganges, this reverses so that to the groundwater flows from the Jamuna to the east. However, the average flow further away from the Jamuna is reversed and flows back to the river. For the Brahmaputra, the river intercepts the regional groundwater flow to the south-east.
5. The total surface water-groundwater fluxes for the northwest region appear to be smaller than previously thought. Some of the estimates here may be lower than reality for a range of reasons, but when taken together with other studies, the estimates are not likely to be more than 20 BCM/yr.

5 Econometric assessment on livelihood outcome

Contributors: Iffat Ara, Jeff Connor, Bertram Ostendorf, John Kandulu

5.1 Introduction

Groundwater in the northwest and north-central regions is critical to the food security of Bangladesh (Chapter 2), and yet there are concerns over its sustainable use (Chapters 2, 3 and 4). The preceding chapters focus on the hydrological and agricultural issues, but there are also socio-economic dimensions to water use and sustainability.

Agriculture, and therefore irrigation, is important in providing 60 percent of rural employment (BBS, 2012). Groundwater levels in the dry season can fall below the level accessible by shallow tubewells and hand dug wells and ponds, which can leave households without drinking water and farmers without irrigation water for critical periods, as noted in Chapter 3. The northwest region does not suffer as much from large floods compared as other parts of the country. However, smaller floods are common in some areas, and flash floods are common in some of the areas in northern part of northwest (Brammer, 1999). The region has a high incidence of health related and social problems, as well as reduced food intake and malnutrition impacting the livelihoods of underprivileged groups, including landless labourers and especially women, children and aged people in northwest region (Mbugua, 2011; Karim et al., 2012; Meinzen-Dick and Zwarteveen, 1998; Koppen and Mahmud, 1995). The northern part of northwest region is affected by the recurrent “Monga’ (local low food security) because of seasonal unemployment of agricultural day labourers and disadvantaged socio-economic groups for a specific period in every year (Elahi and Ara, 2008; Zug, 2006).

The present study covers the northwest region of Bangladesh including 16 districts which represent a major source of national food production (Dey et al., 2013 and Chapter 2). In this chapter, we outline an evaluation of the hypothesis that declining groundwater may impact on prospects for betterment of the livelihood of households in northwest region of Bangladesh.

Understanding livelihood impacts of groundwater changes is challenging because many aspects of spatial setting, household character, and broad economic drivers affect livelihoods. Whilst there have been some isolated and anecdotal evaluations of groundwater impacts on livelihoods, we are not aware of any investigation that features evaluation of how spatially heterogeneous biophysical characteristics including groundwater access as well as household character influence livelihood outcomes like income and nutrition. Against this backdrop the objectives of this analysis are to 1) to understand the extent to which household livelihood assets (including human, social and capital characteristics) interact with biophysical geography to determine household income and nutrition outcomes; 2) to analyse the impact of biophysical attributes related to water and measures related to water management may limit on income and food consumption at household level; 3) to indicate future research prospects at different spatial and household levels to further evaluate these relationships.

This work provides a unique perspective by combining household survey data including detailed inventories of household physical, financial, human, social capital with geographic information characterizing bio-physical resources that may support or limit household livelihood outcomes. The data includes detailed household level income and food consumption measures that provide a basis to relate variations in these important livelihood outcomes to variations observed in household resources and characteristics of the biophysical setting of the regions in which households are located with special focus on how groundwater may influence household livelihoods in northwest region.

5.2 Methods and data

The study presents a statistical (multiple linear regressions) assessment of the influence of household: human, financial, and social assets and water related bio-physical and management factors as natural capital on household level income and food consumption in the northwest region of Bangladesh.

5.2.1 Study area

The study area comprises 16 *zilla* (district) of northwest region (Figure 5.1). The area is bounded by the Jamuna to the east and the Ganges to the south. In addition, the area has an international border between Bangladesh and India to the north and west. As noted in earlier chapters, the region is one the driest part of Bangladesh. Droughts in the region (noted in Chapter 3) have had a severe impact on regional livelihoods.

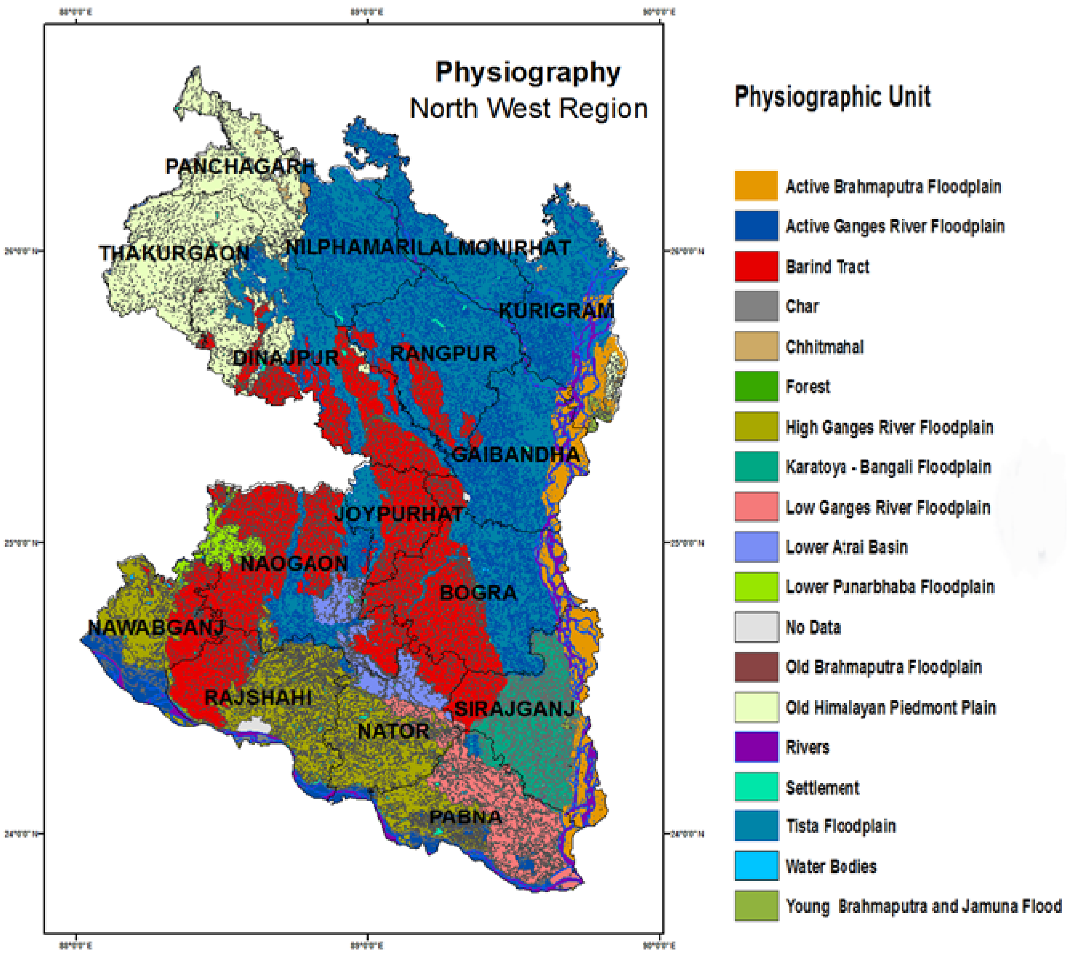


Figure 5.1 Location of study area including physiography and location of Barind Tract in northwest region, indicating the 16 *zillas* studied

5.2.2 Data

Our primary dataset is the 2010 Bangladesh Household Income and Expenditure Survey (HIES) which provides information on household demographic characteristics, income, health, education, assets, employment, and exposure to natural disasters such as flood and drought, for over 12,000 households (BBS 2010). For a sub-sample of surveyed household food consumption is carefully inventoried allowing a calculation of household calorie intake. The national sample of over 12,000 is stratified geographically. Whilst, the survey data doesn't allow exact geo-referencing of households it does identify the *zilla* (district) and *upazilla* (sub-district) in which they are located. We chose household income and food consumption as indicators of household wellbeing for our dependent variables. We then identified a set of additional survey variables that measure various forms of natural, social, financial, human, and physical capital as explanatory variables from income and food consumption outcomes as summarized in Table 5.1 and explained in more detail below.

In addition to HIES data, GIS information from a number of sources was compiled to characterize *zilla* biophysical characteristics that may influence household livelihood outcomes. This includes measures of the extent and depth of land inundation during major flood events; proportion of area influenced by water scarcity under severe drought conditions, proportion of net cultivatable area irrigated; proportion of groundwater irrigation and ratio of area supplied with water from DTW to provide water without STW. More detail on these variables is provided below.

Household survey data

The present study used latest (2010) HIES data which was a collaborative effort of the Bangladesh Bureau of Statistics (BBS) and the World Bank. This current issue HIES provides some new information on: micro-credit, migration, remittance, disability, disaster management, social safety net which are useful in understanding household assets that contribute to household livelihood outcomes.

The 2010 survey featured a two-stage sample design involving a systematic selection procedure with 612 Primary Sampling Units (PSU) from 16 strata (BBS, 2010). The total sample size was 12,240 households including 7,840 from rural area and 4,400 from urban area (World Bank and BBS, 2010).

Variables that taken from HIES for present study are described in Table 5.1. This includes the name, mean, minimum, and maximum and standard deviation values of each variable. The table also indicates which variables are used for each of the two separate (income and calorie consumption) regression exercises.

Zilla biophysical data

Zilla biophysical data was collected from different sources. GIS information on extent and depth of land inundation during major flood events was collected from Centre for Environmental and Geographic Information Services (CEGIS, 2009). The proportion of net cultivatable area irrigated, proportion of groundwater irrigation and ratio of area under DTW and STW were taken from BADC (2010). The proportion of net cultivatable area irrigated was calculated as percentage of the total area under irrigation and the net cultivable area in each district in 2010. On the other hand, the proportion of groundwater irrigation was considered as the percentage of the total area irrigated by groundwater to the total area irrigated (by both surface water and groundwater) for same year. Ratio of area under DTW and STW is calculated through simply divide those by each other.

Proportion of area under severe drought for each district was collected from BCA data (BCA, 2004). GIS techniques were used to assemble drought data as per 64 *zillas* (districts) of Bangladesh for three significant seasons within a year (e.g. pre-*kharif*, *Kharif* and *Rabi*) and then calculated as the percentage of the total area of each district for the category of area under different magnitude of drought condition (e.g. severe, moderate, low and no drought). This analysis considers only the proportion of area under severe drought as natural capital. For this, we calculated average area under severe drought for three seasons of a year.

The present study divided northwest region into three sub-regions which used as dummy variable for further analysis as Barind Tract (bt), northern part of northwest (nnw) and southern part of northwest (snw). Spatial extent of these sub-regions is presented in Table 5.2.

Table 5.1 Data description and summary statistics

Variable definition	Mean	Standard deviation	Min	Max	Included in income regression	Included in food consumption regression
Dependent variables						
Log of household income from all sources	11.10	1.04	2.197225	15.02422		
Average household food calories consumed per capita per day	2441.37	807.11	802.9092	6851.027		
Financial capital						
Household remittances from overseas	13529.94	80777.46	0	1000000	√	
Proportion of household members with paid employment	0.31	0.19	0	1	√	√
Proportion household with paid employment working in agriculture	0.39	0.44	0	1	√	√
Proportion household with paid employment working as agricultural day labour	0.15	0.32	0	1	√	
Taka value of all household credit	12555.18	80033.32	0	2600000	√	√
Average interest rate on all household loans	10.88	34.68	0	360	√	√
Human capital						
Proportion of household reporting chronic illness	0.17	0.23	0	1	√	
Proportion reporting untreated illness	0.02	0.09	0	1	√	
Head of household years of formal education	3.71	4.47	0	19	√	√
Households with female head as binary variable	0.08	0.28	0	1	√	√
Physical capital						√
Taka value of household crop production for own consumption	3978.63	12260.26	0	652180		√
Taka value of household fish production for own consumption	2014.41	19132.10	0	655040		√
Taka value of household livestock production for own consumption	2062.68	9127.63	0	200000		√
Area of agricultural land operated	64.44	125.57	0	2090	√	√
Natural capital						
Major flooding: District area proportion inundated deeper than 360 cm	0.12	0.13	0	0.48799	√	
Household flooding: binary variable reporting exposure to flood	0.02	0.15	0	1	√	√
Household drought: binary variable reporting exposure to drought	0.03	0.18	0	1	√	√
Proportion of *zilla* area under severe drought	3.68	5.24	0	15.77	√	√
Proportion of net cultivable area irrigated	0.81	0.18	0.44	1.16	√	√
Proportion of ground water irrigation	0.97	0.05	0.77	1	√	√
Ration of Deep Tube Well (DTW) area to Shallow Tube Well (STW) area	0.38	0.46	0.02	1.42	√	√
Social capital						
Proportion of household members receiving social safety net assistance	0.08	0.17	0	1	√	√
Interaction terms						
Major flooding* area of agricultural land operated	8.09	24.96	0	487.502	√	√
Major flooding * proportion of people working in agriculture	0.05	0.10	0	0.48799	√	√

Source: Calculated by author's from (HIES, 2010); (BBS, 2011); (BCA, 2004) and (CEGIS, 2009) data

Table 5.2 Distribution of *zillas* as per regions of present study

Zila	Region
DINAJPUR	Barind Tract (bt)
JOYPURHAT	Barind Tract (bt)
BOGRA	Barind Tract (bt)
NAOGAON	Barind Tract (bt)
RAJSHAHI	Barind Tract (bt)
NAWABGANJ	Barind Tract (bt)
PANCHAGARH	North of Northwest (nnw)
NILPHAMARI	North of Northwest (nnw)
LALMONIRHAT	North of Northwest (nnw)
GAIBANDHA	North of Northwest (nnw)
KURIGRAM	North of Northwest (nnw)
RANGPUR	North of Northwest (nnw)
THAKURGAON	North of Northwest (nnw)
NATOR	South of Northwest (snw)
PABNA	South of Northwest (snw)
SIRAJGANJ	South of Northwest (snw)

Regression model

We estimated two regression models. One model (equation 1) estimated household average per capita calorie intake as a function of household human, financial, social, and physical capital (see Table 5.1 for included explanatory variables). A second model (equation 2) estimated household income level as function of household human, financial, social, and physical capital (see Table 5.1 for included explanatory variables). We tested alternative functional forms for the dependent variable in both our income and food consumption regressions and found a log income and linear food consumption form to best fit the data[1]. We also tested several forms of interaction variables[2] and chose to include two interaction terms: 1) proportion of area within a district subject to inundation greater than 180 cm in major flood multiplied by the proportion of household workforce employed in agriculture; 2) proportion of area within a district subject to inundation greater than 180 cm in major flood multiplied by the area of agricultural land operated by a household.

Finally, we included *zilla*'s as fixed effects variables in all regression equations. These account for possible difference across *zilla*'s that may result from unobserved regional heterogeneity related to explanatory variables omitted in the equations. Possible omitted regional differences include:

---

[1] We tested additional useful form for dependent and explanatory variables using the gladder procedure which examines a subset of the ladder of powers (Tukey, 1977) for a conversion that best transforms each variable to a normal distribution.

[2] There were two considerations in interaction term selection, improvement in explanatory power, and avoiding creation of variables that were highly correlated with one another, the former was tested through F-test comparison of model explanatory power with and without interactions terms, the latter was tested through computation of variance inflation factors (VIF) and exclusion of interactions with large VIF (greater than 10) as recommended by Kennedy (2008).

quality of land; physical capital investment differences such as differences in infrastructure, and distances to market. Dummy regional variables for each sub-region (nnw, snw) and Barind Tract (bt) in the middle of northwest region (Figure 5.1) were thus used to account for any regional effects associated with omitted variables that are possibly correlated with the explanatory variable that are included. Thus, consumption model and the income model were:

$$Consumption \ = \ \alpha_0 \ + \ \alpha_1 \, x_{1i} \ + \ \ \alpha_2 \, x_{2i} + \ \alpha_3 \, x_{3i} \ldots \ldots \ldots \ldots . \ \alpha_{kn} \, i_{ki} + \ \alpha_{ri} \, region_{\,r} + \ \varepsilon_i \qquad (1)$$

$$Income \ = \ \beta_0 \ + \ \beta_1 \, x_{1j} \ + \ \ \beta_2 \, x_{2j} + \ \beta_3 \, x_{3j} + \cdots \ldots \ldots . \ \beta_{kn} \, i_{kj} + \ \beta_{ri} region_{\,r} + \ \varepsilon_j \qquad (2)$$

where, α_0, β_0 represents intercepts of the regressions, α_1 , .., α_n and β_1 , .., β_n represent marginal effect coefficients, x_{1i},…, x_{ni} and x_{1j},…, x_{nj} nclude different household and z*illa* biophysical variables for both income and consumption model, ε_i and ε_j are regression error terms, *k* is index of *zilla* (i_{ki} and i_{kj} are an indicator variables with value one for *zilla* k where household i or j is located within the 16 *zillas* in northwest) and region dummy variables $region_{\,r}$ are also included for three sub-regions into which we divide the whole northwest region.

5.3 Regression results and discussion

5.3.1 Per capita calorie consumption regression results

Overall the per capita kilocalorie consumption regression (Table 5.3) had moderate explanatory power with an R^2 value of 0.26. On average, across all households and household members, per capita food consumption equates to 2441 kilocalories per person per day. Eight of eighteen included explanatory variables were statistically significant in explaining variation across households in calorie consumption.

Figure 5.2 reports on the marginal per capita kilocalorie impact of a one standard deviation greater than the sample mean value for each of the eight variables found to be statistically significant in the calorie regression. Key findings are:

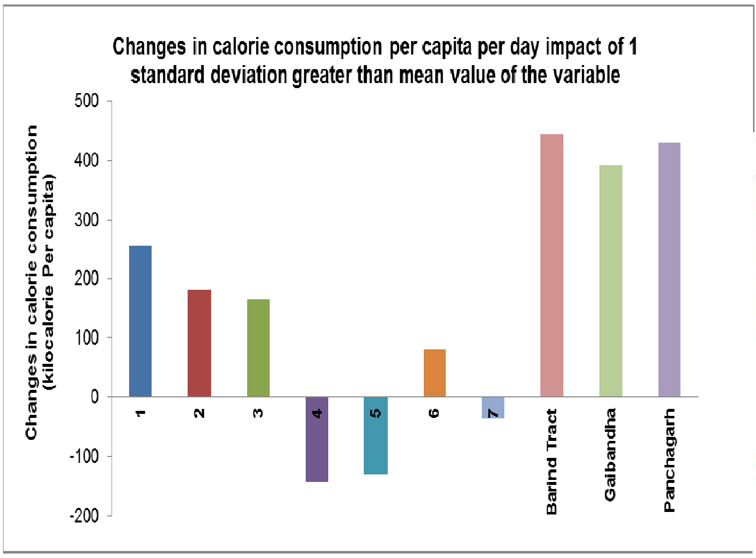
- Four of eight statistically significant effects are from forms of financial capital. As can be seen in Table 5.3 four elements of financial capital are statistically significant determinants of variation in household nutrition outcome.
- Households with a higher proportion of employed members and a higher proportion of people in agriculture activities enjoy better nutritional outcomes.
- Higher proportion of employed member at household level also has positive impact on nutritional outcomes at national level as confirmed by earlier research (Thorne-Lyman et al., 2010).
- Households with more of their working members relying on agricultural day labour have worse nutritional outcomes, also confirmed by earlier research (Abdullah, 1989; Thorne-Lyman et al., 2010).
- Physical capital in the form of access to land and fisheries are also important determinants of household calorie outcomes

- Access to fisheries is an especially important determinant of household consumption. Households with one standard deviation above mean own caught fish consumption, for example, achieve additional 256 per capita kilocalorie consumption on average (Figure 5.2). Previous result indicated that inland fisheries positively influenced nutritional as well as livelihood outcomes in Bangladesh (Thompson et al. 2002).
- Households with one standard deviation above mean agricultural land holding enjoy an extra 82 per capita kilocalorie consumption (Figure 5.2),which confirms evidence from earlier research (Thorne-Lyman et al., 2010).

Table 5.3 Regression result for calorie consumption impact of social , , finance, human, physical and social capital of Northwest Bangladesh including ratio of Deep Tube Well (DTW) and Shallow Tube Well (STW) area

Number of Observation	379
F (26, 352)	4.84
Prob>F	0
R-squared	0.26
Root MSE	632.25

Variables	Coef.	Std. error	t-value	p-value	[95% Conf.	Interval]
Constant	1696.00	128.59	13.20	0.00	1444.06	1949.89
Proportion of household members with paid employment	961.99	212.37	4.53	0.00	544.31	1379.67
Taka value of household crop production for own consumption	0.00	0.00	-0.17	0.86	0.00	0.00
Taka value of household fish production for own consumption	0.01	0.00	2.20	0.02	0.00	0.02
Taka value of household livestock production for own consumption	0.00	0.00	-0.33	0.74	0.00	0.00
Household flooding: binary variable reporting exposure to flood	-258.97	164.43	-1.58	0.11	-582.18	64.24
Household drought: binary variable reporting exposure to drought	2.81	129.36	0.02	0.98	-251.61	257.24
Households with female head as binary variable	-67.00	211.68	-0.32	0.75	-483.34	349.31
Proportion household with paid employment working in agriculture	379.54	187.25	2.03	0.04	11.26	747.82
Proportion household with paid employment working as agricultural day labour	-310.68	142.66	-2.18	0.03	-591.27	-30.10
Taka value of all household credit	0.00	0.00	-0.90	0.37	0.00	0.00
Average interest rate on all household loans	-4.11	2.19	-1.88	0.06	-8.42	0.20
Proportion of household members receiving social safety net assistance	289.48	280.45	1.03	0.30	-262.08	841.05
Head of household years of formal education	9.05	10.13	0.94	0.34	-10.43	29.44
Area of agricultural land operated	0.65	0.36	1.81	0.07	-0.05	1.37
Major flooding* area of agricultural land operated	0.23	5.01	0.05	0.96	-9.63	10.09
Major flooding * proportion of people working in agriculture	361.25	1073.81	0.34	0.73	-1750.64	2473.15
Proportion of zilla area under severe drought	-6.80	3.07	-2.22	0.27	-12.89	-0.78
Ratio of Deep Tube Well (DTW) area to Shallow Tube Well (STW) area	-48.29	123.98	-0.39	0.96	-292.13	195.00
Barind Tract	444.59	260.90	1.70	0.08	-68.56	957.75
South of North West	0.00	(omitted)				
Naogaon	197.19	162.26	1.22	0.22	-121.92	516.32
Nawabganj	-323.88	252.59	-1.28	0.20	-820.67	172.91
Gaibandha	393.78	164.31	2.40	0.01	70.61	716.95
Kurigram	138.95	246.12	0.56	0.57	-345.11	623.02
Lalmonithat	62.94	256.50	0.25	0.81	-441.52	567.41
Nilphamari	250.44	153.69	1.63	0.10	-51.82	552.71
Panchagarh	430.90	181.16	2.38	0.01	74.60	787.21
Rangpur	0.00	(omitted)				



	Determinants	Ranking
🟦	Taka value of household fish production for own consumption	1
🟥	Proportion of household members with paid employment	2
🟩	Proportion household with paid employment working in agriculture	3
🟪	Average interest rate on all household loans	4
🟦	Proportion household with paid employment working as agricultural day labour	5
🟧	Area of agricultural land operated	6
🟦	Proportion of zilla area under severe drought	7

Figure 5.2 Relative calorie impacts of statistically significant factors influencing northwest Bangladesh household average per capita kilocalorie consumption

The main focus of this study is the biophysical factors that may allow measuring how household livelihoods have been influenced by changing water accessibility in the northwest of Bangladesh. Six biophysical variables[3] are included in both calorie consumption and income regression as natural capital:

1. Flood-exposed a binary variable that takes a value of 1 for households reporting exposure to flood in the 2010 HIES survey year
2. Drought-exposed, a binary variable that takes a value of 1 for households reporting exposure to drought in the survey year
3. A regional drought indicator variable, proportion of *zilla* area under severe drought
4. A variable indicating the proportion of net cultivable area within each *zilla* that is irrigated
5. A variable indicating the proportion of irrigated area within each *zilla* that is groundwater (as opposed to surface water) irrigated
6. The ratio of area for each *zilla* that is dependent on deep as opposed to shallow tube wells.

One of six potential included biophysical variables was found to be statistically significant explanations of variations in household calorie outcomes. Presumably this is due to the comparatively course spatial biophysical attributes measurement at the average for the *zilla* in which a household is located. Preferable household have been included specific values to the exact geographic locations. But this was not possible.

From natural capital, one biophysical attribute that could be statistically related to household calorie outcome: the proportion of *zilla* area exposed to drought. The regression explained that:

---

[3] Variable 4, 5 and 6 could not be included in the same model simultaneously for both calorie consumption and income regression. Because the three variables are so highly correlated their simultaneous inclusion did not allow individual effects to be attributed to each variable accurately. In our main model for calorie consumption (shown in Table 5.3) and income (shown in Table 5.4), we only included variable 6 and omitted 4 and 5. We repeated the calorie regression and income regression but replace variable 6 with variable 4 which are shown as Table C.1 and Table C.3 respectively in Appendix C. Also, we repeated again this time with replacement of variable 6 with variable 5 for caloric consumption (Table C.2) and income (Table C.4) in Appendix C.

- A typical household in a northwest *zilla* with 1 percent more area exposed to severe drought could expect to consume 6.8 fewer kilocalories than a typical household with all other assets the same.
- On average households in the most drought exposed *zilla* (15% of area drought exposed) could expect to consume 107 less kilocalorie per person per day than people in a zero drought exposed area all other household assets equal (Table 5.3).
- Household in severe drought prone areas consume 99 fewer kilocalories on average for each person in a day (Table C.2 in Appendix C).
- Proportion of the area under severe drought and net cultivable area under irrigation were not significant in explaining calorie consumption (Table C.1 in Appendix C).
- Households residing in severe drought prone *zillas* with one standard deviation above the mean proportion of *zilla* area exposed to drought ingest 35 less kilocalorie per capita per day (Table 5.3).

Regional impacts on calorie consumption identified in the regression can described as follows:

- The proportion of severe drought area differed sub-regionally in northwest (Shahid, 2008; Shahid and Behrawan, 2008) as shown in Figure 5.3a.
- Figure 5.3b shows predicted variation across northwest *zillas* in area under severe drought and how this impacts on calorie consumption (Figure 5.3b).
- Barind Tract; Gaibandha and Panchaghar districts enjoyed better nutrition outcome than other *zillas* in northwest region with 444, 393 and 430 more kilocalorie consumption per capita per day on average than the regional average respectively (Figure 5.2).

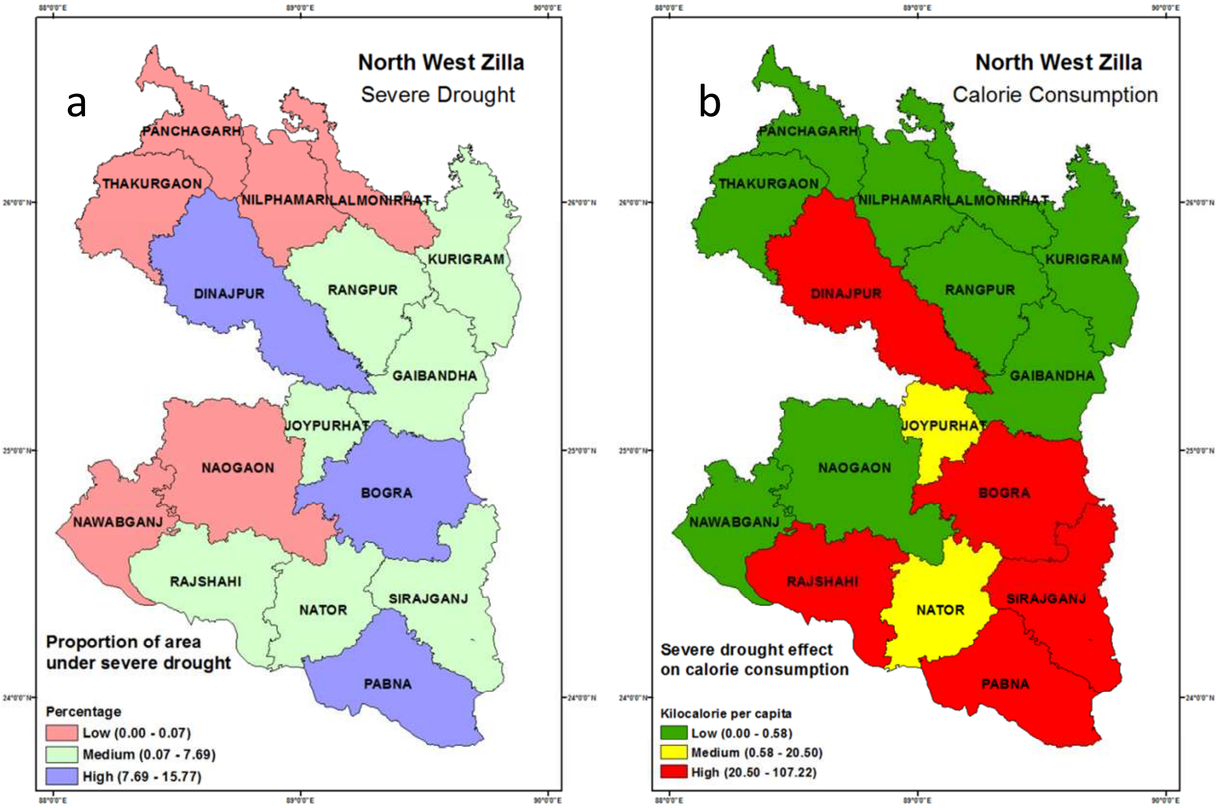


Figure 5.3 Proportion of severe drought area (a) and regional impact of severe drought on calorie consumption (b) in northwest

5.3.2 Yearly income regression results

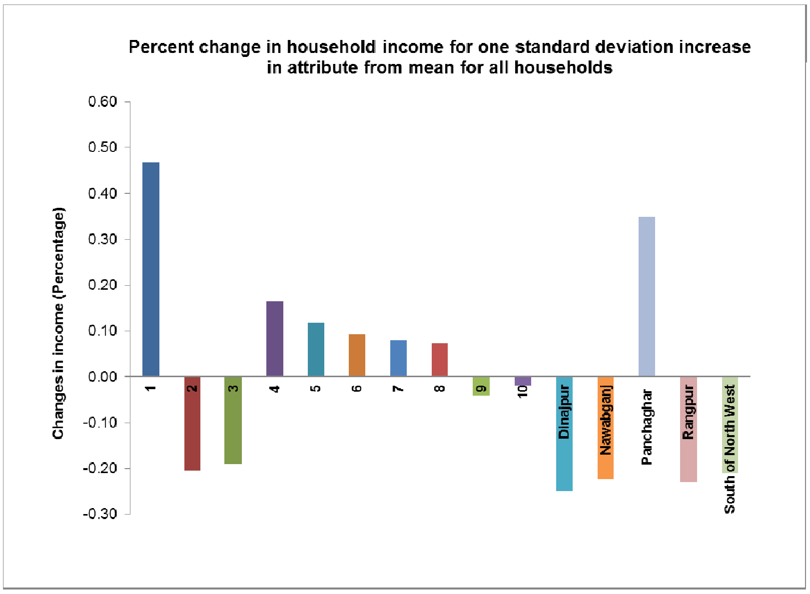
The income regression had moderate explanatory power with an R^2 value of 0.29. Ten variables were found to be statistically significant determinants of income variation. Calculations of the marginal influence of one standard deviation more than the sample mean level of each significant variable are shown in Figure 5.4. Key findings are:

Four forms of household financial capital were statistically significant as income determinants:

- Households that receive one standard deviation greater than the mean level of remittances earn nearly 47% more than the average household income (Figure 5.4) which confirms similar findings in earlier research (Nargis and Hossain, 2006).
- Households that has one more standard deviation than the average percent of members in paid employment and a household that has one standard deviation more credit enjoy 9 and 8 percent more income on average respectively. Previous results showed the influence of paid employment (Nargis and Hossain, 2006) and credit access on improved livelihood in Bangladesh (Khandker et al., 1998), especially in Northern Bangladesh (Amin et al., 2003)
- A household that has one standard deviation greater than the mean level of paid employment working in the agricultural sector receives 19 percent less income than the average.

Three forms of household human capital were statistically significant as income determinants:

- A household that has one standard deviation greater than mean level of formal education earns nearly 16 percent more than the average household income. Earlier research confirmed the positive impact of education on income (Kam et al., 2005; Nargis and Hossain, 2006)
- A female headed household get 20 percent less than average household income. Previous result showed that female headed household have less access on income (Lewis, 1993; Koppen and Mahmud, 1995; Karim et al., 2012).
- A household that has one standard deviation greater than mean proportion of household reporting chronic illness is impacted moderately with an expected average 4 percent less than a typical household income (Figure 5.4). It was found that adult illness reduced overall income at household level (Pryer, 1993).



	Determinants	Ranking
🟦	Household remittances from overseas	1
🟥	Households with female head as binary	2
🟩	Proportion household with paid employment working in agriculture	3
🟪	Head of household years of formal education	4
🟦	Area of agricultural land operated	5
🟧	Proportion of household members with paid employment	6
🟦	Taka value of all household credit	7
🟥	Major flood: District area proportion inundated deeper than 360 cm	8
🟩	Proportion of household reporting chronic illness	9
🟪	Household flooding: binary variable reporting exposure to flood	10

Figure 5.4 Percentage change in household income for one standard deviation increase in attribute from mean for all households

One form of physical household capital came up with a significant p-value of 0.000 which was agricultural land operated (Table 5.4). A household that has one standard deviation greater than mean level of agricultural land receives nearly 11 percent more than the average household income (Figure 5.4) as also confirmed by earlier research (Thorne-Lyman et al., 2010).

Two forms of natural capital were statistically significant as income determinants:

- Major flood prevalence appears to impacts household income positively as a household located in an area that has one standard deviation greater than mean area exposed to major flood events earns on average nearly 11 percent more than the average household income (Table C.1 in Appendix C). This possibly indicates the value of soil renewal from major floods translates to greater yields and agricultural income.
- A household exposed to flood in the survey year could expect 11.9 percent less income on average in the year.
- A usual household within a drought prone district and who depend on both deep and shallow tube well for their irrigation did not have identifiably different income

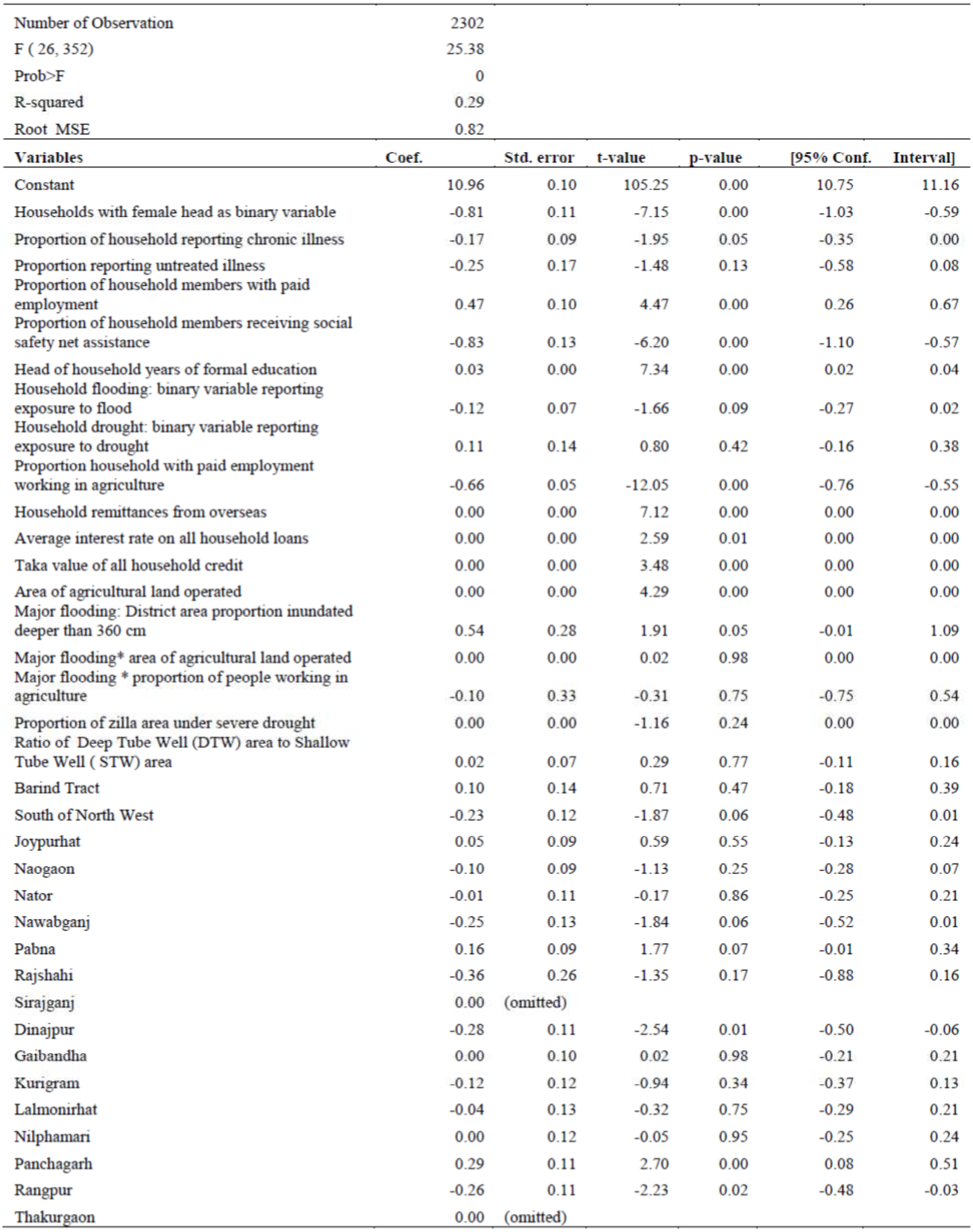
- A household within a district which have more area under groundwater irrigation and severe drought did not have statistically significant income (p-values 0.21 and 0.23 respectively) Table C.4 in Appendix C).

Proportion of net cultivable area under irrigation and proportion of area under severe drought were not significant income household income variation (Table C.3 in Appendix C).

Regional differences in income identified with the regression are described as follows:

- Regionally proportion of *zilla* area which was inundated by greater 360 cm in major flood varies (Figure 5.5a).
- The Figure 5.5b illustrates the impact of major flood impacts on income.
- The southern part of the northwest (snw), Dinajpur, Rangpur and Nawabganj *zilla* gets worse yearly income outcomes compared to other *zillas* in northwest as 32 percent, 22 percent and 22 percent less than the regional mean respectively (Table 5.4).
- Only Panchaghar *zilla* in northwest earned better yearly income as it was 34 percent more than the average rest for all other *zillas* in northwest.

Table 5.4 Regression result for income impact of social , finance, human, physical and social capital of Northwest Bangladesh including ratio of Deep Tube Well (DTW) and Shallow Tube Well (STW) area



Number of Observation	2302
F (26, 352)	25.38
Prob>F	0
R-squared	0.29
Root MSE	0.82

Variables	Coef.	Std. error	t-value	p-value	[95% Conf.	Interval]
Constant	10.96	0.10	105.25	0.00	10.75	11.16
Households with female head as binary variable	-0.81	0.11	-7.15	0.00	-1.03	-0.59
Proportion of household reporting chronic illness	-0.17	0.09	-1.95	0.05	-0.35	0.00
Proportion reporting untreated illness	-0.25	0.17	-1.48	0.13	-0.58	0.08
Proportion of household members with paid employment	0.47	0.10	4.47	0.00	0.26	0.67
Proportion of household members receiving social safety net assistance	-0.83	0.13	-6.20	0.00	-1.10	-0.57
Head of household years of formal education	0.03	0.00	7.34	0.00	0.02	0.04
Household flooding: binary variable reporting exposure to flood	-0.12	0.07	-1.66	0.09	-0.27	0.02
Household drought: binary variable reporting exposure to drought	0.11	0.14	0.80	0.42	-0.16	0.38
Proportion household with paid employment working in agriculture	-0.66	0.05	-12.05	0.00	-0.76	-0.55
Household remittances from overseas	0.00	0.00	7.12	0.00	0.00	0.00
Average interest rate on all household loans	0.00	0.00	2.59	0.01	0.00	0.00
Taka value of all household credit	0.00	0.00	3.48	0.00	0.00	0.00
Area of agricultural land operated	0.00	0.00	4.29	0.00	0.00	0.00
Major flooding: District area proportion inundated deeper than 360 cm	0.54	0.28	1.91	0.05	-0.01	1.09
Major flooding* area of agricultural land operated	0.00	0.00	0.02	0.98	0.00	0.00
Major flooding * proportion of people working in agriculture	-0.10	0.33	-0.31	0.75	-0.75	0.54
Proportion of zilla area under severe drought	0.00	0.00	-1.16	0.24	0.00	0.00
Ratio of Deep Tube Well (DTW) area to Shallow Tube Well (STW) area	0.02	0.07	0.29	0.77	-0.11	0.16
Barind Tract	0.10	0.14	0.71	0.47	-0.18	0.39
South of North West	-0.23	0.12	-1.87	0.06	-0.48	0.01
Joypurhat	0.05	0.09	0.59	0.55	-0.13	0.24
Naogaon	-0.10	0.09	-1.13	0.25	-0.28	0.07
Nator	-0.01	0.11	-0.17	0.86	-0.25	0.21
Nawabganj	-0.25	0.13	-1.84	0.06	-0.52	0.01
Pabna	0.16	0.09	1.77	0.07	-0.01	0.34
Rajshahi	-0.36	0.26	-1.35	0.17	-0.88	0.16
Sirajganj	0.00	(omitted)				
Dinajpur	-0.28	0.11	-2.54	0.01	-0.50	-0.06
Gaibandha	0.00	0.10	0.02	0.98	-0.21	0.21
Kurigram	-0.12	0.12	-0.94	0.34	-0.37	0.13
Lalmonirhat	-0.04	0.13	-0.32	0.75	-0.29	0.21
Nilphamari	0.00	0.12	-0.05	0.95	-0.25	0.24
Panchagarh	0.29	0.11	2.70	0.00	0.08	0.51
Rangpur	-0.26	0.11	-2.23	0.02	-0.48	-0.03
Thakurgaon	0.00	(omitted)				

* See Table 5.1 for explanation of variables, and Table C.5 in Appendix C for *zilla* name and unique *zilla* code

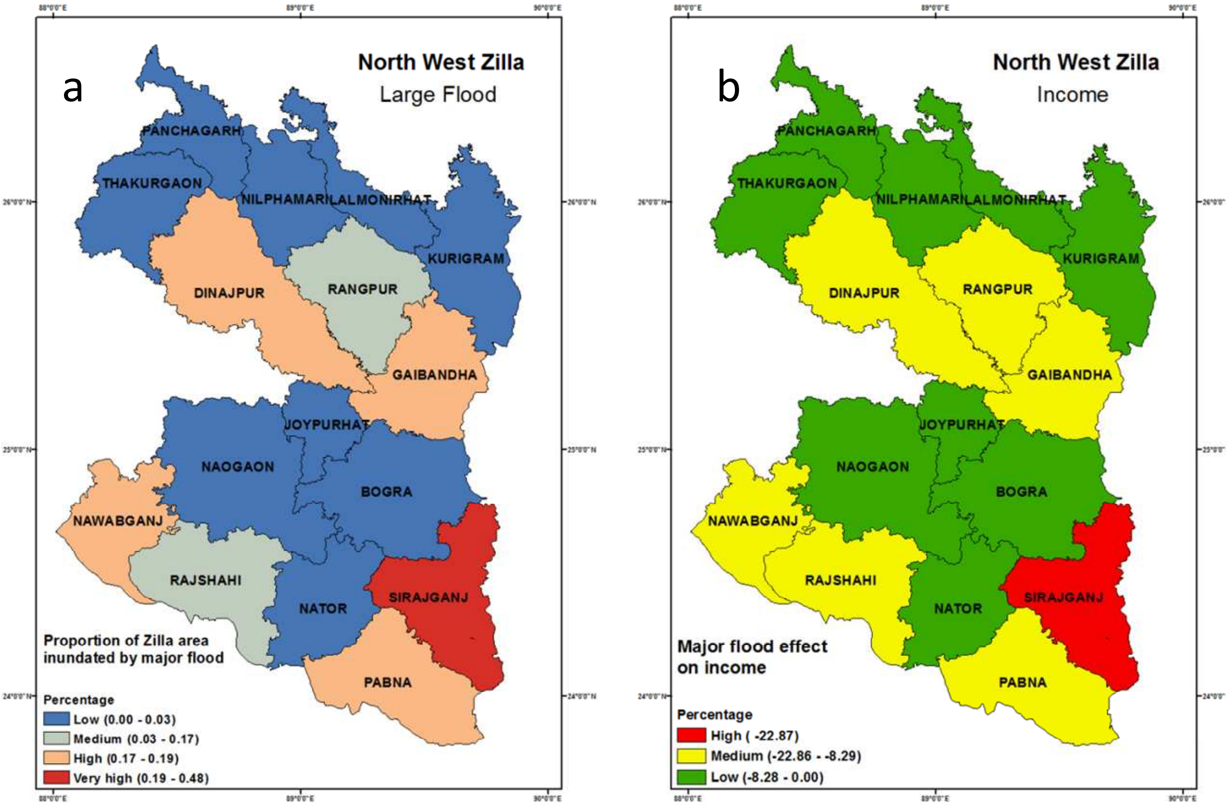


Figure 5.5 Proportion of *zilla* area inundated by greater 360 cm in major flood (a) and regional impact of major flood on yearly income as percentage (b) in northwest

5.4 Conclusion

We found that a comprehensive understanding of Northwest Bangladesh household livelihood outcomes requires understanding of: a) household financial, human, physical assets, and b) the spatially varying biophysical environmental and natural asset bases in regions where households are located. Our results support prior findings that socio-economic development such as industrialization that creates wage income is a major contributor to both household income and nutritional well-being (Khandker et al., 1998; Nargis and Hossain, 2006). Household human capital in the form of education is another key determinant of income outcomes (Kam et al., 2005). Still household livelihoods, especially as measured by nutrition outcomes, are also influenced by the natural resource base in the region in which a household is located and the manner in which regional resources are managed. For example, household access to inland fisheries is a large determinant of household per capita kilocalorie consumption. Additionally, we find that greater drought vulnerability significantly reduces household per capita kilocalorie consumption.

While we attempted to account for both household (financial, social, physical, human) capital and location biophysical attributes, in general, marginal effects of household capital measures from the HIES survey could be more accurately identified than biophysical impacts. This is likely because biophysical attributes were only on a zilla average basis for the zilla in which a household is located. We conjecture that if future HIES surveys could add household spatial coordinates and be merged with more detailed spatially explicit biophysical data, more statistically significant biophysical effects could be identified.

A key policy implication of this work is a finding that in parts of northwest region, many households appear to struggle with food security and this exposure appears to correlate with drought exposure. While we could not identify food security impacts related to groundwater level variation, we believe that this primarily due to data limitations and also recent marginal seasonal affect. We conjecture that more drought prone sub-regions with worse nutrition outcomes suffer these as result of localized water scarcity in dry season (Fujita and Hossain, 1995; Abdullah, 1989). In addition, relative importance of ground water is described in relation to drought exposure in North West of Bangladesh. Overuse of ground water extraction may happen for recurrence drought in every year at many districts in North West Bangladesh. As a result it may impact on livelihood outcome. As a whole, such kind of over extraction of ground water may not sustain in future for both agriculture and domestic purposes.

6 Conclusions and recommendations

Contributors: Mohammed Mainuddin, Mac Kirby, Glen Walker, Jeff Connor

6.1 Conclusions

The key outcome expected from this study is a strengthened rationale for further investment for a detailed study on sustainability of groundwater irrigation in the northwest and north-central regions on Bangladesh. We have tried to achieve this by:

1. Providing a snap shot of groundwater irrigation, dependency on groundwater irrigation for food security, and current concerns of the sustainability of groundwater (Chapter 2).
2. Assessing the relative contributions of groundwater pumping and rainfall variation to the observed variations in regional water balance using a dynamic regional water balance model (Chapter 3).
3. Analysing the historical data of groundwater water level and the river flow to understanding the surface water and groundwater interaction (vertical recharge, lateral movement, their significance on overall water balance) and its trends (Chapter 4).
4. Using geochemical parameters of the observation wells to understand groundwater-surface water interactions (Chapter 4).
5. Examining the impact of water related physical factors on the livelihoods of the population particularly on women and the poor and landless people in the regions (Chapter 5).

At the end of main Chapters (Chapters 2-5) we have drawn relevant conclusions in detail. Here, we describe the main messages that can be drawn from the study.

1. Groundwater irrigation is the main factor behind the current self sufficiency in rice production and at the heart of the agricultural development of the country. Sustaining groundwater irrigation particularly in the irrigation intensive northwest and north-central regions is vital for future food security of the country.
2. The increased area of irrigation and increased volume of groundwater pumping over the last three decades has contributed to declines in groundwater levels. The regional average trend in declining groundwater level appears to be at least partly explained by the trend in increasing irrigation rather than the absolute level of irrigation. Therefore a halt in the trend of increasing irrigation (which may have happened in the last few years) may see a reduction in the trend of decreasing groundwater level, albeit at lower groundwater levels. The lower groundwater levels will cause difficulties with access for drinking water and irrigation water.
3. Within the region are areas, particularly in the Barind Tract, of unsustainable over-use of groundwater.
4. Increasing groundwater extraction has resulted in fallen groundwater levels in the pre-monsoon period and this has meant a shift towards less groundwater moving to streams

and more water moving from streams; more water infiltrating through the land surface, with a probable reduction in surface run-off and reduced return flow to streams.

5. Aquifers are losing water to most major streams. The exceptions appear to be above junctions of major rivers and/or in areas where landscape is flattening. The influence of the streams on the groundwater appears to be constrained to within a few kilometres of the stream.
6. The total surface water-groundwater fluxes for the northwest region appear to be smaller than previously thought. Some of the estimates here may be lower than reality for a range of reasons, but when taken together with other studies, the estimates are not likely to be more than 20 BCM/yr.
7. Socio-economic development through industrialization that creates wage income is a major contributor to both household income and nutritional well-being.
8. Biophysical constraints such as drought will impact groundwater access in the future.
9. Women should be incorporated into mainstream development activities to enjoy better livelihoods.

6.2 Recommendations

The evidence presented in this report appears sufficient to encourage further investment into exploring the sustainable utilization of the surface water and groundwater resources for maintaining future food security of the country. Accordingly, the following studies are recommended.

1. Examine the impact of different external drivers (such as population growth, climate change, upstream development, construction of barrages, etc.) on the overall water balance and surface-water groundwater interaction, availability, and sustainability.
2. Examine the impact of future water availability on the irrigated agriculture, regional socio-economy, livelihoods, and the environments and, in particular, conduct a social cost-benefit analysis of potential investments or policies.
3. Develop regional scale understanding and evaluation of the surface water and groundwater resources, surface water and groundwater interaction, recharge/discharge mechanisms and trends, sustainable limit of groundwater use using hydrological and hydro-geological information, and detail modelling.

Appendix A MIKE SHE outputs

A.1 Description of the model

In connection with another project under BMDA, IWM developed a groundwater model for Pabna, Sirajgonj, Bogra, Gaibandha, Rangpur, Kurigram, Nilphamari and Lalmonirhat districts. The main purpose of the study was to explore modern technique with the view to increase agricultural production by bringing more potential area under irrigation. To evaluate the overall water resources of the study area, a mathematical model describing the condition in the unsaturated and saturated zone of the subsurface together with rainfall, overland flow and evapotranspiration and the condition of flow in the river, is required. The model enables better understanding of the river-aquifer interaction, as well as, providing a tool that can be used to manage the water resources in the best possible way considering the relative contribution of the components on the water balance in the area. The best option of future surface water and groundwater developments which will effectively utilize all available water resources with no or minimum of negative environmental impacts having full social acceptance is possible to find out through the surface water groundwater interaction modelling technique. Accordingly integrated MIKE 11-MIKE SHE modelling system was been adopted in this study.

The MIKE 11 hydrodynamic module uses an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries. The module can describe sub-critical as well as supercritical flow conditions through a numerical scheme and simulate main hydraulic processes i.e. flow, velocity and water level in the river (http://www.mikebydhi.com/Products/WaterResources/MIKE11.aspx). MIKE SHE is a comprehensive mathematical modelling system that covers the entire land-based hydrological cycle. It is a finite difference model, which solves systems of equations describing the major flow and related processes in the hydrological system and simulates surface flow, infiltration, flow through the unsaturated zone, evapotranspiration and groundwater flow (http://www.mikebydhi.com/Products/WaterResources/MIKESHE.aspx).

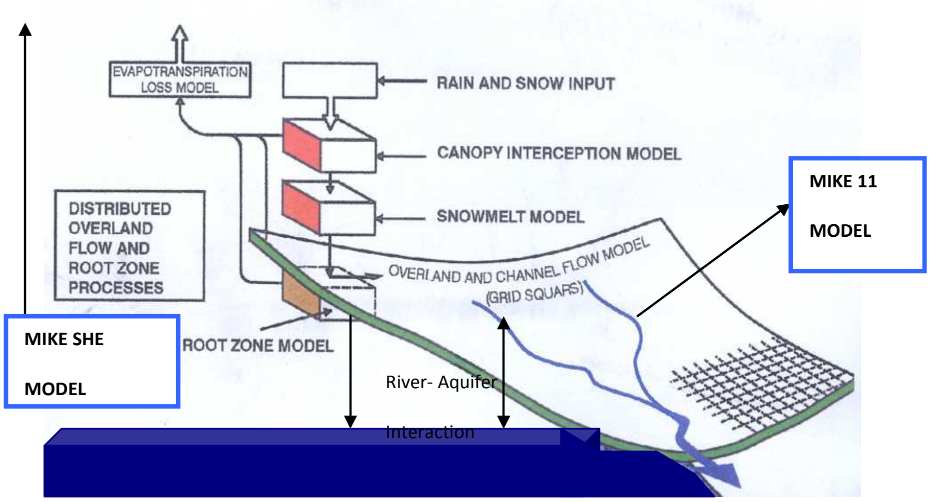


Figure A.1 MIKE 11 - MIKE SHE Interactive Modelling System

The MIKE 11 and MIKE SHE models are interactively linked and capable of producing water balance and change of storages in the form of groundwater recharge/discharge and fluctuations in water tables. The basic components of MIKE 11 and MIKE SHE have been shown in Figure A.1. The approach of the model study is shown in a schematic plan illustrated below (Figure A.2).

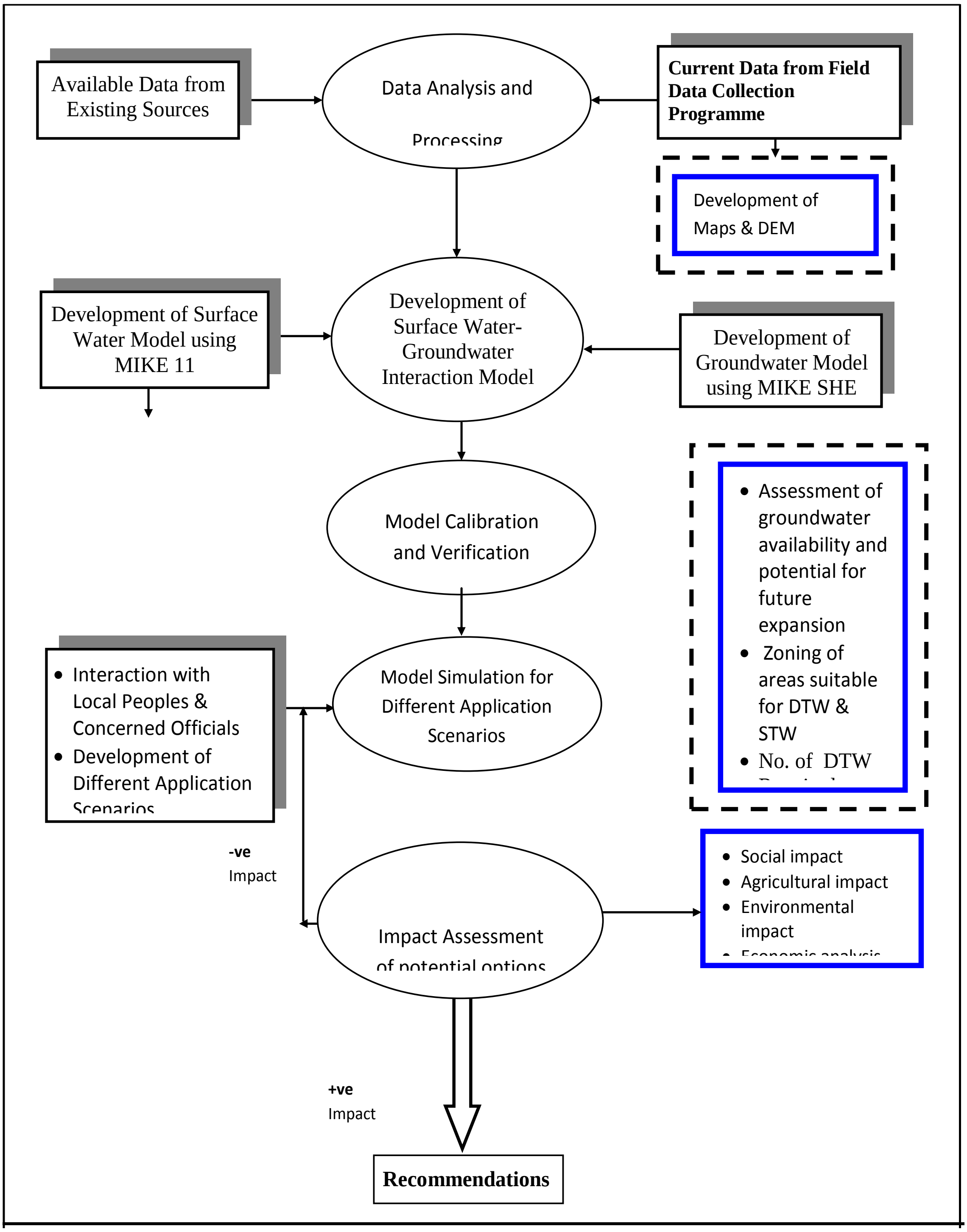


Figure A.2 Schematic diagram of modelling activities

A.2 Technical background of integrated Mike She-Mike 11 modelling

Natural hydrologic systems as well hydrologic problems are very complex. It is found that the integrated MIKE 11-MIKE SHE includes the entire complex processes in the land phase of the hydrologic cycle:

- Precipitation (rain or snow)
- Evapotranspiration, including canopy interception
- Overland sheet flow
- Channel flow
- Unsaturated sub-surface flow
- Saturated groundwater flow.

The MIKE SHE/MIKE 11 is a physically-based, spatially-distributed, finite difference, integrated surface water and groundwater model.

A.2.1 Channel and overland flows

MIKE SHE, coupled with MIKE 11, is capable of modelling open channel flow using the kinematic wave, diffusive wave, and dynamic wave approximation. MIKE 11 supports any level of complexity and offers simulation engines that cover the entire range from simple Muskingum routing to the higher order dynamic wave formulation of the Saint-Venant equations. MIKE 11 can simulate a full range of structures (dams, weirs, culverts, gates, etc) in its solution domain.

Overland flow is simulated using the diffusive wave approximation and special provisions are available in MIKE SHE for flow routing between the overland flow plane and channels that depend on channel bank geometry and user selected flooding options. Using rectangular coordinates in horizontal plane, the conservation of mass is given by

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}(uh)+\frac{\partial}{\partial y}(vh)=i \qquad (1)$$

and the momentum equations are given by

$$S_{fx}=S_{ox}-\frac{\partial h}{\partial x}-\frac{u}{g}\frac{\partial u}{\partial x}-\frac{1}{g}\frac{\partial u}{\partial t}-\frac{qu}{gh} \qquad (2a)$$

$$S_{fy}=S_{oy}-\frac{\partial h}{\partial y}-\frac{v}{g}\frac{\partial v}{\partial y}-\frac{1}{g}\frac{\partial v}{\partial t}-\frac{qy}{gh} \qquad (2b)$$

where, $h(x,y)$ is the flow depth; $u(x,y)$ and $v(x,y)$ are the flow velocities in *x*- and *y* directions, respectively; $i(x,y)$ is the net input into overland flow (net rainfall less infiltration); S_{fx} and S_{fy} are the friction slopes in the *x*- and *y*-directions, respectively; S_{ox} and S_{oy} are the slope of the ground surface in *x*- and *y*-directions, respectively; *g* is the gravitational constant; q is the discharge per unit width. Equations (1), (2a) and (2b) are known as St. Venant equations and when solved yield a fully dynamic description of shallow (two-dimensional) free surface flow. If we drop the last three terms of the momentum equations, we are ignoring momentum losses due to local and convective accelerations and lateral inflows, the remaining terms of the equations constitute the diffusive wave approximation. If the depth of flow does not vary significantly between adjacent cells, the fourth term may be dropped further, the resulting equations are called kinematic wave approximation.

In MIKE SHE, a river is typically considered to be a line located between model grid cells. The river-aquifer exchange is calculated from both sides of the river, depending on the head gradient. This is valid if the river width is small relative to the model cells. Otherwise, an area-inundation flooding approach is to be adopted. Thus, during low flow conditions, when the river is narrow (less than one grid size) and water flow is confined to the main river channel, the river-aquifer exchange method is adopted. If the area-inundation option is used, MIKE SHE calculates distributed surface water stages by comparing the simulated MIKE 11 water level with topographic elevations. In this case, surface water is treated as normal ponded water, which implies that surface water exchange can take place through the normal unsaturated zone infiltration, otherwise, through the normal overland-saturated zone exchange.

A.2.2 Unsaturated flow, rainfall and evapotranspiration

MIKE SHE utilizes three methods to simulate flow in the unsaturated zone but assumes that flow is vertical in all three methods. The basis for this assumption is that the flow is primarily vertical at the scale typically simulated with MIKE SHE (catchment scale).

Once infiltrated water enters the surficial aquifer, the 3D ground water equations takeover. Two of the available unsaturated zone methods in MIKE SHE are: the full Richard's equation and a simplified Richard's equation that neglects capillary tension.

The full and simplified Richard's equation methods use real soil properties and soil moisture-relationships that can be developed using Brooks and Corey or Van Genuchten relationships. The third method, which is a simplified wetland module, useful for areas with a shallow groundwater table, that uses a linear relationship between depth to the water table and average soil moisture content and a linear infiltration equation.

The driving force for transport of water in the unsaturated zone is $h = z + \psi$ where, h is the hydraulic head, ψ is the pressure head (–ve in unsaturated zone), and z is the position head with respect to datum (+ve downward).

The volumetric flux is then obtained from Darcy's law:

$$q = -K(\psi)\frac{\partial h}{\partial z} \qquad (3)$$

where, $K(\psi)$ is the unsaturated hydraulic conductivity. Assuming that the soil matrix is incompressible and the soil water has a constant density, the one-dimensional continuity equation yields the tension-based Richards equation as follows:

$$\frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right] = C(\psi)\frac{\partial \psi}{\partial t} + R(z) \qquad (4)$$

where, $C(\psi)$ (= $\partial\theta/\partial\psi$) is the soil water capacity obtained from the slope of the soil moisture retention curve; $R(z)$ is the root extraction sink term; and ϑ is the volumetric soil-moisture.

Solution of the above Richards equation requires the knowledge of the characteristics curves *K(ψ)* and *C(ψ)* or *ϑ(ψ)*. The root extraction term when integrated over the entire root zone depth equals the total actual evapotranspiration. Direct evaporation from the soil is calculated only for the first node below the ground surface.

As unsaturated zone extends from the ground surface to the watertable, the vertical flow is determined by the boundary conditions at each end of the grid column. The upper boundary condition is either a constant flux condition (Neuman) within each time step determined by rainfall rate on the ground surface, or, a constant head condition (Dirichlet) within each time step determined by level of ponded water on the ground surface; these conditions switch between them depending on infiltration capacity and rainfall rate. The lower boundary, on the other hand, in most cases is a pressure boundary determined by water table elevation. The initial conditions for ψ are generated by MIKE SHE assuming an equilibrium soil moisture/pressure profile with no-flow. The equilibrium profile is calculated assuming zero pressure at the watertable and decreasing linearly in the unsaturated zone up to ψ_{FC} (ψ field capacity) and then remains constant for all nodes above that point. The assumption is that the flow is almost zero at moisture contents below field capacity. The method assumes that the soil profile is divided into discrete computational nodes, as a general guideline, one should choose a finer spatial resolution in the top nodes and coarser resolution in the bottom nodes.

Interception and evapotranspiration can be simulated in combination with the full or simplified Richard's equation unsaturated zone modules using an empirical evapotranspiration module (Kristensen and Jensen, 1975). If the wetland unsaturated zone module is used, evaporation is determined using a top-down approach (interception storage, detention storage, unsaturated zone, and groundwater) until potential evaporation is satisfied, if possible, or water levels are below a specified seasonally- and spatially varying evapotranspiration extinction depth.

A.2.3 Saturated flow

MIKE SHE includes a 3D saturated zone model in a heterogeneous aquifer with shifting conditions between unconfined and confined conditions. The spatial and temporal variations of the dependent hydraulic head are described mathematically by the non-linear Boussinesq equation. The geology is described in terms of layers or lenses with attached hydraulic properties. Properties can be specified either on a cell-by-cell basis or by property zones defined by polygons or grid-code files. MIKE SHE allows grid-independent geology specification, which allows changing the horizontal or vertical mesh quickly.

The governing flow equation for three-dimensional saturated flow is:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_s \frac{\partial h}{\partial t}+Q \qquad (5)$$

where, K_x, K_x, and K_x are the hydraulic conductivities along the *x*, *y* and *z* axes assumed parallel to the principle directions of anisotropy of the domain; *Q* is the source/sink term; S_s is the specific storage coefficient stitches between confined and unconfined conditions of the aquifer.

Boundary conditions are specified for each computational layer. MIKE SHE supports traditional groundwater boundary conditions and offers large flexibility in terms of spatial and temporal variation of boundary conditions. Boundary conditions may be specified on a cell-by-cell basis, but typically it is more convenient to attach boundary conditions to geometric features such as polygons (lakes), lines (rivers) or points (pumps, injections, drains). A lake could, for instance, be a polygon with an attached water level time series and leakage coefficient. Similar to the meteorological time-series data, boundary time-series data may be specified in separate time-series files that include different and non-equidistant time steps. MIKE SHE automatically synchronizes all time-series data thus, eliminating tedious time-series preprocessing. Simulation time steps and stress periods may be specified independent of input time series.

The MIKE SHE allows for flow through drains in the soil, to simulate intermediate hydrograph response (interflow) in regional modelling. The drainage flow may also be used to simulate relatively fast surface runoff for cases where the space resolution of the individual grid squares is too large to represent small scale variations in the topography. MIKE SHE gives opportunity for routing drainage water to local depressions, rivers or model boundaries.

The overland, unsaturated, and saturated zone modules and MIKE 11 are explicitly coupled which allows the time step of each component to be determined based on the response time of the component processes. The explicit coupling allows simulations to be tailored to particular problems but requires extreme diligence to ensure that mass balance errors do not occur. Special provisions are available in MIKE SHE to adjust the time step during a simulation based on changes in input fluxes (i.e., rainfall). The rainfall time step can vary from 15 minutes to one hour to one day, and a mix of time steps is possible. Thus, one-day time steps can be used for most of the period, with a one-hour time step during critical rainfall periods.

A.3 Description of parameterisation and calibration process

A.3.1 Model calibration

The purpose of model calibration is to achieve an acceptable agreement with measured data by adjusting the input parameters within acceptable range. As a coupled surface water groundwater model contains huge number of input data, the parameters to adjust during the calibration could be numerous. During the calibration it is therefore important to adjust the parameters within the acceptable range determined from field measurements, and also to minimize the number of adjusted parameters. In this study, the initial input parameters have been obtained from field measurements and other sources. The model has been calibrated for the period 2006 to 2010.

In the present model, calibration has been done against groundwater levels, river water levels and river flows. The calibration of the coupled model follows complicated repetitive procedure. Calibration of one parameter has influence on the others. Initial calibration has been started with the groundwater parameters. The controlling parameters for groundwater flow in the aquifers have been adjusted, so that the simulated groundwater level matches the observed level. While there are some minor parameters to influence the groundwater calibration, however, it appears that the hydraulic conductivity is the main parameter for groundwater model calibration. The evapotranspiration and unsaturated zone parameters, and drainage levels have also been adjusted to match the fluctuations of the observed groundwater heads. The controlling parameters for river flow have been adjusted so that the simulated river water levels and discharges corresponds the observed data. Then the controlling parameters for river-aquifer interaction have been adjusted. The main parameters for river-aquifer interaction are the river leakage coefficient and the conductivity of the upper layer. The final calibration parameters for the model have been given in Table A.1.

Table A.1 Final calibration parameter

GEOLOGICAL LAYER	HORIZONTAL HYDRAULIC CONDUCTIVITY (M/DAY)			VERTICAL HYDRAULIC CONDUCTIVITY (M/DAY)			SPECIFIC YIELD			STORAGE CO-EFFICIENT		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
Aquiclude	9.56	1.30	5.18	4.58	0.60	2.59	0.106	0.011	0.048	0.000001		
Aquitard	14.25	1.99	7.78	6.99	0.86	3.63	0.149	0.015	0.068	0.00001		
Aquifer	94.78	20.5	51.75	18.32	2.59	10.37	0.213	0.022	0.097	0.00009		

A.3.2 River leakage

The exchange of water between rivers and surrounding aquifers are controlled by the head difference between the surface water and groundwater schemes and hydraulic conductance. The head difference is simulated by MIKE SHE and MIKE 11 model, while conductance is described either by use of the parameters from the geological model or from a user specified leakage coefficient. The leakage coefficient is used to control the water exchange between the river and the aquifer and thereby also to regulate either the groundwater level or surface water level. As a general rule the same leakage coefficient has been applied to the whole area, but in areas where a higher or lower leakage is expected the value has been changed.

A.3.3 Calibration against groundwater level

During calibration of the model, a total of 65 BWDB monitoring wells were selected for calibration. The monitoring wells were selected in such a way that its satisfactory calibration would represent the entire study area. The calibration of interaction model has been carried out against observed ground water level for the period 2006-2010. The sample calibration plots are given in Figure A.3.

A.3.4 Interaction between river and aquifer

Using model result, the interaction between the river and aquifer was investigated for some river under this project. This was done for the river Dharla, Bangali, Korotoya and Teesta. The interaction was also investigated through analytically. Though there some uncertainties in both the process. The comparison of the result from model and analytical is given in Table A.2.

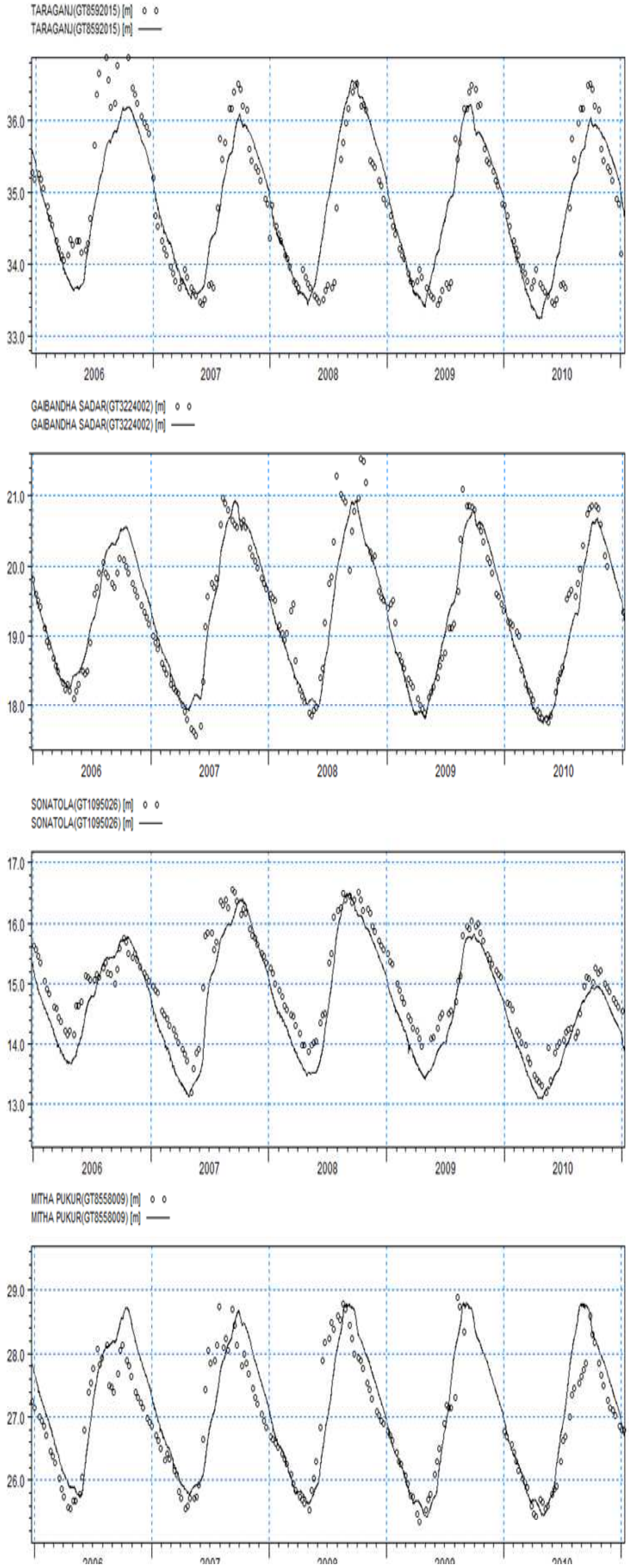
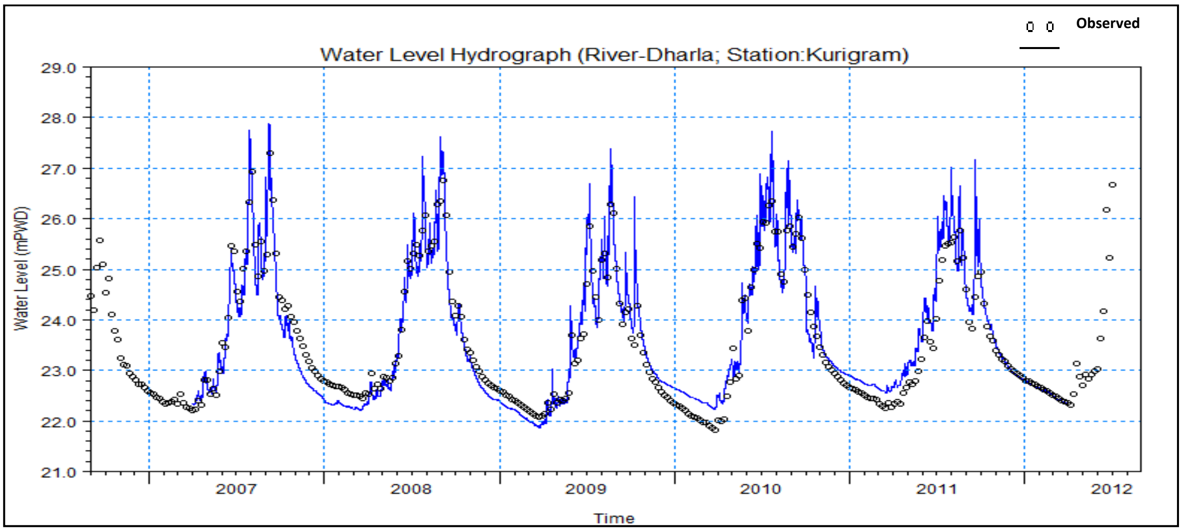


Figure A.3 Calibration plot against groundwater level

A.3.5 Calibration against surface water level and discharge

In order to get reliability of the surface water and groundwater interaction process, the surface water – groundwater interaction model has also been calibrated against surface water levels and discharges. Manning's number (M), which is considered as one of the controlling parameter, was adjusted during the calibration period so that the observed values of water level and discharges match with the simulated values. The results of the model have been compared at certain key locations where observed water level and discharge data are available. Overall a satisfactory match has been achieved between simulated and observed water level in the study area. However, in some cases model appears to over simulate the level than the observed. This could be improved with better understanding of storage due to structure and incorporation of structure operation into the model. Due to unavailability of structure operation, further improvement was not possible. Discharge comparison also shows a satisfactory match. Sample plots of calibration are shown in Figure A.4.



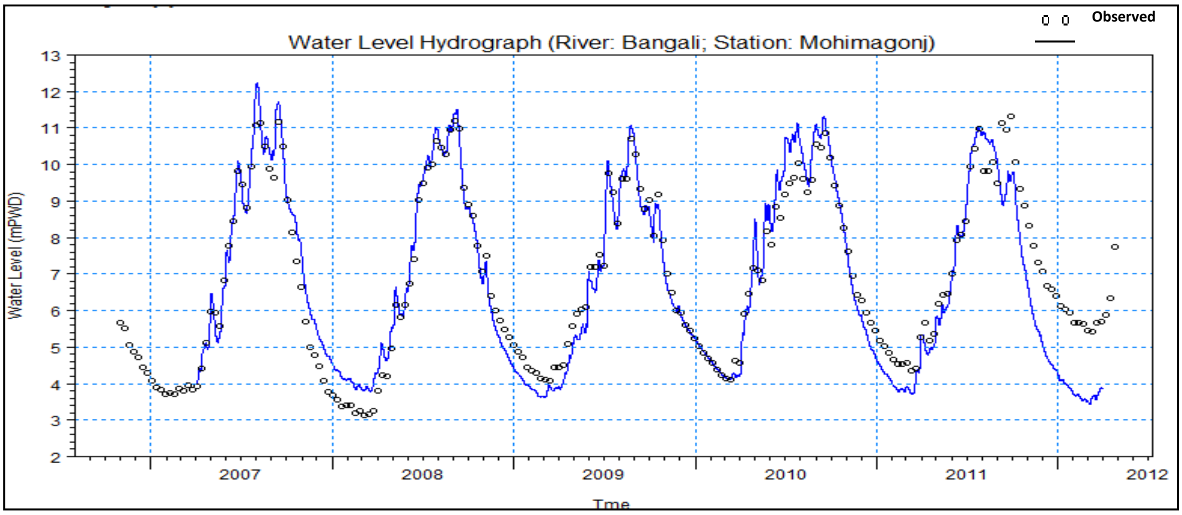


Figure A.4 Calibration plots against surface water level

Appendix B Interaction with Old Brahmaputra River

This section describes some preliminary results of an activity to estimate the interaction with Brahmaputra river and surrounding aquifer within the north-central region. Data was collated from three different locations (Figure B.1), namely at transact 1-1, transact 2-2 and transact 3-3. There was no groundwater level monitoring stations besides the river Old Brahmaputra. The hydrographs of groundwater level were compared with the hydrographs of surface water level for different transects (Figure B.2 to B.6). From the hydrograph analysis, it is observed that no relation of surface water level at Old Brahmaputra and the groundwater level from the available groundwater monitoring wells.

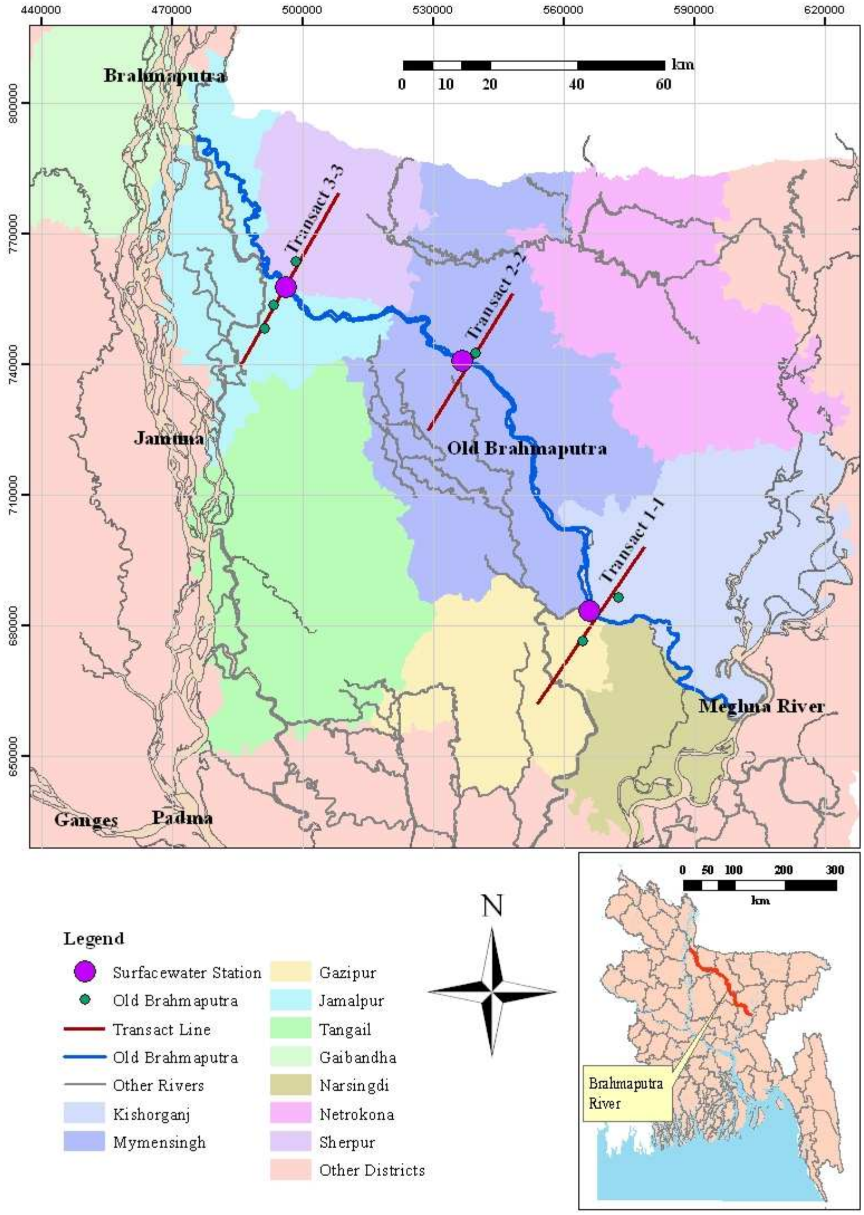


Figure B.1 Location for investigation of GW-SW interaction for Old Brahmaputra

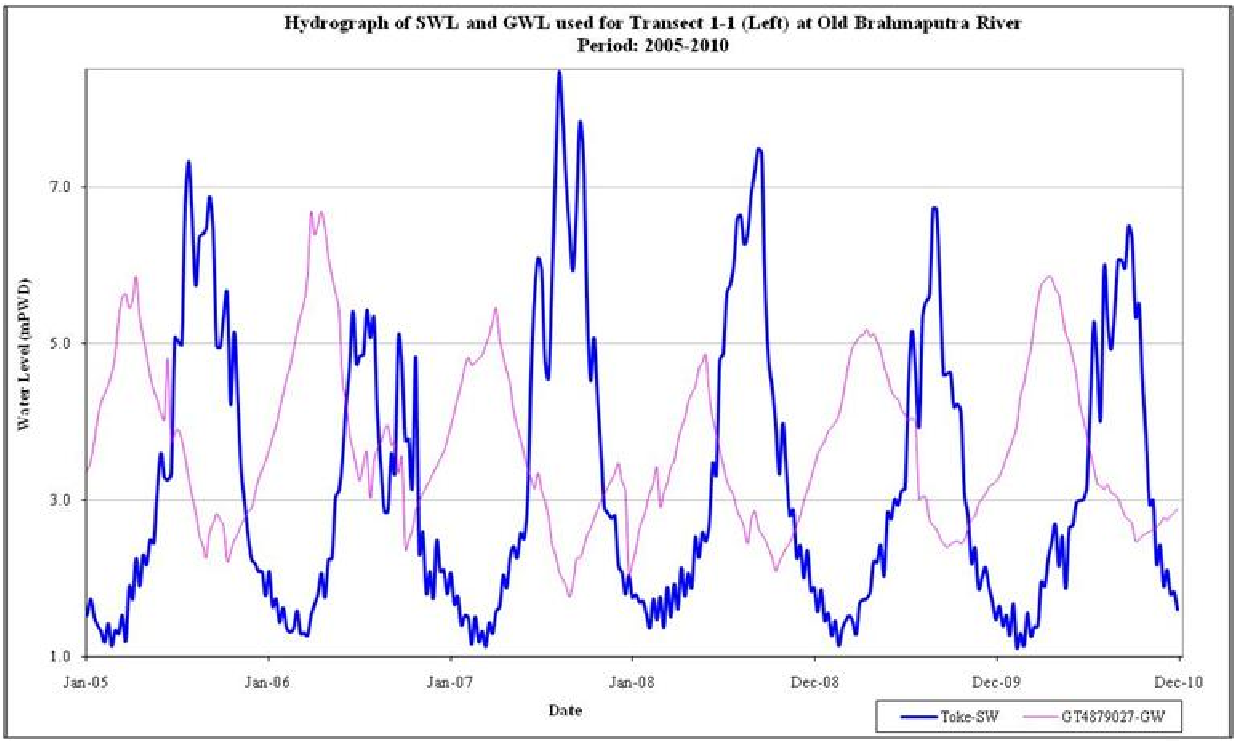


Figure B.2 Comparison of River Water & Groundwater for Transect 1-1 (left)

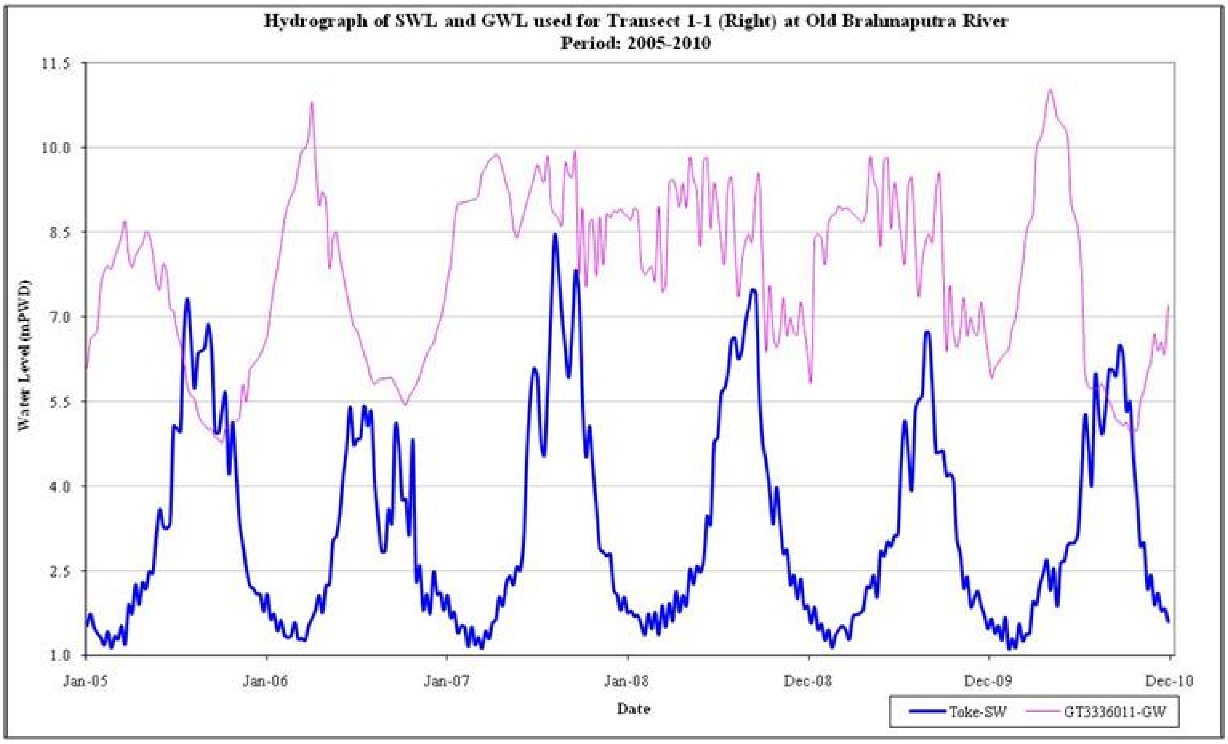


Figure B.3 Comparison of River Water & Groundwater for Transect 1-1 (right)

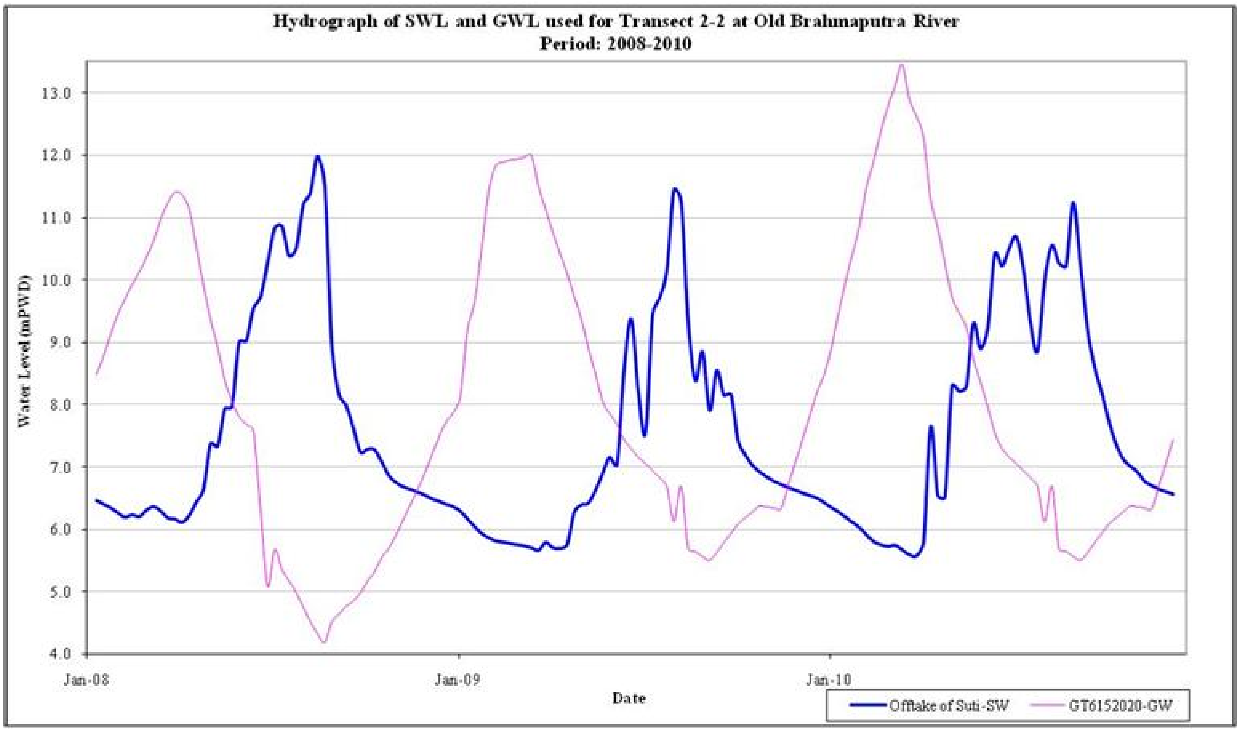


Figure B.4 Comparison of River Water & Groundwater for Transect 2-2)

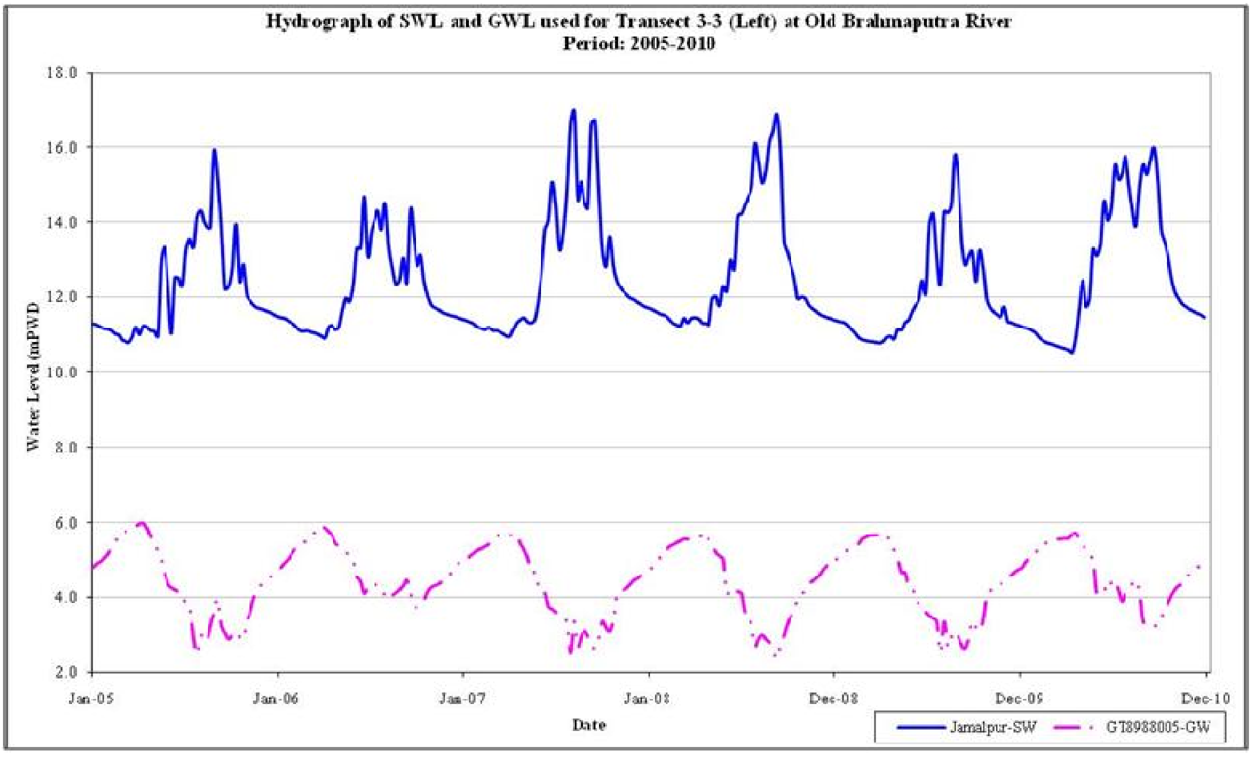


Figure B.5 Comparison of River Water & Groundwater for Transect 3-3 (left)

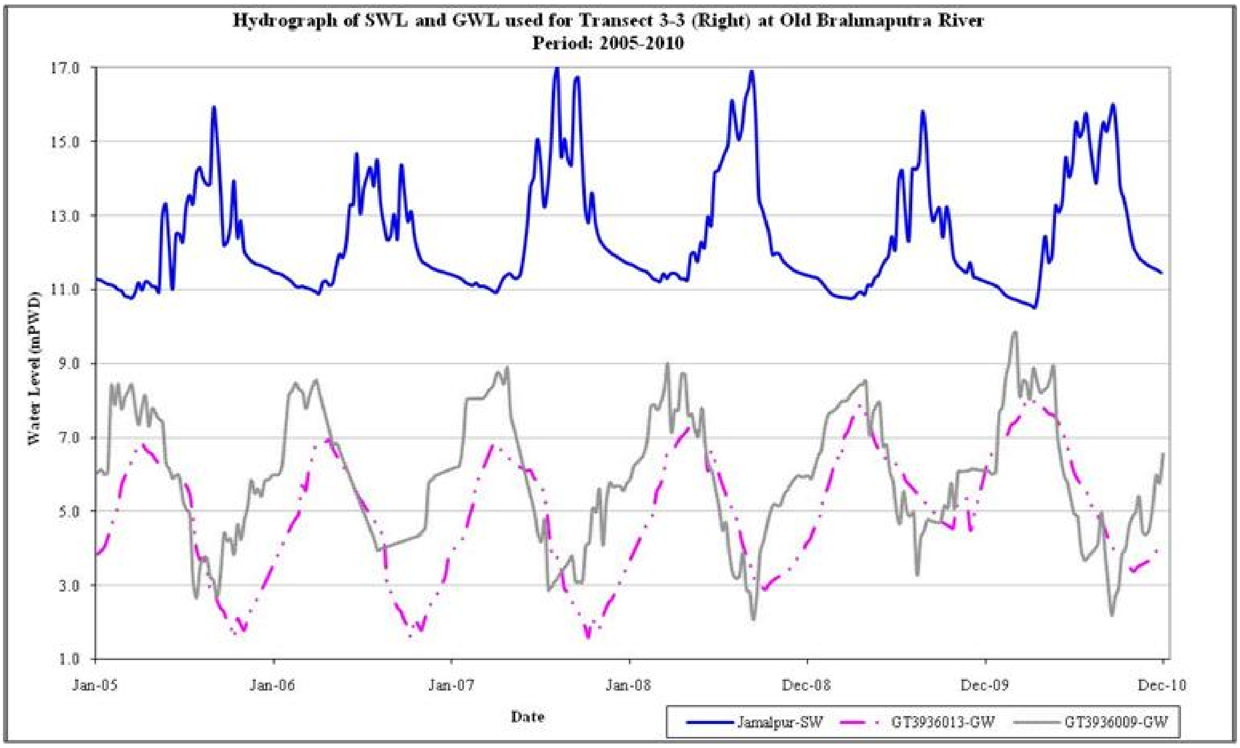
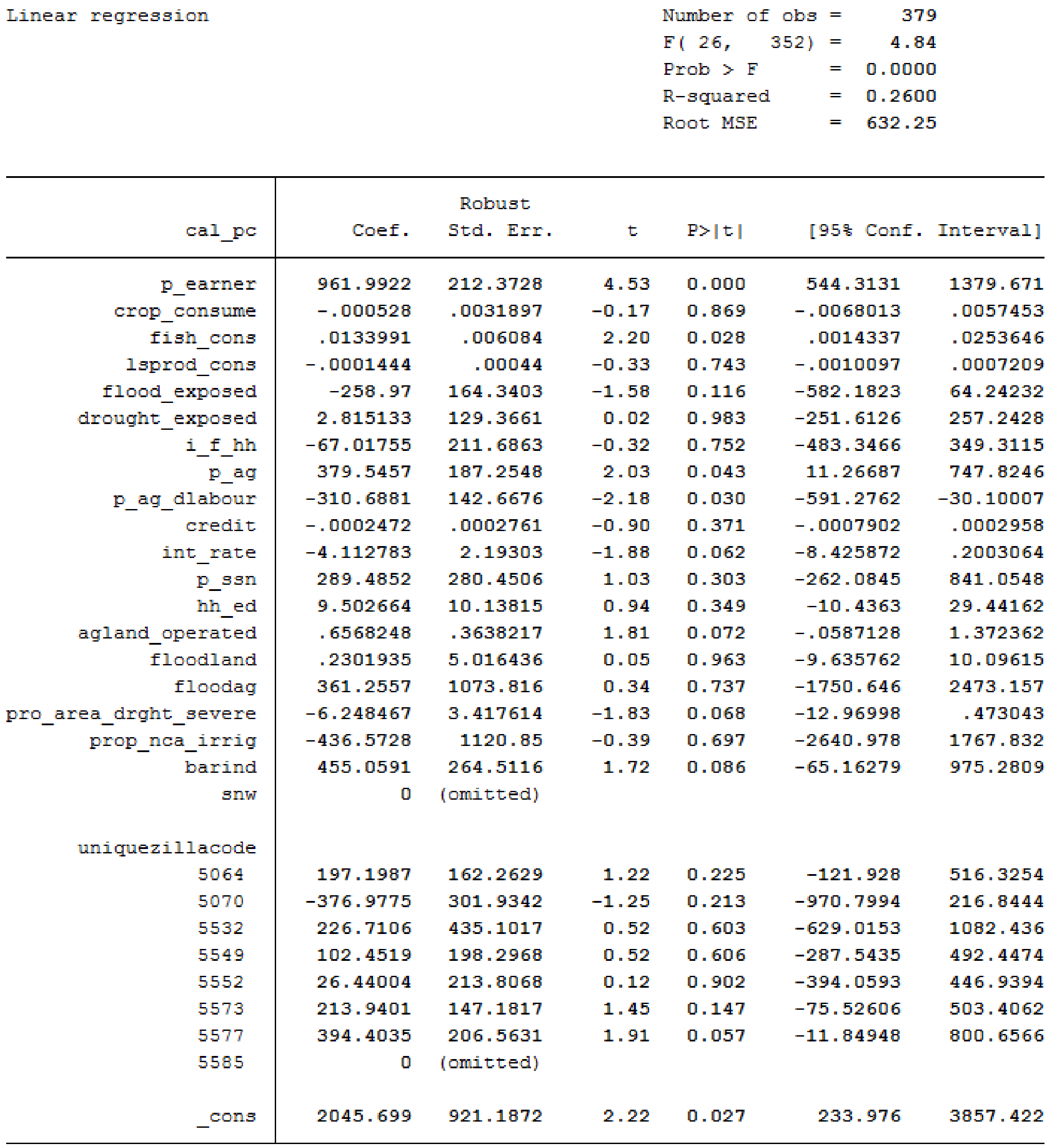


Figure B.6 Comparison of River Water & Groundwater for Transect 3-3 (left)

Appendix C Additional regressions

C.1 Additional calorie consumption regressions

Table C.1 Regression result for calorie consumption including prop_nca_irrig

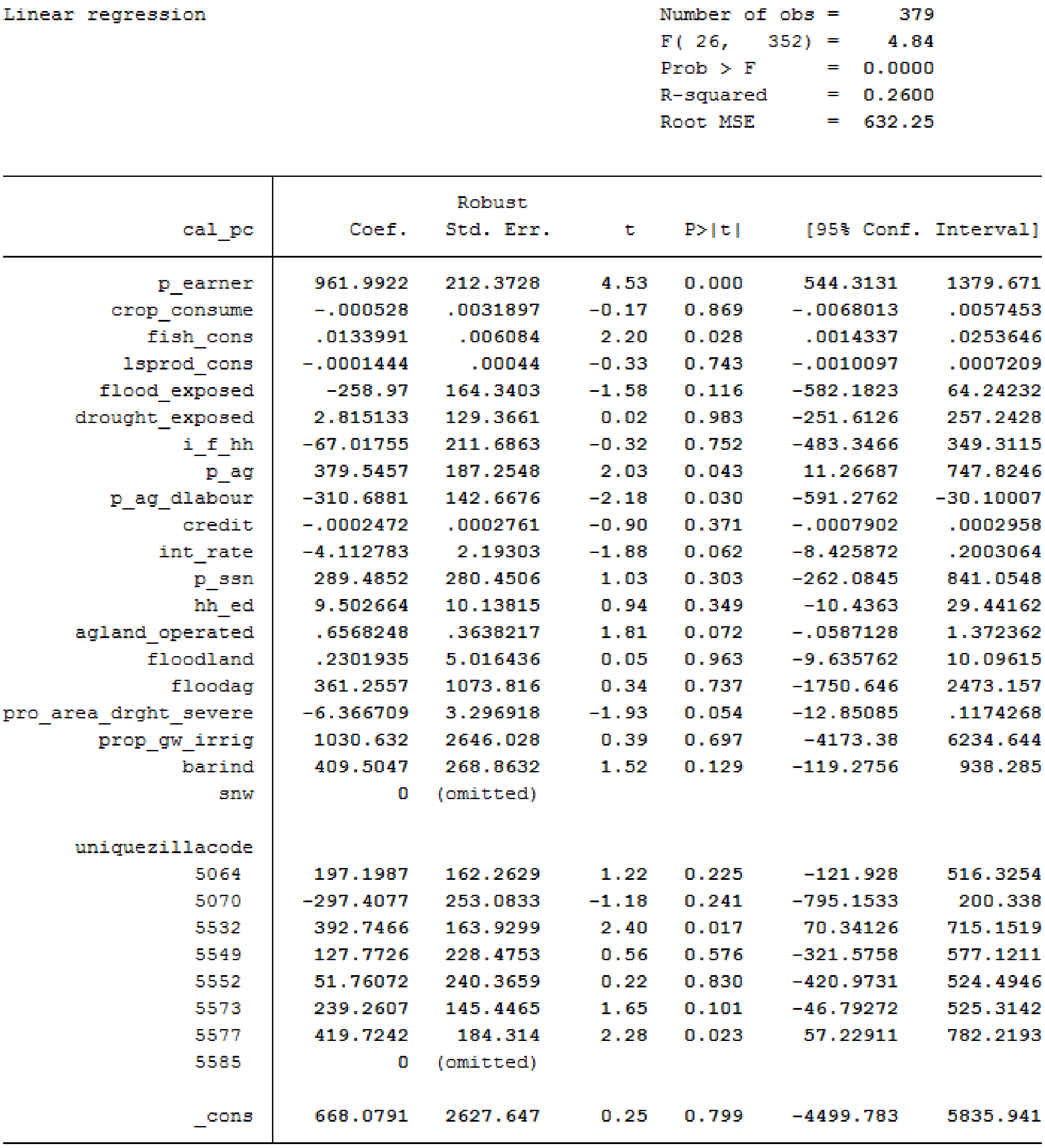


```
Linear regression                                      Number of obs =     379
                                                       F( 26,   352) =    4.84
                                                       Prob > F      =  0.0000
                                                       R-squared     =  0.2600
                                                       Root MSE      =  632.25

------------------------------------------------------------------------------------
                   |               Robust
            cal_pc |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------------+----------------------------------------------------------------
          p_earner |   961.9922   212.3728     4.53   0.000     544.3131    1379.671
      crop_consume |   -.000528   .0031897    -0.17   0.869    -.0068013    .0057453
         fish_cons |   .0133991    .006084     2.20   0.028     .0014337    .0253646
       lsprod_cons |  -.0001444     .00044    -0.33   0.743    -.0010097    .0007209
     flood_exposed |    -258.97   164.3403    -1.58   0.116    -582.1823    64.24232
   drought_exposed |   2.815133   129.3661     0.02   0.983    -251.6126    257.2428
            i_f_hh |  -67.01755   211.6863    -0.32   0.752    -483.3466    349.3115
              p_ag |   379.5457   187.2548     2.03   0.043     11.26687    747.8246
       p_ag_dlabour|  -310.6881   142.6676    -2.18   0.030    -591.2762   -30.10007
            credit |  -.0002472   .0002761    -0.90   0.371    -.0007902    .0002958
          int_rate |  -4.112783    2.19303    -1.88   0.062    -8.425872    .2003064
             p_ssn |   289.4852   280.4506     1.03   0.303    -262.0845    841.0548
            hh_ed  |   9.502664   10.13815     0.94   0.349     -10.4363    29.44162
    agland_operated|   .6568248   .3638217     1.81   0.072    -.0587128    1.372362
         floodland |   .2301935   5.016436     0.05   0.963    -9.635762    10.09615
           floodag |   361.2557   1073.816     0.34   0.737    -1750.646    2473.157
pro_area_drght_severe|  -6.248467   3.417614    -1.83   0.068    -12.96998     .473043
     prop_nca_irrig|  -436.5728    1120.85    -0.39   0.697    -2640.978    1767.832
            barind |   455.0591   264.5116     1.72   0.086    -65.16279    975.2809
               snw |          0  (omitted)
                   |
    uniquezillacode|
             5064  |   197.1987   162.2629     1.22   0.225     -121.928    516.3254
             5070  |  -376.9775   301.9342    -1.25   0.213    -970.7994    216.8444
             5532  |   226.7106   435.1017     0.52   0.603    -629.0153    1082.436
             5549  |   102.4519   198.2968     0.52   0.606    -287.5435    492.4474
             5552  |   26.44004   213.8068     0.12   0.902    -394.0593    446.9394
             5573  |   213.9401   147.1817     1.45   0.147    -75.52606    503.4062
             5577  |   394.4035   206.5631     1.91   0.057    -11.84948    800.6566
             5585  |          0  (omitted)
                   |
             _cons |   2045.699   921.1872     2.22   0.027      233.976    3857.422
------------------------------------------------------------------------------------
```

* See Table C.5 for *zilla* name and unique *zilla* code

Table C.2 Regression result for calorie consumption including prop_gw_irrig



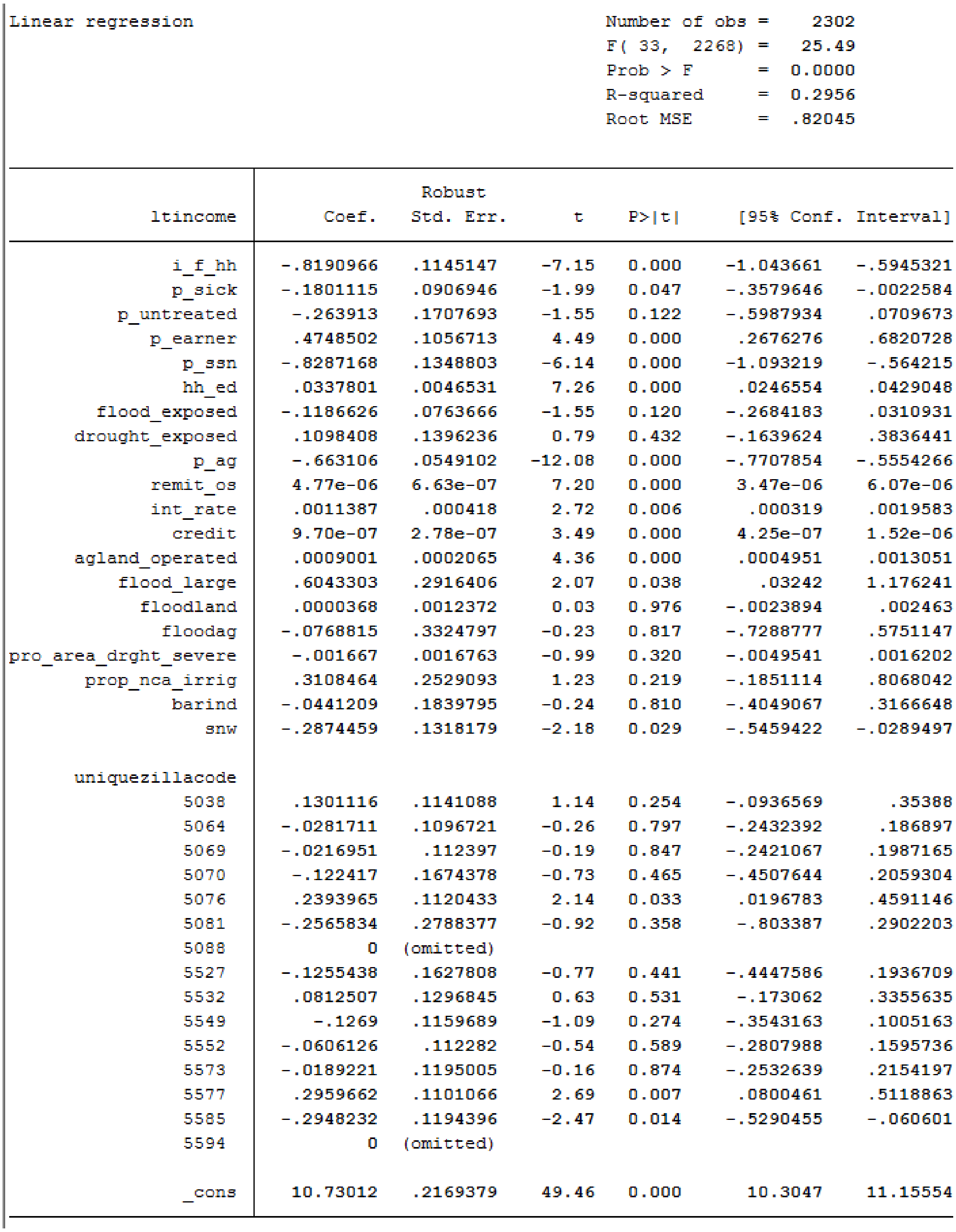
```
Linear regression                                      Number of obs =     379
                                                       F( 26,   352) =    4.84
                                                       Prob > F      =  0.0000
                                                       R-squared     =  0.2600
                                                       Root MSE      =  632.25

------------------------------------------------------------------------------------
                    |               Robust
             cal_pc |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
--------------------+---------------------------------------------------------------
           p_earner |   961.9922   212.3728     4.53   0.000     544.3131    1379.671
       crop_consume |   -.000528   .0031897    -0.17   0.869    -.0068013    .0057453
          fish_cons |   .0133991    .006084     2.20   0.028     .0014337    .0253646
        lsprod_cons |  -.0001444     .00044    -0.33   0.743    -.0010097    .0007209
      flood_exposed |    -258.97   164.3403    -1.58   0.116    -582.1823    64.24232
    drought_exposed |   2.815133   129.3661     0.02   0.983    -251.6126    257.2428
             i_f_hh |  -67.01755   211.6863    -0.32   0.752    -483.3466    349.3115
               p_ag |   379.5457   187.2548     2.03   0.043     11.26687    747.8246
       p_ag_dlabour |  -310.6881   142.6676    -2.18   0.030    -591.2762   -30.10007
             credit |  -.0002472   .0002761    -0.90   0.371    -.0007902    .0002958
           int_rate |  -4.112783    2.19303    -1.88   0.062    -8.425872    .2003064
              p_ssn |   289.4852   280.4506     1.03   0.303    -262.0845    841.0548
              hh_ed |   9.502664   10.13815     0.94   0.349     -10.4363    29.44162
     agland_operated |   .6568248   .3638217     1.81   0.072    -.0587128    1.372362
          floodland |   .2301935   5.016436     0.05   0.963    -9.635762    10.09615
            floodag |   361.2557   1073.816     0.34   0.737    -1750.646    2473.157
pro_area_drght_severe |  -6.366709   3.296918    -1.93   0.054    -12.85085    .1174268
        prop_gw_irrig |   1030.632   2646.028     0.39   0.697     -4173.38    6234.644
             barind |   409.5047   268.8632     1.52   0.129    -119.2756     938.285
                snw |          0  (omitted)
                    |
     uniquezillacode |
               5064 |   197.1987   162.2629     1.22   0.225     -121.928    516.3254
               5070 |  -297.4077   253.0833    -1.18   0.241    -795.1533     200.338
               5532 |   392.7466   163.9299     2.40   0.017     70.34126    715.1519
               5549 |   127.7726   228.4753     0.56   0.576    -321.5758    577.1211
               5552 |   51.76072   240.3659     0.22   0.830    -420.9731    524.4946
               5573 |   239.2607   145.4465     1.65   0.101    -46.79272    525.3142
               5577 |   419.7242    184.314     2.28   0.023     57.22911    782.2193
               5585 |          0  (omitted)
                    |
              _cons |   668.0791   2627.647     0.25   0.799    -4499.783    5835.941
------------------------------------------------------------------------------------
```

* See Table C.5 for *zilla* name and unique *zilla* code

C.2 Additional income regressions

Table C.3 Regression result for income including prop_nca_irrig

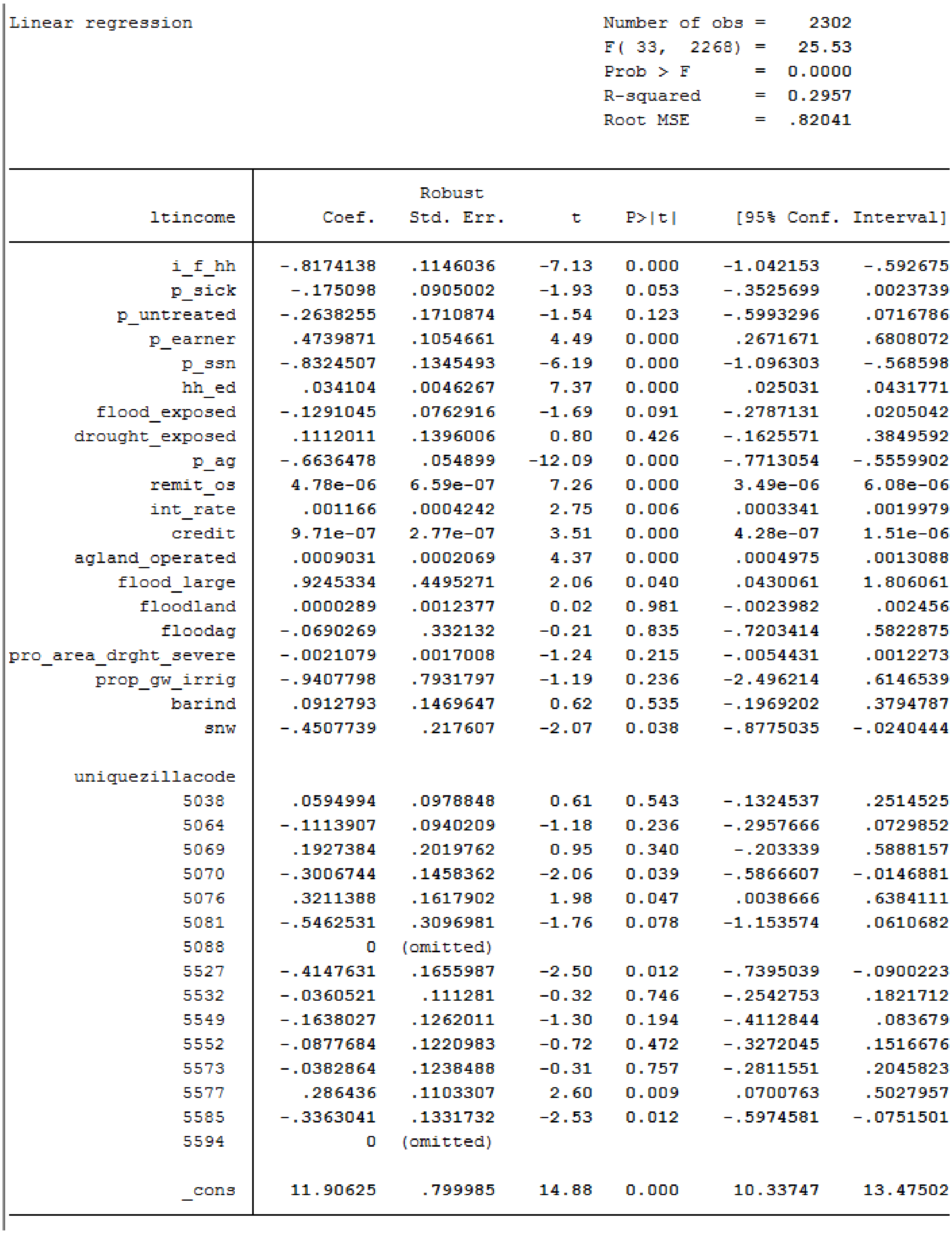


```
Linear regression                                      Number of obs =     2302
                                                       F( 33,  2268) =    25.49
                                                       Prob > F      =   0.0000
                                                       R-squared     =   0.2956
                                                       Root MSE      =   .82045

---------------------------------------------------------------------------------------
                      |               Robust
             ltincome |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------------+----------------------------------------------------------------
               i_f_hh |  -.8190966   .1145147    -7.15   0.000    -1.043661   -.5945321
               p_sick |  -.1801115   .0906946    -1.99   0.047    -.3579646   -.0022584
          p_untreated |   -.263913   .1707693    -1.55   0.122    -.5987934    .0709673
             p_earner |   .4748502   .1056713     4.49   0.000     .2676276    .6820728
                p_ssn |  -.8287168   .1348803    -6.14   0.000    -1.093219    -.564215
                hh_ed |   .0337801   .0046531     7.26   0.000     .0246554    .0429048
        flood_exposed |  -.1186626   .0763666    -1.55   0.120    -.2684183    .0310931
      drought_exposed |   .1098408   .1396236     0.79   0.432    -.1639624    .3836441
                 p_ag |   -.663106   .0549102   -12.08   0.000    -.7707854   -.5554266
            remit_os |   4.77e-06   6.63e-07     7.20   0.000     3.47e-06    6.07e-06
             int_rate |   .0011387    .000418     2.72   0.006      .000319    .0019583
               credit |   9.70e-07   2.78e-07     3.49   0.000     4.25e-07    1.52e-06
      agland_operated |   .0009001   .0002065     4.36   0.000     .0004951    .0013051
          flood_large |   .6043303   .2916406     2.07   0.038       .03242    1.176241
            floodland |   .0000368   .0012372     0.03   0.976    -.0023894     .002463
              floodag |  -.0768815   .3324797    -0.23   0.817    -.7288777    .5751147
pro_area_drght_severe |   -.001667   .0016763    -0.99   0.320    -.0049541    .0016202
        prop_nca_irrig |   .3108464   .2529093     1.23   0.219    -.1851114    .8068042
               barind |  -.0441209   .1839795    -0.24   0.810    -.4049067    .3166648
                  snw |  -.2874459   .1318179    -2.18   0.029    -.5459422   -.0289497
                      |
      uniquezillacode |
                5038  |   .1301116   .1141088     1.14   0.254    -.0936569      .35388
                5064  |  -.0281711   .1096721    -0.26   0.797    -.2432392     .186897
                5069  |  -.0216951    .112397    -0.19   0.847    -.2421067    .1987165
                5070  |   -.122417   .1674378    -0.73   0.465    -.4507644    .2059304
                5076  |   .2393965   .1120433     2.14   0.033     .0196783    .4591146
                5081  |  -.2565834   .2788377    -0.92   0.358     -.803387    .2902203
                5088  |          0  (omitted)
                5527  |  -.1255438   .1627808    -0.77   0.441    -.4447586    .1936709
                5532  |   .0812507   .1296845     0.63   0.531     -.173062    .3355635
                5549  |     -.1269   .1159689    -1.09   0.274    -.3543163    .1005163
                5552  |  -.0606126    .112282    -0.54   0.589    -.2807988    .1595736
                5573  |  -.0189221   .1195005    -0.16   0.874    -.2532639    .2154197
                5577  |   .2959662   .1101066     2.69   0.007     .0800461    .5118863
                5585  |  -.2948232   .1194396    -2.47   0.014    -.5290455    -.060601
                5594  |          0  (omitted)
                      |
                _cons |   10.73012   .2169379    49.46   0.000      10.3047    11.15554
---------------------------------------------------------------------------------------
```

* See Table C.5 for *zilla* name and unique *zilla* code

Table C.4 Regression result for income including prop_gw_irrig



```
Linear regression                               Number of obs =      2302
                                                F( 33,  2268) =     25.53
                                                Prob > F      =    0.0000
                                                R-squared     =    0.2957
                                                Root MSE      =    .82041

------------------------------------------------------------------------------
                     |               Robust
            ltincome |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
---------------------+--------------------------------------------------------
              i_f_hh |  -.8174138   .1146036    -7.13   0.000    -1.042153    -.592675
              p_sick |   -.175098   .0905002    -1.93   0.053    -.3525699    .0023739
         p_untreated |  -.2638255   .1710874    -1.54   0.123    -.5993296    .0716786
            p_earner |   .4739871   .1054661     4.49   0.000     .2671671    .6808072
               p_ssn |  -.8324507   .1345493    -6.19   0.000    -1.096303    -.568598
               hh_ed |    .034104   .0046267     7.37   0.000      .025031    .0431771
       flood_exposed |  -.1291045   .0762916    -1.69   0.091    -.2787131    .0205042
     drought_exposed |   .1112011   .1396006     0.80   0.426    -.1625571    .3849592
                p_ag |  -.6636478    .054899   -12.09   0.000    -.7713054   -.5559902
            remit_os |   4.78e-06   6.59e-07     7.26   0.000     3.49e-06    6.08e-06
            int_rate |    .001166   .0004242     2.75   0.006     .0003341    .0019979
              credit |   9.71e-07   2.77e-07     3.51   0.000     4.28e-07    1.51e-06
     agland_operated |   .0009031   .0002069     4.37   0.000     .0004975    .0013088
         flood_large |   .9245334   .4495271     2.06   0.040     .0430061    1.806061
           floodland |   .0000289   .0012377     0.02   0.981    -.0023982     .002456
             floodag |  -.0690269    .332132    -0.21   0.835    -.7203414    .5822875
pro_area_drght_severe |  -.0021079   .0017008    -1.24   0.215    -.0054431    .0012273
       prop_gw_irrig |  -.9407798   .7931797    -1.19   0.236    -2.496214    .6146539
              barind |   .0912793   .1469647     0.62   0.535    -.1969202    .3794787
                 snw |  -.4507739    .217607    -2.07   0.038    -.8775035   -.0240444
                     |
     uniquezillacode |
               5038  |   .0594994   .0978848     0.61   0.543    -.1324537    .2514525
               5064  |  -.1113907   .0940209    -1.18   0.236    -.2957666    .0729852
               5069  |   .1927384   .2019762     0.95   0.340     -.203339    .5888157
               5070  |  -.3006744   .1458362    -2.06   0.039    -.5866607   -.0146881
               5076  |   .3211388   .1617902     1.98   0.047     .0038666    .6384111
               5081  |  -.5462531   .3096981    -1.76   0.078    -1.153574    .0610682
               5088  |          0  (omitted)
               5527  |  -.4147631   .1655987    -2.50   0.012    -.7395039   -.0900223
               5532  |  -.0360521    .111281    -0.32   0.746    -.2542753    .1821712
               5549  |  -.1638027   .1262011    -1.30   0.194    -.4112844     .083679
               5552  |  -.0877684   .1220983    -0.72   0.472    -.3272045    .1516676
               5573  |  -.0382864   .1238488    -0.31   0.757    -.2811551    .2045823
               5577  |    .286436   .1103307     2.60   0.009     .0700763    .5027957
               5585  |  -.3363041   .1331732    -2.53   0.012    -.5974581   -.0751501
               5594  |          0  (omitted)
                     |
               _cons |   11.90625    .799985    14.88   0.000     10.33747    13.47502
------------------------------------------------------------------------------
```

* See Table C.5 for *zilla* name and unique *zilla* code

Table C.5 *Zilla* name and unique *zilla* code within northwest of Bangladesh

No	Zilla name	Unique Zilla Code
1	BOGRA	5010
2	DINAJPUR	5527
3	GAIBANDHA	5532
4	JOYPURHAT	5038
5	KURIGRAM	5549
6	LALMONIRHAT	5552
7	NAOGAON	5064
8	NATOR	5069
9	NAWABGANJ	5070
10	NILPHAMARI	5573
11	PABNA	5076
12	PANCHAGARH	5577
13	RAJSHAHI	5081
14	RANGPUR	5585
15	SIRAJGANJ	5088
16	THAKURGAON	5594

Acronyms and abbreviations

BADC	Bangladesh Agricultural Development Corporation
BMDA	Barind Multipurpose Development Authority
BRDB	Bangladesh Rural Development Board
BTM	Bangladesh Transverse Mercator
BUET	Bangladesh University of Engineering & Technology
BWDB	Bangladesh Water Development Board
BBS	Bangladesh Bureau of Statistics
DAE	Department of Agricultural Extension
DEM	Digital Elevation Model
DTW	Deep Tubewell
GW	Groundwater
GWL	Groundwater Level
HTW	Hand Tubewell
HYV	High Yielding Variety
IWM	Institute of Water Modelling
IDA	International Development Agency
NWMP	National Water Management Plan
PWD	Public Works Datum
SW	Surface Water
SWL	Surface Water Level
SRDI	Soil Resources Development Institute
STW	Shallow Tubewell

Measurement units

BCM	billion cubic metres)
Cfs	Cubic feet per Second
MCM	million cubic metres

References

Abdullah, M. (1989) The Effect of Seasonally on Intrahousehold Food Distribution and Nutrition in Bangladesh.

Adel, M.A. (2001) Effect on water resources from upstream water diversion in the Ganges Basin. Journal of Environmental Quality 30, 356-368.

Adhikary, S. K. Gupta, A.D., Babel, M.S., Perret, S.R., Clemente, R. (2012) Simulating river-aquifer dynamic interaction in the regional unconfined aquifer of southwestern Bangladesh." Journal of Engineering Science 03(1), 147-160.

Ahmad, M.D., Kirby, M., Islam, M.S., Hossain, M.J. Islam, M.M. (2014) Groundwater use for irrigation and its productivity: status and opportunities for crop intensification to achieve food security in Bangladesh. Water Resources Management. 28, 1415-1429: DOI 10.1007/s11269-014-0560-z.

Amin, S., Rai, A. S., Topa, G. (2003) Does microcredit reach the poor and vulnerable? Evidence from northern Bangladesh. Journal of Development Economics 70, 59-82.

BADC (2010) The Minor Irrigation Survey Report 2009-2010. Bangladesh Agricultural Development Corporation, Dhaka, Bangladesh.

Bangladesh Water Development Board (BWDB) (1987) Water Supply Paper-487, Regeneration Study of the Ganges, Ground Water Circle II, Bangladesh Water Development Board.

Bangladesh Water Development Board (BWDB) (1990) Water Survey for Barind Integrated Area Development Project, Volume l, Main Report

BARC (2011) Research Priorities in Bangladesh Agriculture: Agricultural Research Vision 2030 and Beyond. , Bangladesh Agricultural Research Council, Farmgate, Dhaka, Bangladesh.

BBS (2010) Report of the Household Income & Expenditure Survey 2010. Bangladesh Bureau of Statistics. Ministry of Planning, Dhaka, Bangladesh.

BBS (2011) 2010 Year Book of Agricultural Statistical of Bangladesh. Bangladesh Bureau of Statistics, Dhaka, Bangladesh.

BBS (2012). Year book of Agricultural Statistics of Bangladesh 2012. Bangladesh Bureau of Statistics, Government of Bangladesh.

BCA (2004) Bangladesh Country Almanac. Dhaka-1230, Bangladesh: CIMMYT Bangladesh.

Besbes, M., Delhomme J. P.,De Marsily, G. (1978) Estimating Recharge from Ephemeral Streams in Arid Regions, A Case Study at Kairouan, Tunisia, Water Resources Research 14(2), 281-290.

Brammer, H. (1999) Agricultural Disaster Management in Bangladesh. Dhaka: University Press Limited.

Bruinsma, J. (Ed.) (2003) World Agriculture: Towards 2015/1030, A FAO Perspective, Food and Agricultural Organization of the United Nations, Rome, 432 pp.

CEGIS (2009) Major flood inundation by greater 360 mm. ed. C. f. E. a. G. I. Services. Dhaka, Bangladesh.

Chowdhury, E.H. (1998) A Study on Groundwater Recharge and Discharge Characteristics over a reach of Ganges River, M Engg Thesis, BUET.

Comprehensive Assessment of Water Management in Agriculture (2007) Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan, and Colombo: International Water Management Institute

CSIRO, WARPO, BWDB, IWM, BIDS, CEGIS (2014) Bangladesh Integrated Water Resources Assessment: final report. CSIRO, Australia. Available at https://publications.csiro.au/rpr/pub?pid=csiro:EP142841 (accessed May 2014).

Dey, N.C., Bala, S. K., Islam, A. S., Rashid, M. A. (2013) Sustainability of groundwater use for irrigation in Northwest Region. Dhaka, Bangladesh: National Food Policy Capacity Strengthening Programme, Govt. of Bangladesh, USAID, Food and Agricultural Organization (FAO).

Elahi, K.M., Ara, I. (2008) Understanding the Monga in Northern Bangladesh. Dhaka, Bangladesh: Academic Press and Publishers Library.

FAO (2003) International Rice Commission Newsletter. Special edition, Vol. 52, Food and Agricultural Organization of the United Nations, Rome. ftp://ftp.fao.org/docrep/fao/006/y5167E/y5167E00.pdf

Fisher, G. Tubiello, F.N., van Velthuizen, H., Wiberg, D.A. (2007) Climate change impacts on irrigation water requirements: Effects of mitigation, 1990–2080. Technological Forecasting & Social Change 74, 1083–1107.

Fujita, K., Hossain, F. (1995) Role of the ground water market in agricultural development and income distribution: A case study in a Northwest Bangladesh village. The Developing Economies 33, 460-463.

Government of Bangladesh (2010) Outline Perspective Plan of Bangladesh 2010-2021: Making Vision 2021 a Reality. General Economic Division, Planning Commission, Government of The People's Republic of Bangladesh. http://www.plancomm.gov.bd/Final_Draft_OPP_June_2010.pdf

Hanjra, M.A., Qureshi, M.E. (2010) Global water crisis and future food security in an era of climate change. Food Policy 35, 365-377.

Haq, N. (2013). Fresh Water "More Precious Than Gold" in Bangladesh. Inter Press Service News Agency. http://www.ipsnews.net/2013/05/fresh-water-more-precious-than-gold-in-bangladesh/

Haque, M.A.M., Jahan, C.S., Mazumder, Q.H., Newaz, S.M.S., Mirdha, G.C., Mamud, P., Adham, M.I. (2012). Hydrogeological Condition and Assessment of Groundwater Resource Using Visual Modflow Modeling, Rajshahi City Aquifer, Bangladesh. Journal Geological Society of India 79, 77-84.

HIES (2010) Household Income-Expenditure Survey, 2009-12 Project. Dhaka, Bangladesh: Bangladesh Bureau of Statistics.

Hodgson, G., Ali, R., Turneer, J., Ahmad, M., Dawes, W., Masud, M.S., Hossain, M.J., Alam, S., Islam, M.M., Saha, G.K., Barman, T.D. (2014) Bangladesh Integrated Water Resources Assessment supplementary report: Water table trends and associated vertical water balance in Bangladesh. Water for a Healthy Country Flagship, CSIRO, Australia.

Hoque, M.M., Islam, M.S. (undated) Conjunctive Use of Groundwater and Surface Water for Buri Teesta Irrigation Project. Available at http://teacher.buet.ac.bd/akmsaifulislam/publication/PBURIPAK.PDF

Hossain, G., Howladar, M.F., Nessa, L., Ahmed, S.S., Chowdhury, Q. (2010). Hydrochemistry and Classification of Groundwater Resources of Ishwardi Municipal Area, Pabna District, Bangladesh. Geotech Geol Eng 28, 671–679.

Imon, A. H. M. R., Ahmed, M. (2013) Water Level Trend in the Barind Area. Malaysian Journal of Mathematical Sciences 7, 1-15.

Islam, M. T. (2009) Barind Aquifer-Ganges River Interaction, M. Eng. Thesis, WRE, BUET, Bangladesh.

Islam, M.D.J., Mondal, M.K. (1992) Water management strategy for increasing monsoon rice production in Bangladesh. Agricultural Water Management 22, 335-343.

IWM (2006) Groundwater Model Study for Deep Tubewell Installation Project in Barind Area, Final Report, Barind Multipurpose Development Authority, Ministry of Agriculture, GoB.

IWM (2014a) Bangladesh Integrated Water Resources Assessment supplementary report: Surface Water and Groundwater Interaction. Institute of Water Modelling, Dhaka.

IWM (2014b) Surface Water Assessment of Bangladesh and Impact of Climate Change: A supplementary report of the Bangladesh Integrated Water Resources Assessment Institute of Water Modelling, Dhaka.

Jahan, C.S., Mazumder, Q.H., Islam, A.T.M.M, Adham, M.I. (2010) Impact of irrigation in Barind area, NW Bangladesh – an evaluation based on meteorological parameters and fluctuation trend in groundwater table. Journal Geological Society of India 76, 134-142.

Jensen, J.R., Mannan, S.M.A., Uddin, S.M.N. (1993) Irrigation requirement of transplanted monsoon rice in Bangladesh. Agricultural Water Management 23, 199-212.

Jolly, I.D., Walker, G.R., Narayan, K.A. (1994) Floodwater recharge processes in the Chowilla anabranch system. Soil Research 32(3), 417-435.

Kam, S.-P., Hossain, M., Bose, M. L., Villano, L. S. (2005) Spatial patterns of rural poverty and their relationship with welfare-influencing factors in Bangladesh. Food Policy 30, 551-567.

Karim, K. M. R., Emmelin, M., Resurreccion, B. P., Wamala, S. (2012) Water Development Projects and Marital Violence: Experiences from Rural Bangladesh. Health Care for Women International 3.

Karim, M. A. (1972) Ground Water Potential in Northern Areas of Dinajpur and Rangpur Districts, Bangladesh Water Development Board.

Karimi P, Bastiaanssen, W.G.M., Molden, D. (2013) Water Accounting plus (WA+) - a water accounting procedure for complex river basins based on satellite measurements. Hydrology and Earth System Sciences 17, 2459-2472.

Kennedy, P. (2008) A Guide to Econometric. USA: Blackwell Publishing.

Khan, F.K., Islam, M.A. (1966) Water balance of East Pakistan. Oriental Geographer 10, 1-9.

Khandker, S.R., Samad, H.A., Khan, Z. H. (1998) Income and employment effects of micro-credit programmes: Village-level evidence from Bangladesh. The Journal of Development Studies 35, 96-124.

Kirby, M, Ahmad, M.D., Poulton, P., Zhu, Z., Lee, G., Mainuddin, M. (2013) Review of water, crop production and system modelling approaches for food security studies in the Eastern Gangetic Plains. CSIRO Report, AusAID - CSIRO Alliance. Available at https://publications.csiro.au/rpr/pub?pid=csiro:EP134291

Kirby, M., Ahmad, M.D., Mainuddin, M., Palash, W., Qadir, E., Shah-Newaz, S.M. (2014) Bangladesh Integrated Water Resources Assessment, supplementary report: approximate regional water balances. CSIRO, Australia. Available at https://publications.csiro.au/rpr/pub?pid=csiro:EP141282 (accessed May 2014).

Kirby, M., Mainuddin, M. Eastham, J. (2010) Water-use accounts in CPWF basins: Model concepts and description. CPWF Working Paper: Basin Focal Project series, BFP01.Colombo, Sri Lanka: The CGIAR Challenge Program on Water and Food. 21pp. http://cgspace.cgiar.org/bitstream/handle/10568/4084/CPWF_BFP_WP_01.pdf?sequence=3 (accessed March 2014).

Koppen, B. V., Mahmud, S. (1995) Women and water-pumps in Bangladesh: the impact of participation in irrigation groups on women's status.

Kristensen, K.J., Jensen, S.E. (1975) A model for estimating actual evapotranspiration from potential evapotranspiration. Nordic Hydrology 6(3), 170–188.

Lewis, D.J. (1993) Going it alone: Female-headed households, rights and resources in rural Bangladesh. The European journal of development research 5, 23-42.

Macdonald and Partners, Sir M. (1977) BADC/IDA Tubewell Project, Vol. III, Groundwater; Bangladesh Agricultural Development Corporation.

Mainuddin, M., Kirby, M., Chowdhury, R.A.R., Sanjida, L., Sarker, M.H., Shah-Newaz, S.M. (2014) Bangladesh Integrated Water Resources Assessment supplementary report: land use, crop production, and irrigation demand. CSIRO: Water for a Healthy Country Flagship, Australia. Available at https://publications.csiro.au/rpr/pub?pid=csiro:EP141373 (accessed May 2014)

Mainuddin, M., Kirby, M., in review. National food security of Bangladesh to 2050. Food Security.

Mainuddin, M., Rawson, H.M., Poulton, P.L., Ali, R., Roth, C., Islam, K.M., Saifuzzaman, M., Rahman, M.M., Quader, M.E., Shah-Newaz, S.M., Sarker, M.H., Islam, M.S. (2013) Scoping study to assess constraints and opportunities for future research into intensification of cropping systems in Southern Bangladesh. Australian Centre for International Agricultural Research, Canberra.

Mbugua, A. (2011) Water scarcity in Northern Bangladesh. Parbatipur, Dinajpur, Bangladesh: VSO and GBK.

Meinzen-Dick, R. Zwarteveen, M. (1998) Gendered participation in water management: Issues and illustrations from water users‘ associations in South Asia. Agriculture and Human Values, 15 337-345.

Ministry of Agriculture, FAO (2013) Master Plan for Agricultural Development in the Southern Region of Bangladesh. Ministry of Agriculture of the Government of Bangladesh and Food and Agriculture Organization of the United Nations.

Mirza, M.M.Q. (1997) Hydrological changes in the Ganges system in Bangladesh in the post-Farakka period. Hydrological Sciences Journal 42, 613-631.

Molden, D., Sakthivadivel, R. (1999) Water Accounting to Assess Use and Productivity of Water, International Journal of Water Resources Development 15:1-2, 55-71, DOI: 10.1080/07900629948934

Morel-Seytoux, H.J. M. (1975) A Combined Model of Water Table and River Stage Evolution, Water Resources Research 11(6), 968-972.

Mridha, G.C. (2005) Groundwater-Surface Water Interactions Model for Water Resources Management, A Case Study in Northwestern Bangladesh, M. Sc Thesis, VUB, Belgium.

Nargis, N., Hossain, M. (2006) Income dynamics and pathways out of rural poverty in Bangladesh, 1988–2004. Agricultural Economics 35, 425-435.

Nobi, N., Gupta A.D. (1997) Simulation of Regional Flow and Salinity Intrusion an Integrated Stream-Aquifer System in Coastal Region: Southwest Region Bangladesh, Journal of Groundwater 135, 786-797.

Pryer, J. (1993) The impact of adult ill-health on household income and nutrition in Khulna, Bangladesh. Environment and Urbanization, 5, 35-49.

Rahman, M.A., Roehrig, J. (2006) Estimation of potential recharge and groundwater resources assessment – a case study in low Barind area Bangladesh. In Conference in International Agricultural research for Development, University of Bonn, October 11-13 2006. Available at http://www.tropentag.de/2006/abstracts/full/463.pdf (accessed April 2013)

Rahman, M.A., Jackson, R. (2006) Estimation of Potential recharge and groundwater resources assessment- A case study in low Barind area, Bangladesh. Conference on International Agricultural Research for Development, Tropentag 2006 University of Bonn, October 11-13, 2006

Rahman, M.M., Mahbub, A.Q.M. (2012) Groundwater depletion with expansion of irrigation in Barind Tract: a case study of Tanore Upazila. Journal of Water Resource and Protection 4, 567-575.

Rosegrant, M.W., Paisner, M.S., Meijer, S., Witcover, J. (2001) Global Food Projections to 2020: Emerging Trends and Alternative Futures. International Food Policy Research Institute, Washington D.C.

Roy, S.D. (2013) Flood damage *Aman* seedlings in Lalmonirhat char villages. The Daily Star, 16 July 2013. http://www.thedailystar.net/beta2/news/flood-damages-*Aman*-seedlings-in-lalmonirhat-char-villages/

Seckler, D., Molden, D. Amarasinghe, U., de Fraiture, C. (2000) Water issues for 2025: A research perspective. International Water Management Institute, Colombo, Sri Lanka

Shahid, S. (2008) Spatial and temporal characteristics of droughts in the western part of Bangladesh. Hydrological Processes 22, 2235-2247.

Shahid, S., Behrawan, H. (2008) Drought risk assessment in the western part of Bangladesh. Natural Hazards 46, 391-413.

Shahid, S., Hazarika, M.K. (2010) Groundwater drought in the northwestern districts of Bangladesh. Water Resources Management 24, 1989-2006.

Shamsudduha, M., Chandler, R. E., Taylor, R., Ahmed, K. M. (2009) Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-Meghna Delta. Hydrol. Earth Syst. Sci., 13, 2373–2385.

Shamsudduha, M., Taylor, R.G., Ahmed, K. M., Zahid, A. (2011) The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh. Hydrogeology Journal 19, 901–916.

The Daily Star (2013). No rice imports in last two years. The Daily Star, 28 August 2013, Dhaka, Bangladesh.

Thompson, P., Roos, N., Sultana, P., Thilsted, S. H. (2002) Changing Significance of Inland Fisheries for Livelihoods and Nutrition in Bangladesh. Journal of Crop Production 6, 249-317.

Thorne-Lyman, A. L., Valpiani, N., Sun, K., Semba, R. D., Klotz, C. L., Kraemer, K., Akhter, N., Moench-Pfanner, S. de Pee, R., Sari, M., Bloem, M. W. (2010) Household Dietary Diversity and Food Expenditures Are Closely Linked in Rural Bangladesh, Increasing the Risk of Malnutrition Due to the Financial Crisis. The Journal of Nutrition 140, 182S-188S.

Tukey, J. W. 1977. Exploratory Data Analysis. Reading MA: Addition-Wesley.

UN Population Division (2012) Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2010 Revision, http://esa.un.org/unpd/wpp/index.htm

WARPO (2000) National Water Management Plan. Water Resources Planning Organisation, Dhaka.

World Bank, BBS (2010) Bangladesh Household Income and Expenditure Survey: Key Findings and result. ed. Ministry of Planning. Dhaka, Bangladesh: Government of the people's Republic of Bangladesh.

Zug, S. (2006) Monga - seasonal food insecurity in Bangladesh - bringing the information together. Journal of Social Studies 111.

CONTACT US

t 1300 363 400
+61 3 9545 2176
e enquiries@csiro.au
w www.csiro.au

YOUR CSIRO

Australia is founding its future on science and innovation. Its national science agency, CSIRO, is a powerhouse of ideas, technologies and skills for building prosperity, growth, health and sustainability. It serves governments, industries, business and communities across the nation.