

Groundwater Dynamics and Arsenic Mobilisation in Bangladesh: a National-Scale Characterisation

A thesis submitted for the degree of Doctor of Philosophy in the Faculty of Social and
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*This thesis is dedicated in loving memory
to my late father, my beloved mother,
lovely wife, and family*

Declaration

I, Mohammad Shamsudduha, confirm that the work presented in this thesis entitled “Groundwater Dynamics and Arsenic Mobilisation in Bangladesh: a National-Scale Characterisation”, is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis with an appropriate reference.



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Date: 08 September 2011

Abstract

Elevated arsenic (As) concentrations in groundwater-fed drinking water supplies in Bangladesh are a major public health problem but the hydrogeological conditions that give rise to the mobilisation and regional-scale distribution of As in shallow groundwater remain unknown. Published hypotheses developed from highly localised case studies are, to date, untested regionally and contradictory. My doctoral thesis makes a novel and substantial contribution to knowledge of the relationship between groundwater dynamics and As mobilisation in the Bengal Basin by (1) characterising national-scale groundwater storage dynamics and recharge processes in the shallow aquifer of Bangladesh and (2) relating statistically static and dynamic hydrogeological factors to the observed variation of As concentrations in groundwater. After constructing a national database of shallow groundwater levels from a network of 1267 monitoring stations, robust statistical techniques are applied to characterise long-term (1985 to 2005) trends and seasonality in groundwater levels, net recharge, and groundwater storage; the latter is supported by analysis of remotely sensed data derived from GRACE (Gravity Recovery and Climate Experiment). These characterisations highlight the critical influence of groundwater abstraction on net recharge to the shallow aquifer. Net annual recharge in Bangladesh has increased in response to intensive abstraction challenging conventional definitions of “safe yield”. To examine the national-scale variability in groundwater As concentrations generalised regression models were constructed using geology and hydrological factors. Crucially, these models reveal that areas of increasing groundwater-fed irrigation and net recharge are associated with lower As concentrations. These findings are inconsistent with current hypotheses that contend irrigation-induced recharge mobilises groundwater As in shallow aquifers. Inverse associations between As concentrations and both mean annual recharge and trends in groundwater-fed irrigation suggest that As has been actively flushed from the shallow aquifer as a result of recently increased net recharge induced by intensive irrigation in Bangladesh.

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List of Acronyms

AEZ (Agro Ecological Zones)
BADC (Bangladesh Agricultural Development Corporation)
BARC (Bangladesh Agricultural Research Council)
BGS (British Geological Survey)
BWDB (Bangladesh Water Development Board)
CGWB (Central Ground Water Board)
CSR (Center for Space Research)
DEM (Digital Elevation Model)
DPHE (Department of Public Health Engineering)
DTW (Deep Tubewell)
DWASA (Dhaka Water Supply and Sewerage Authority)
ESRI (Environmental Systems Research Institute)
FAO (Food and Agriculture Organisation)
GBM (Ganges-Brahmaputra-Meghna)
GIS (Geographical Information System)
GLDAS (Global Land Data Assimilation System)
GPS (Global Positioning System)
GRACE (Gravity Recovery and Climate Experiment)
GRGS (The Group de Recherche en Géodesie Spatiale)
GWL (Groundwater Level)
GWT (Groundwater Table)
HTW (Hand Tubewell)
IBRD (International Bank for Reconstruction and Development)
IPCC (Intergovernmental Panel on Climate Change)
IRRI (International Rice Research Institute)
LLP (Low Lift Pump)
LOWESS (Locally Weighted Scatterplot Smoothing)
MCM (Million Cubic Metres)
MPO (Master Plan Organisation)
NADA (Nondetects And Data Analysis)
NASA (National Aeronautics and Space Administration)
NHS (National Hydrochemical Survey)
PWD (Public Works Datum)
ROS (Regression on Ordered Statistics)
SPARRSO (Space Research and Remote Sensing Organization)
SRTM (Shuttle Radar Topography Mission)
STL (Seasonal-Trend decomposition procedure based on Loess)
STW (Shallow Tubewell)
SWS (Surface Water Storage)
TWS (Terrestrial Water Storage)
UNDP (United Nations Development Programme)
WARPO (Water Resources Planning Organisation)
WHO (World Health Organisation)
WTF (Water Table Fluctuation)

Part A:

Introduction and Rationale

Chapter 1

Introduction and Study Area

1.1 Background and Rationale

Elevated arsenic (As) in groundwater is a major environmental and public health concern in low-lying floodplains and mega-deltas in South and Southeast Asia (Figure 1.1) (Fendorf et al. 2010) where nearly 100 million people are currently exposed to unsafe levels of As in drinking water supplies (Ravenscroft et al. 2009). The health impact of the enriched As in drinking water supplies, particularly in rural parts of Bangladesh, was recognised a decade ago as the largest mass poisoning in history (Smith et al. 2000). A recent study (Argos et al. 2010) in an As-affected area of central Bangladesh attributes more than a fifth (21.4%) of all deaths to the exposure to As concentrations greater than the WHO standard of 10 µg/L in drinking water supplied by hand-operated tubewells. Despite the rising public health concerns associated with the long-term, regular consumption of high concentrations of As in drinking water, current understanding of groundwater dynamics and hydrogeological conditions under which As is mobilised in shallow groundwater are unclear.

The geogenic nature of groundwater As and its mobilisation primarily from iron-oxhydroxide minerals through the reductive dissolution process mediated by microbial metabolism of organic carbon (OC) has been widely accepted by the global scientific community (Bhattacharya et al. 1997; Nickson et al. 1998; BGS and DPHE 2001; Harvey et al. 2002; Islam et al. 2004; McArthur et al. 2004; Saunders et al. 2005; Zheng et al. 2005; Shamsudduha et al. 2008). Controversy over the source and nature of the OC remains. Several hypotheses proposed over the last decade postulate that OC derives from buried peat deposits (McArthur et al. 2001), carbon-enriched recharge from surface-water (Harvey et al. 2002), co-deposition of plant materials with sediments over geologic time (BGS and DPHE 2001; Meharg et al. 2006), or recharge water from ponds (Neumann et al. 2010). Since the distribution of observed groundwater As in Bangladesh and other Asian Mega-Deltas cannot be entirely explained by the variation of solid-phase As in aquifer sediments (Neumann et al. 2010), the type and sources of OC which drive the

microbial reductions remain critical in explaining the variation in groundwater As concentrations.

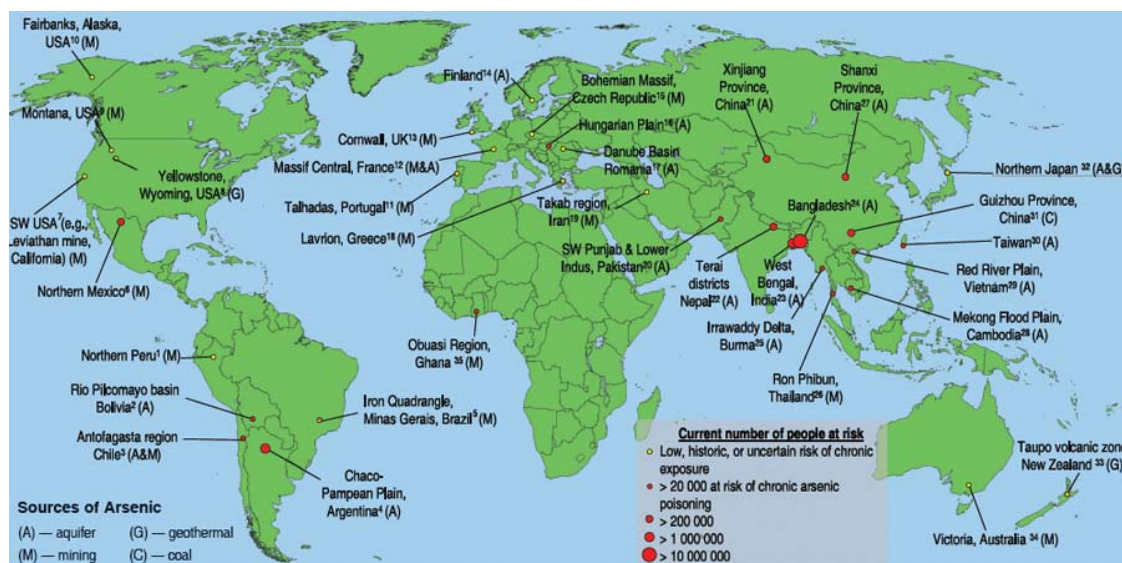


Figure 1.1 Map showing locations of As-contaminated areas around the world (Garelick and Jones 2008). Highest number of people exposed to elevated As concentrations in drinking water supplies are in Bangladesh and West Bengal, India.

Groundwater flow plays an important role in the transportation and distribution of As and its evolution in alluvial aquifers (Fendorf et al. 2010; Hoque 2010). Groundwater flow systems in the Bengal Basin of Bangladesh and other Asian lowland river basins and deltas all feature highly seasonal characteristics (i.e., high amplitude in annual groundwater levels) due to monsoonal climate and similar hydrogeological conditions (Harvey et al. 2002; Benner et al. 2008; Larsen et al. 2008). Shallow (<50 m below ground level, bgl) groundwater flow systems are highly dynamic reflecting transient, intra-annual patterns of recharge and discharge (Fendorf et al. 2010). Unlike other Asian Mega-Deltas (Figure 1.2) groundwater-fed irrigation to sustain dry-season hybrid rice (Boro) cultivation is substantial in the Ganges-Brahmaputra-Meghna (GBM) Delta of Bangladesh. Intensive irrigation and return flow from agricultural fields modify regional and local flow patterns (MPO 1987; WARPO 2000; Ravenscroft et al. 2005; Harvey et al. 2006; Mukherjee et al. 2007; Michael and Voss 2008; Michael and Voss 2009a).

A range of contrasting hypotheses has been proposed to establish causal links between groundwater recharge and As mobilisation in the Bengal Basin (Figure 1.3; Table 1.1 provides a summary). Based on geochemical observations and hydrogeological conditions at localised study sites in Bangladesh a series of hypotheses have been proposed which assert that irrigation-induced recent recharge triggered groundwater As

mobilisation by drawing OC from agricultural fields (Harvey et al. 2002; Harvey et al. 2006). Specifically, intensive irrigation is thought to induce mixing of young, OC-enriched groundwater with older groundwater at depths where As concentrations are the highest (Klump et al. 2006); recent recharge from ponds carries reactive OC into shallow aquifers facilitated by intensive irrigation pumping and mobilise groundwater As (Neumann et al. 2010).

In contrast, it has also been proposed (BGS and DPHE 2001; McArthur et al. 2004; Ravenscroft et al. 2005; Stute et al. 2007; van Geen et al. 2008) that recharge flushes the aquifer which subsequently depletes mobilisable As content over time. Recent groundwater-fed irrigation has induced more recharge to shallow aquifers and, therefore, flushed out As from aquifer's sediments and water in areas of greater groundwater recharge. The assumptions central to these hypotheses have never been tested at the basin or national scale beyond the localised study areas. It is also unknown whether recharge or groundwater-fed irrigation can explain the national-scale variability in observed As concentrations in shallow aquifers.

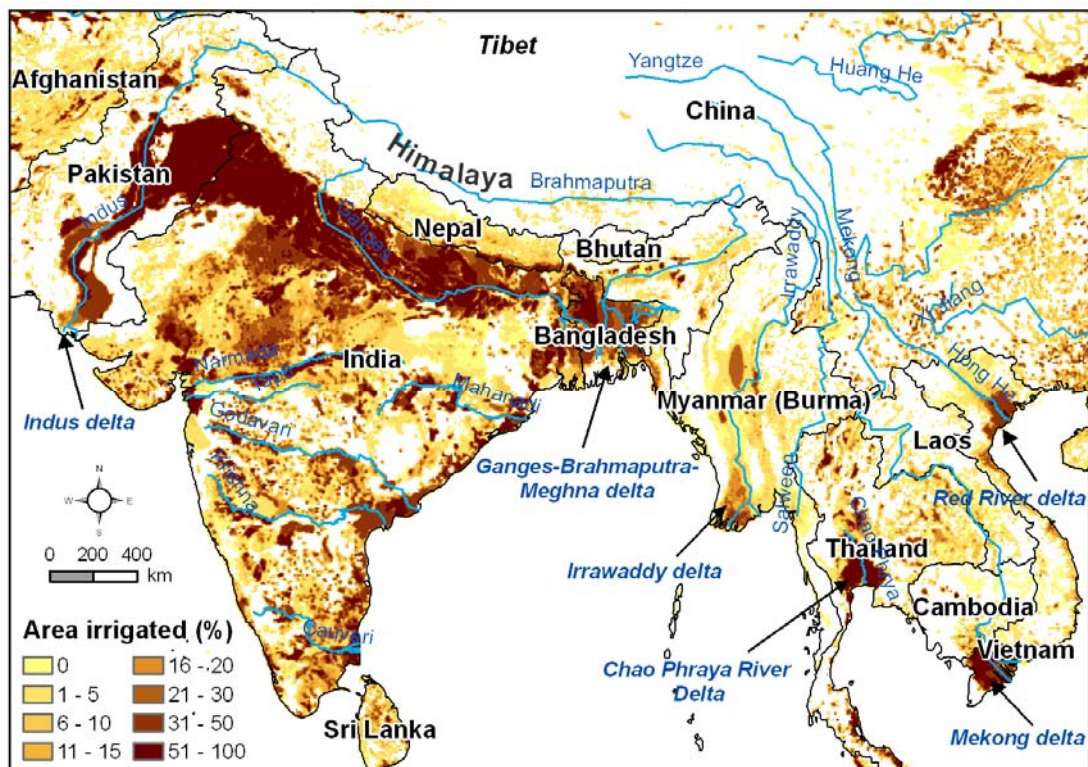


Figure 1.2 General location of the mega deltas of South and Southeast Asian countries. Areas in these deltas that are equipped for irrigation (shown in colour shades) are taken from the digital global map of irrigation (Siebert et al. 2006). Areas under irrigation are shown as percentages of the surface area. In the GBM delta, groundwater-fed irrigation accounts for 30% of the country's total land area. Irrigation is, however, mainly conducted from surface water in many of these mega deltas in Asia.

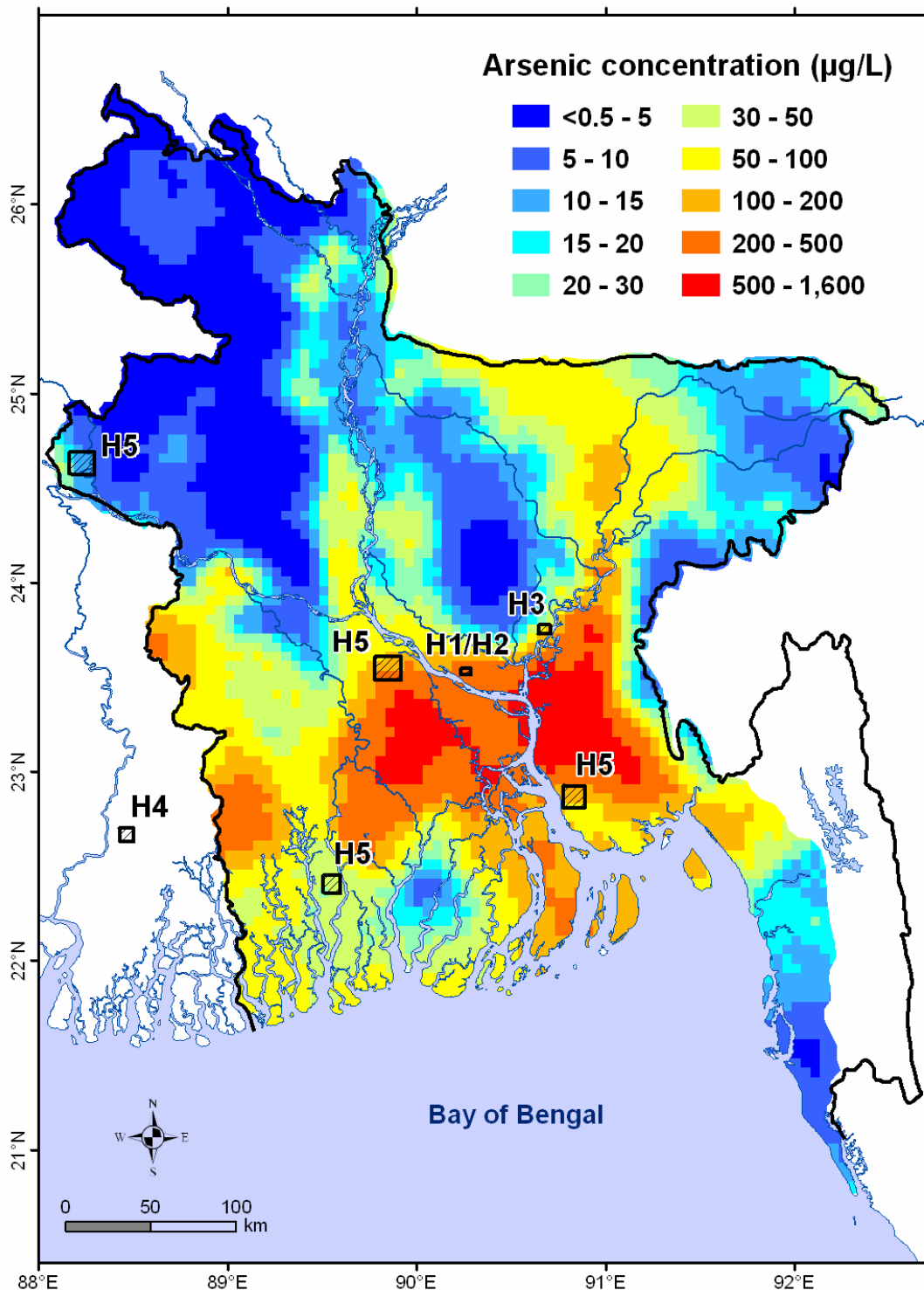


Figure 1.3 Spatial distribution of groundwater As concentrations in shallow (<50 m bgl) aquifers in Bangladesh. The gridded map of As concentrations was created by interpolating 2410 data points using Ordinary Kriging method with a fitted variogram model. Locations for the study sites associated with various As mobilisation hypotheses are shown on the map. Keys: H-1: young carbon hypothesis (Harvey et al., 2002, 2006); H-2: groundwater mixing hypothesis (Klump et al., 2006); H-3: aquifer flushing hypothesis (Stute et al., 2007; van Geen et al., 2008); H-4: As-peat hypothesis (Ravenscroft et al., 2001; McArthur et al., 2004); and H-5: As-OC codeposition hypothesis (Meharg et al., 2006).

Table 1-1 Proposed hypotheses on the mobilisation of groundwater As in shallow aquifers in Bangladesh. Assumed processes or mechanism(s) associated with each of these hypotheses are summarised below. Hydrodynamic components (direct or indirect) of each hypothesis have been derived. References for each hypothesis are also listed.

No	Hypothesis	Mechanism for As mobilisation	Hydrodynamic components	Geological control	References
H1	Young carbon hypothesis	Ponds and irrigation return-flows provide organic carbon for Fe-oxyhydroxides reduction and mobilisation of As at shallow depths	Irrigation enhances recharge (induced) by lowering groundwater levels and creating vertical hydraulic gradients in shallow aquifers	Geologically independent	Harvey et al. (2002; 2006)
H2	Groundwater mixing hypothesis	Pumping for intensive irrigation causes convergent groundwater flow and promotes mixing between shallow, younger and deeper, older groundwaters	Changes in hydraulics due to irrigation causes As mobilisation. Irrigation increases the rate of groundwater renewal by pumping large water volumes	Geologically independent	Klump et al. (2006)
H3	Aquifer flushing hypothesis	Irrigation induces recharge and thereby reduces the residence times of shallow groundwater. At shallow depths (<20 m bgl), As positively correlate with groundwater residence times	As concentrations at shallow depths are controlled by aquifer flushing rates. Increased irrigation results in a reduction of As concentrations in shallow aquifers. Areas of low recharge have high As concentrations	Geologically independent	McArthur et al. (2004); Stute et al. (2007); van Geen et al. (2008)
H4	As-peat hypothesis	Peat provides the organic carbon to drive the microbial reduction of Fe-oxyhydroxides. Spatial distributions of As do not correlate with areas of intensive abstractions for irrigation	No direct indication of hydrodynamics control. Higher As concentrations negatively correlate with dry-season water levels and also with groundwater-fed irrigation trends. Less irrigated areas have higher As concentrations	Geologically dependent	Ravenscroft et al. (2001; 2005); McArthur et al. (2004)
H5	As-OC codeposition hypothesis	As was codeposited with organic carbon in the aquifer sediments. Areas of higher abstraction for irrigation have lower As concentrations in groundwater	No direct indication of hydrodynamics control. As concentrations are highest where irrigation is lowest. In other words, low-As concentrations are associated with areas of declining groundwater levels due to irrigation	Geologically dependent	Meharg et al. (2006)

One of the challenges to examine the impacts of hydrogeological factors on As concentrations is, to date, the absence of a national database of time series observations of shallow groundwater levels. The impact of intensive groundwater-fed irrigation on the recharge to shallow aquifers in Bangladesh has also not been assessed. Control of near-surface geology on the regional distribution of groundwater As has been suggested in previous research (BGS and DPHE 2001; Ahmed et al. 2004) yet no study has examined the simultaneous effects of surface geology and hydrogeological factors on the national-scale variations of groundwater As concentrations.

1.1.1 Research Goals and Objectives

Principal goals of this research are (1) to understand shallow groundwater dynamics in the highly-seasonal hydrological systems in the Ganges-Brahmaputra-Meghna (GBM) Delta in Bangladesh, and (2) to identify relationships between observed changes in groundwater dynamics and mobilisation of As in shallow alluvial aquifers. These goals will be achieved by considering the following objectives specific to this research:

- constructing a national database of monitoring groundwater levels in Bangladesh in order to examine shallow groundwater dynamics and storage changes;
- estimating actual (net) groundwater recharge to shallow aquifers by applying the national groundwater-level database;
- examining the variability in observed As concentrations in shallow groundwater in Bangladesh; and
- testing a range of previously proposed hypotheses on the mobilisation of As in groundwater by applying the knowledge of shallow groundwater dynamics and hydrogeological factors.

1.1.2 Thesis Structure

This thesis is presented as a series of inter-related but mostly self-contained chapters which address the research aims and follow the specific objectives outlined above. There are three parts of this thesis consisting of single or multiple chapters. Each chapter features a review of the literature relevant to that component of the thesis. Chapter 1 presents the research goals and a brief description of the study area. Construction of the national groundwater-level database and exploratory analyses of shallow groundwater levels and their spatio-temporal dynamics are presented in Chapter 2. A further extension

to Chapter 2, changes in shallow groundwater storage in Bangladesh have been presented in Chapter 3. Estimation of actual groundwater recharge using datasets generated and presented in the previous chapters is presented in Chapter 4. Application of the knowledge of shallow groundwater dynamics and recharge estimates in a statistical modelling framework to understand the mobilisation of As in groundwater in Bangladesh is presented in Chapter 5. Statistical models developed in the previous chapter are applied to test existing As-mobilisation hypotheses in Chapter 6. Conclusions and recommendation on future research are presented in Chapter 7 of this thesis.

1.2 Study Area

1.2.1 Location, Physiography, and Climate

The study area of this research is Bangladesh which is located within the Bengal Basin (Figure 1.4) which features one of the world's largest deltas, the Ganges-Brahmaputra-Meghna (GBM) Delta (also known as Bengal Delta or Ganges Delta). The GBM Delta occupies most of Bangladesh and some part of West Bengal, an eastern state of India. The rest of the country is covered with lowland floodplains, alluvial fans, marshy swamps and forests. Bangladesh, except from some hilly terrains in the east, is extremely flat with a gentle topographic gradient that gradually decreases from north to south into the Bay of Bengal. Another noticeable physiographic feature in the country is the Pleistocene terrace represented by the Madhupur and Barind Tracts that are slightly more elevated than the adjacent floodplains (Alam et al. 2003). Almost all of Bangladesh is covered with recently (Holocene) deposited alluvium deposits. The highland terraces are composed of older alluviums of Pleistocene age (Goodbred and Kuehl 2000). The hilly terrains in the northeast and southeastern parts are composed of Quaternary and Tertiary sedimentary deposits (Alam et al. 1990; Uddin and Lundberg 1998).

Bangladesh has a subtropical monsoon climate characterised by variable seasonal rainfall, moderately warm temperature, and high humidity (WARPO 2000). The climate is influenced primarily by monsoon, and partly by pre-monsoon and post-monsoon circulations (Agrawala et al. 2003). Seasons are mainly divided into four: dry winter (December to February), summer or pre-monsoon (March to May), monsoon (June to September), and post-monsoon (October to November). Winter is relatively cooler and drier with the average temperature ranging from a minimum of 7 to 13°C to a maximum of 24 to 31°C (Agrawala et al. 2003). Pre-monsoon is generally hot with an average

maximum temperature of 37°C, predominantly in the west, and erratic heavy rainfall associated with occasional thunderstorms and tropical cyclones.

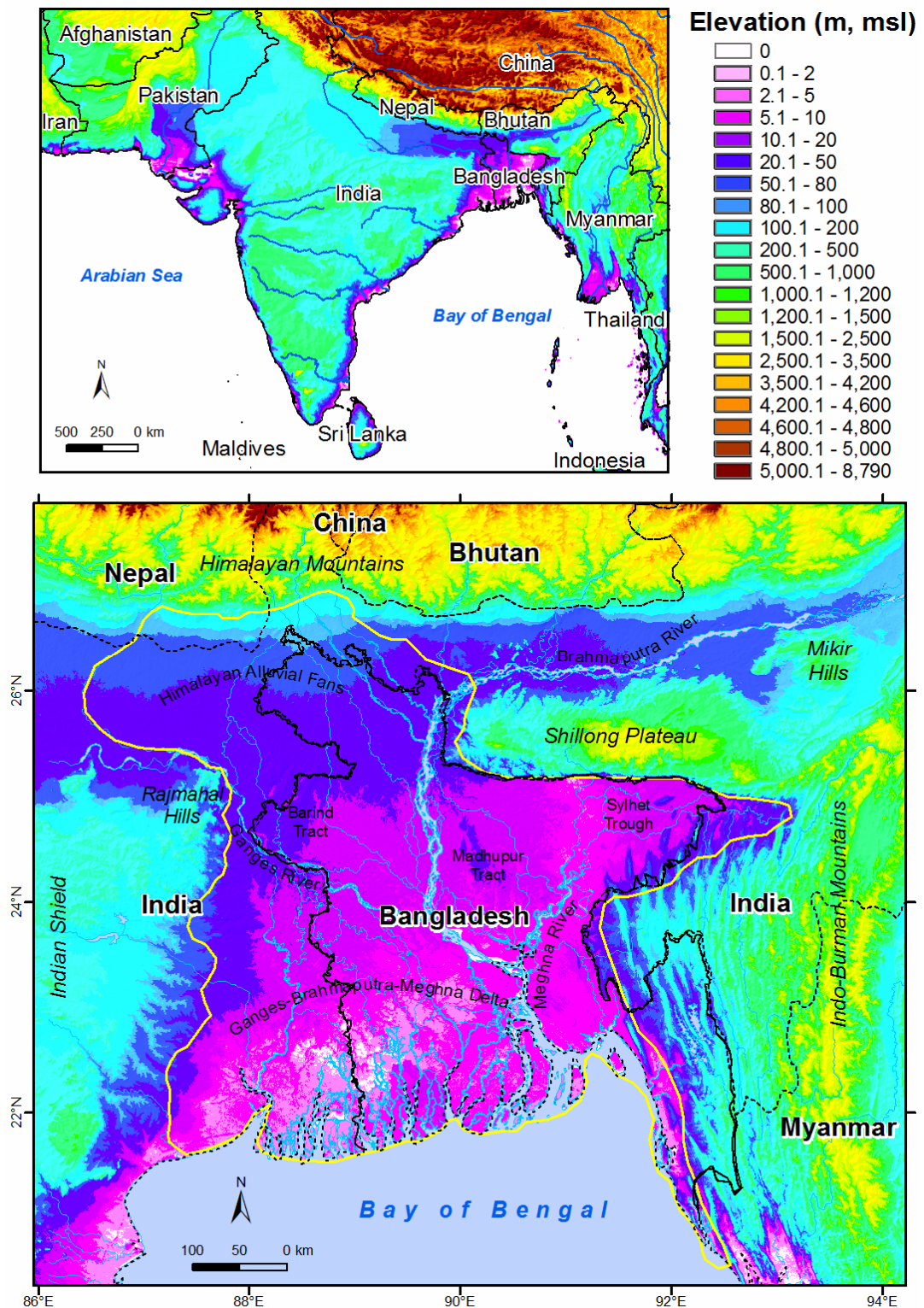


Figure 1.4 Location map of Bangladesh and the approximate outline of the Bengal Basin (yellow line). The basin is surrounded by the Himalayan Mountains to the far north, Shillong Plateau to near north, Indian Shield to west, Indo-Burman Mountains in east, and it is open to the Bay of Bengal in south. The basin is extremely flat characterised by numerous river channels, floodplains and delta plains.

Hot and humid monsoon season brings heavy torrential rainfall which accounts for ~80% of the annual rainfall in the country. The brief post-monsoon season is characterised by some rainfall associated with cyclones. The mean annual rainfall is approximately 2300 mm with great spatial and temporal variations. Annual rainfall ranges from 1200 mm in the west to over 5000 mm in the east and northeastern parts of Bangladesh (Figure 1.5) (MPO 1991).

1.2.2 Surface Geology and Soil

Bangladesh occupies much of the Bengal Basin, one of the largest sedimentary basins in the world and the major depocenter of sedimentary fluxes from the Himalayan and Indo-Burman mountain ranges which are drained by the Ganges-Brahmaputra-Meghna (GBM) river system (Shamsudduha and Uddin 2007). This river system forms the world's largest delta, the Ganges-Brahmaputra-Meghna (GBM) Delta that covers almost all of Bangladesh. The surficial geology (Figure 1.6) is characterised by the Quaternary sedimentary deposits that are surrounded along basin margins by Precambrian metamorphic and igneous rocks to the west (Indian Shield) and near-north (Shillong Massif), fluvial Siwalik deposits to the far north (The Himalayas), and folded bedrocks of Tertiary age (Indo-Burman Mountains) to the northeast and southeast (Uddin and Lundberg 1998; Goodbred and Kuehl 2000). The Pleistocene terrace deposits (i.e., Madhupur and Barind Tracts), located in slightly elevated (10-20 m above sea level) central and northwestern parts of Bangladesh (Figure 1.6), are generally brown or tan colour, highly weathered, and more compacted than floodplain and deltaic deposits that are generally young (Holocene age), gray colour, and composed of sand, silt, clay, and occasional peat deposits (UNDP 1982; BGS and DPHE 2001). Sediments in northeastern Sylhet depression and southern tidal-deltaic regions are predominantly silt and clay with little sand (Goodbred and Kuehl 2000). Spatial distributions and thickness of the upper silt and clay (USC) unit show (Figure 1.6) that aquifers across the country are overlain by silt and clay sequences ranging from 5 to 15 m thick (MPO 1987). In northwestern regions (alluvial fan deposits), this USC unit does not exist where very fine to fine sands generally occur at the surface. However, shallow aquifers occur at relatively deeper (>15 mbgl) depths in the Madhupur and Barind Tracts, Sylhet depression, and southern GBM Delta where the USC unit is thick.

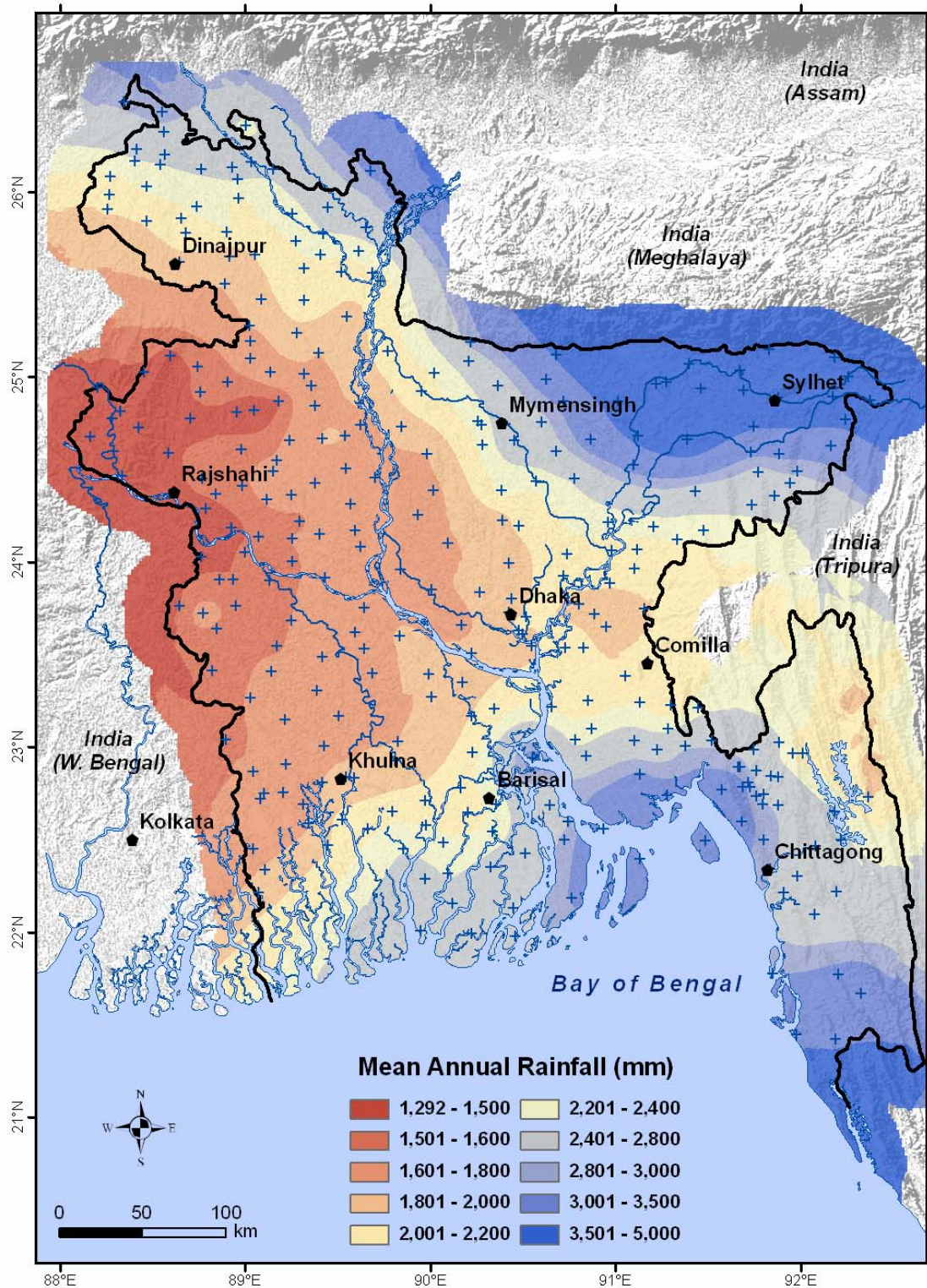


Figure 1.5 Map showing the mean annual rainfall in Bangladesh. Values are interpolated from a total of 302 gauging stations throughout Bangladesh. Highest rainfall occurs in the east and northeastern parts whereas lowest rainfall is observed in western parts of the country. Mean annual rainfall is interpolated using the geostatistical method (Ordinary Kriging with a fitted variogram model). Locations of rainfall monitoring stations and major district towns in Bangladesh are shown on the map.

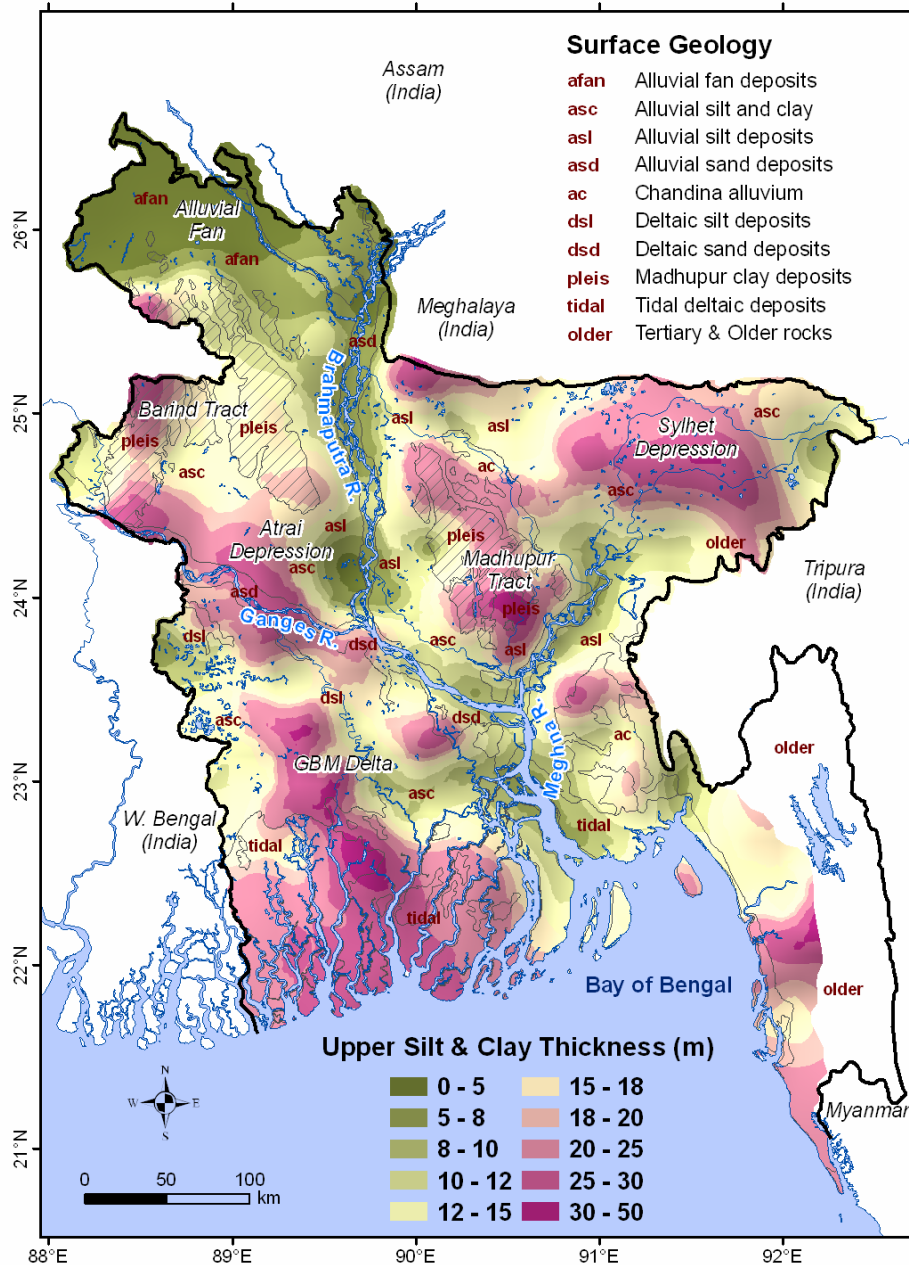


Figure 1.6 Map of the thickness of the upper silt and clay (USC) unit in Bangladesh derived from borehole lithologs compiled in this study from UNDP (1982), MPO (1987), and other borehole data. Major surficial geological units are mapped highlighting (hatch lines) the location of thick clay-covered Madhupur and Barind Tracts (Pleistocene deposits). Note that data ranges for each class are discrete in that, for example, 0-5 m means 0 to <5 m.

The composition of soil in different surface geological units of Bangladesh varies as a function of proportions of sand (grain size: 125-2000 μm), loam (mostly silt; 4-125 μm), and clay (<4 μm) (Figure 1.7). Average soil composition for individual soil classes was examined and later aggregated over a total of 30 agro-ecological zones in the country by Bangladesh Agricultural Research Council (BARC 1988). Soil composition in alluvial fans, major river valleys, and Tertiary deposits in eastern hilly terrains are predominantly sandy. In contrast, soil composition in Pleistocene terraces (Madhupur clay formation),

tidal delta, and marshy peat-land are mainly clayey. Surface geology and soil composition which generally characterise shallow aquifers in Bangladesh largely control the timing and pathways of groundwater recharge to aquifers (MPO 1987; WARPO 2000).

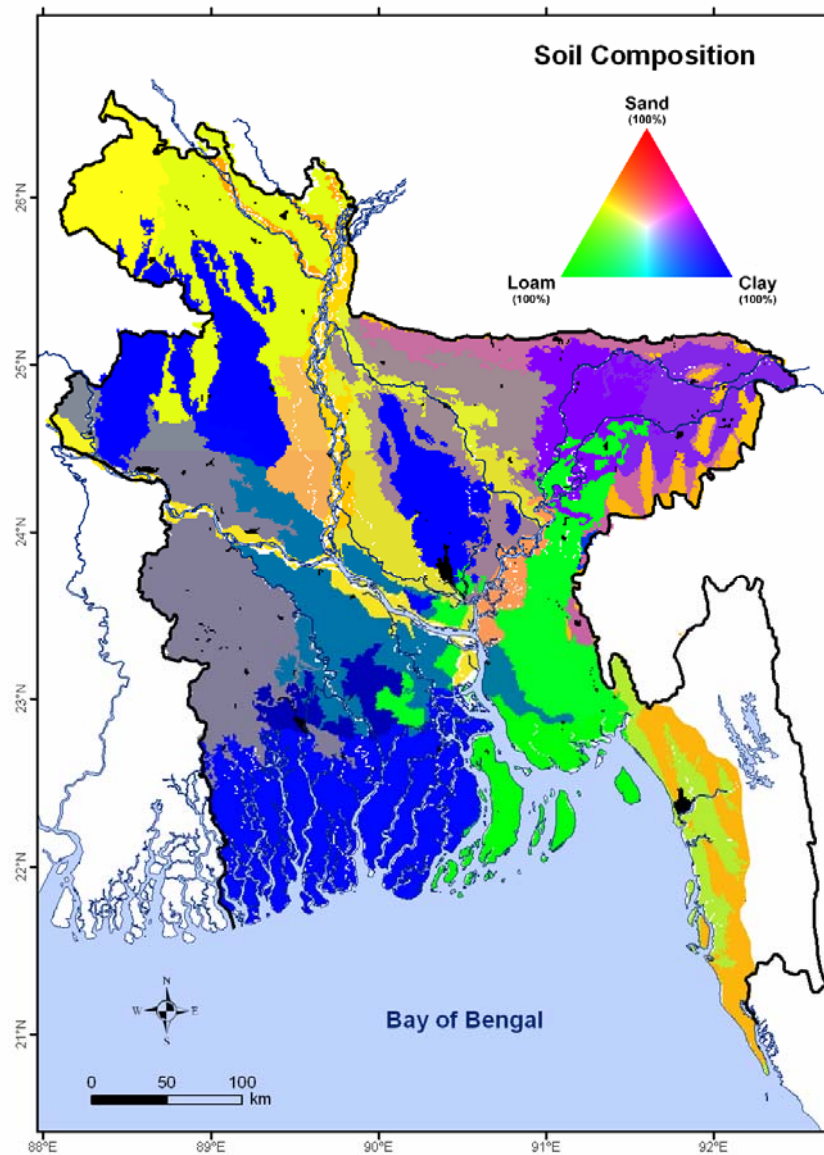


Figure 1.7 Spatial variations in soil composition (shown as a RGB colour composite map) in Bangladesh. Soil composition, presented as a proportion of red (sand), green (loam), and blue (clay) colours, compiled and aggregated over 30 agro-ecological zones by the Bangladesh Agricultural Research Council (BARC, 1988).

1.2.3 Hydrogeology and Groundwater

Groundwater levels are encountered in highly productive alluvial aquifers at very shallow depths of <10m below ground level (bgl) beneath the Holocene floodplains and Pleistocene terraces in Bangladesh (Ravenscroft et al. 2005). In the coastal and island areas groundwater is mostly saline. Freshwater is, however, encountered at very shallow depths (<25 mbgl) and also below 150-200 mbgl. Aquifers in Bangladesh are generally

formed by medium to fine grained unconsolidated sands. Generally, aquifers that occur at depths <100 mbgl are generally known as “shallow”, and those occurring below 100-150 mbgl are called “deep” aquifers although the location of the contact between shallow and deep aquifers and evidence of any regional hydrological separation have not been well constrained (Michael and Voss 2009b). Locally, the shallow aquifer can be hydraulically separated from the deep aquifer by a low-permeability layer (generally a clay layer of local to regional extent). Shallow aquifers can vary from unconfined to confined but, in most places, the short-term responses of these aquifers to pumping are leaky to semi-confined. The hydraulic conductivity of these alluvial aquifers varies from as low as 3 to 86 m/day with specific yield values ranging from 0.02 to 0.20 on average (BWDB 1994; Michael and Voss 2009b). Shallow aquifers are highly transmissive with transmissivity values ranging from 1500 to 5000 m²/day. Aquifers beneath the Pleistocene terraces show low transmissivity (Ravenscroft et al. 2005).

1.2.4 Groundwater-fed Irrigation in Bangladesh

Agriculture in Bangladesh was entirely dependent on surface water and monsoon rainfall prior to the 1970s (UNDP 1982). Irrigated agriculture using groundwater through power-operated pumps was introduced in the 1970s to produce high-yielding Boro rice in some parts of Bangladesh (MPO 1987). Boro rice grows during the dry season (December to April) when rainfall is low and episodic and typically requires 0.4 to 1.5 m of irrigation which is almost entirely groundwater-fed (Ravenscroft et al. 2009). Initially, few irrigation wells were installed in northwestern parts of Bangladesh, but during the international campaign of “Clean Drinking Water Decade” (1980 to 1990), the government and private sector installed millions of drinking water (Hand tubewells, HTW) and shallow irrigation wells (WARPO 2000; BGS and DPHE 2001; World Bank 2005). By 2006, nearly 78% of the irrigated rice-fields were supplied by groundwater of which approximately 80% of the irrigation water derived from low-capacity (average discharge rate 10 L/s) shallow tubewells (STW; depth <80 mbgl); the rest was irrigated by high-capacity (average discharge rate 56 L/s) deep tubewells (DTW; depth >80 mbgl) to produce Boro rice (UNDP 1982; Bangladesh Bureau of Statistics 2009). Groundwater-fed irrigation (STW and DTW combined) is highest in northwestern and southwestern districts and lowest in eastern and southern deltaic regions in Bangladesh where surface-water irrigation is supplied mainly by low-lift pumps (LLP) and irrigation canals (BADC 2008). The total land area irrigated by DTWs and other surface-water based technologies

remains relatively unchanged since the 1990s but the STW-based irrigation has linearly increased by two orders of magnitude over the last 30 years (Figure 1.8).

To assess the impact of groundwater abstraction on recharge in Bangladesh, three different periods are defined over which groundwater recharge is estimated. The first period (1975 to 1980) is the “pre-developed groundwater-fed irrigation (PGI)” which occurs prior to the onset of widespread groundwater-fed irrigation in the country. During the PGI period, shallow tubewell (STW) based irrigation covered an average area of 57,000 hectare (*ha*) and deep tubewell (DTW) covered an average area of 138,000 *ha* (Figure 1.6). The second period (2002 to 2007) is the “developed groundwater-fed irrigation (DGI)” that occurs after widespread development of groundwater for irrigation in Bangladesh. During the DGI period, STW-based average irrigated area increased to 3,044,000 *ha* and DTW-supplied area increased to 702,000 *ha*. The period (1985 to 2007) represents the development phase of groundwater-fed irrigation (LGI) in Bangladesh.

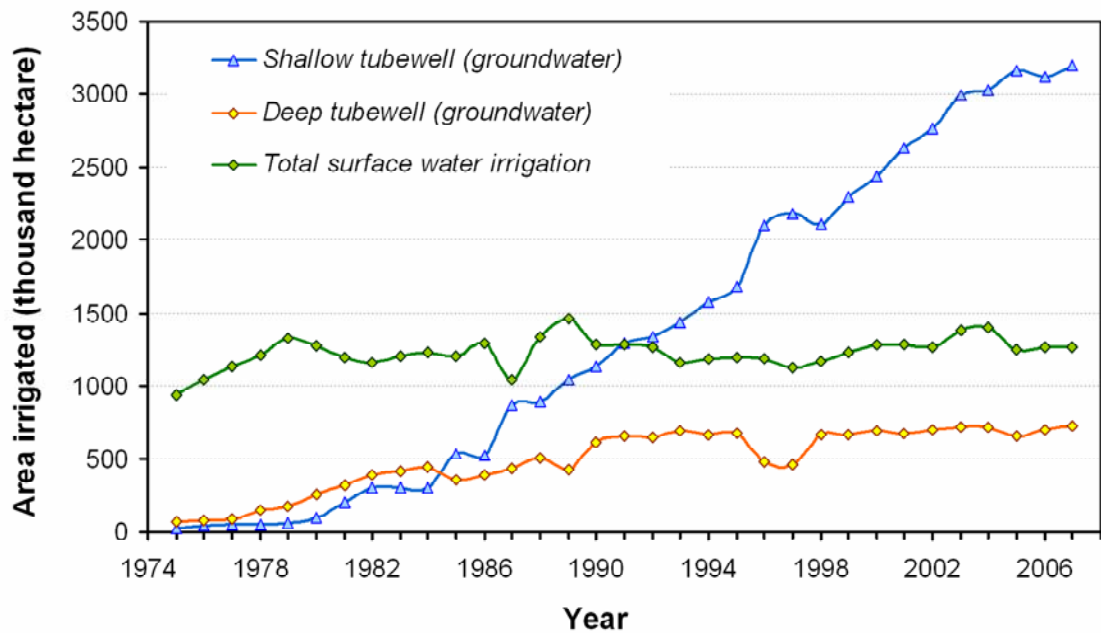


Figure 1.8 Temporal trends in annual records of the area irrigated by shallow tubewells, deep tubewells, and surface water in Bangladesh over the period of 1975 to 2007 (Data source: Bangladesh Ministry of Agriculture).

Part B:

Groundwater Storage Dynamics and Recharge

Chapter 2

Recent Trends in Shallow Groundwater Levels

This chapter starts with a rationale for exploring shallow groundwater dynamics in a highly-seasonal hydrological system of the Ganges-Brahmaputra-Meghna Delta in the Bengal Basin, Bangladesh. It describes the observed groundwater levels and provides an account of the national groundwater-level database compiled in this study. Statistical methods for analysing time-series data and characterisation of temporal trends and seasonality in shallow groundwater levels in Bangladesh are presented.

2.1 Introduction

Asian Mega-Deltas feature regionally extensive shallow aquifers within sedimentary sequences deposited over the last 10 ka (see Figure 1.2 in Chapter 1) (Benner et al. 2008). Groundwater levels in shallow aquifers (depth <50 mbgl) underlying Asian Mega-Deltas are highly seasonal as a result of intensive precipitation during the annual monsoon (Klump et al. 2006; Mukherjee et al. 2007; Berg et al. 2008; Larsen et al. 2008; Norrman et al. 2008). Seasonal fluctuations vary considerably both at spatial and temporal scales and range from 2 to 8 m in the Ganges-Brahmaputra-Meghna (GBM) Delta (BGS and DPHE 2001), 2 to 5 m in the Red River Basin (Norrman et al. 2008), 2 to 8 m in the Mekong Basin (Benner et al. 2008; Berg et al. 2008), and 1 to 5 m in the Chao Phraya Basin (Suwanlert 2004). Shallow groundwater abstraction for dry-season irrigation which has taken place since 1970s in the GBM Delta (WARPO 2000) and more recently in the Irrawaddy Basin and Mekong Delta (Dawe 2005; FAO 2006), serves to increase seasonality in shallow groundwater levels. Decomposition of groundwater level time-series records into trend, seasonal and irregular components enables an understanding of the processes that control flow within groundwater systems (Taylor and Alley 2001). The highly seasonal nature of the shallow groundwater systems in Asian Mega-Deltas complicates resolution of trends in groundwater levels and, hence, groundwater storage.

Statistical methods for trend analysis vary from simple linear regression to more advanced parametric and nonparametric methods (Helsel and Hirsch 2002). Classical

approaches such as the Mann-Kendall trend test (Mann 1945; Kendall 1975) and its seasonal counterpart have been widely used for testing trends in hydrological time-series (Hirsch et al. 1982; Aziz and Burn 2006; Thas et al. 2007). The Mann-Kendall and Seasonal Kendall tests are, however, unable to resolve trends adequately in a time series characterised by serial dependence (Hirsch and Slack 1984; Hamed and Rao 1998). A further difficulty is that most standard methods are designed to detect monotonic trend in a series (Hipel and McLeod 1994). This restriction limits their usefulness where temporary variations of a long-term trend and change in seasonality are important in assessing the impacts of short-term climate change and anthropogenic activities (Qian et al. 2000). A disadvantage, which is arguably more serious, is that traditional trend test procedures are designed to identify trends in the time series but not to characterise them. A systematic characterisation of variability permits an evaluation of hydrodynamic responses. This study resolves trends in shallow groundwater levels within the GBM Delta by applying linear regression and a seasonal-trend decomposition procedure to a groundwater-level database of 1.8 million weekly records from 1267 monitoring wells over the period of 1985 to 2005 in Bangladesh.

2.2 The Ganges-Brahmaputra-Meghna Delta in Bangladesh

The GBM Delta is situated in the Bengal Basin which lies in front of the Himalayan foredeep (Goodbred and Kuehl 2000). River flow in this region is highly seasonal, with 80% of the annual discharge occurring during the four months of southwestern monsoon (Coleman 1969). The modern Bengal Basin comprises about 100,000 km² of lowland floodplains and delta plains and is bound by Tertiary highlands related to the uplift of the Himalayas (Goodbred and Kuehl 2000). Global climatic changes, physical and chemical weathering in the Himalayas and subsidence in the Bengal Basin interacted to control the Quaternary alluvial sedimentation and thus hydrogeology of this region (BGS and DPHE 2001; Ravenscroft et al. 2005). Highly productive aquifers occur within these thick unconsolidated alluvial sediments of the Pleistocene and Holocene ages that were deposited by the GBM river system (Shamsudduha and Uddin 2007). Aquifers occur at relatively shallow depths (5 to 20 mbgl) beneath the broad alluvial floodplain, alluvial fan and deltaic deposits, and at comparatively deeper depths (15 to 45 mbgl) underlying the Madhupur clay and Barind clay deposits in Bangladesh (Ravenscroft et al. 2005). Aquifers that are found within the geologically complex bedrock terrains in eastern parts of the country are of variable thickness and depth. Recent alluvium and upper part of the

Dupi Tila sand of Pliocene-Pleistocene age form shallow aquifers which are generally located within the depth of 100 m below surface (Ahmed et al. 2004). In Bangladesh, younger or recent alluvium and fan deposits are the focus of shallow groundwater development (UNDP 1982).

The hydrogeology of the GBM deltaic aquifers has been substantially modified by groundwater abstraction (Agrawala et al. 2003; Harvey et al. 2006; Stute et al. 2007). In Bangladesh, groundwater is widely used for domestic, industrial and agricultural purposes but dry-season irrigation for high-yielding Boro rice cultivation withdraws the most groundwater in Bangladesh (BADC 2003). Intensive abstraction for irrigation (25 to 75 wells per km² of irrigated land) occurs in many areas of northwestern Bangladesh and began during the early 1970s with the installation of deep (depth 100 to 300 mbgl) tubewells (DTW) by the Bangladesh Water Development Board (BWDB) (BADC 2003). Initially, irrigation from groundwater was provided by these DTW in addition to surface water irrigation with low-lift pumps (LLP) and traditional methods (BADC 2003). During the 1980s and 1990s the government, with support from international organizations, installed thousands of shallow (depth <100 mbgl) irrigation tubewells (STW) following the recognition of large quantities of groundwater at relatively shallow depths (BGS and DPHE 2001; World Bank 2005). The regional-scale impact of abstraction on shallow groundwater levels has yet to be assessed. The impact of sea-level rise on groundwater levels and mechanisms controlling salinity in coastal regions are also unclear.

2.3 Datasets and Statistical Methods

2.3.1 National Groundwater-level Database of Bangladesh

A national database of 1.8 million records of weekly groundwater level data has been compiled from a dense network (one per 105 km²) of 1267 monitoring wells that have been managed by BWDB, Bangladesh since the early 1970s. Monitoring of groundwater levels in this region, however, initiated in the early 1960s. Groundwater levels are referenced to a common datum (Public Works Datum, PWD) which was originally set to the mean sea level (msl) with a vertical error of ± 0.45 m during the Great Trigonometric Survey in the Indian Subcontinent throughout the 19th century (Roy 1986). During the 1960s most of these monitoring wells were dug wells; many of these were subsequently replaced by piezometers. The total number of monitoring wells that operated from 1961 to 2006 is 2154; 735 were dug wells and 1419 were piezometers of variable depths

ranging from 3.9 to 352 mbgl. Most dug wells have now been replaced by monitoring piezometers at the same location; faulty piezometers have also been replaced throughout the recording period. In some cases, newly installed piezometers were drilled deeper or shallower than those they replaced. The total number of unique well locations in the present database is approximately 1267. In these analyses, each replacement well is treated as a separate monitoring station to avoid potential problems associated with spurious trends due to well substitution. In the newly compiled weekly groundwater level database, there are 1189 piezometers and 78 dug wells. This study used the “R” statistical language (R Development Core Team 2009) to read and re-structure groundwater level data from two original data formats (i.e., flat text-file and Microsoft Access database) maintained by BWDB. All water-level records were subjected to systematic quality control procedures. Wells with unreliable and only a few groundwater level data were flagged and discarded from subsequent analyses. Wells with no available information on the depth to the well screen and wells with more than 50% of missing records were also discarded.

2.3.2 Datasets and Exploratory Analyses

Three groups of monitoring wells were defined for the statistical analyses reported below. Group A comprises 1035 shallow monitoring wells (66 dug wells and 969 piezometers) yielding 1.1 million, quality controlled, groundwater-level observations that were used for exploratory analyses (Figure 2.1). The record lengths in Group A wells range from 7 to 41 years, with a mean of 22. Exploratory analyses were restricted to the period from 1985 to 2005 in order to be consistent with the dominant observation period of the majority of monitoring wells. All wells in Group A have <20% missing data with a mean of 5.5% for the entire group. Group B is a subset of 454 wells from Group A that have been specially selected for trend analysis because their record lengths extend over the entire period from 1985 to 2005; the mean proportion of missing data is 5.9%. Group C is a subset of Group B comprising 282 wells for which missing records (mean 5%) are of sufficiently short duration and thus could be imputed (infilling of missing values) using a simple linear interpolation method. Where data in Group C wells were found missing either in the average driest (April) and or the wettest (September) months of a particular year, the missing value was imputed by taking the mean of groundwater levels of the relevant period from two adjacent years. Group C wells were used for STL decomposition analysis as this method requires time series without gaps.

Exploratory analyses of the Group A wells investigated the general distribution of groundwater levels across Bangladesh. Groundwater levels for individual wells, selected to reflect variations in surface geological units, were plotted to investigate variations in groundwater-level time series in different regions. Time series plots of various summary statistics at monthly, annual and decadal timescales were also produced to develop a preliminary assessment of trends. For each Group A well, the median groundwater level was calculated for each month to summarise the seasonal structure in the record.

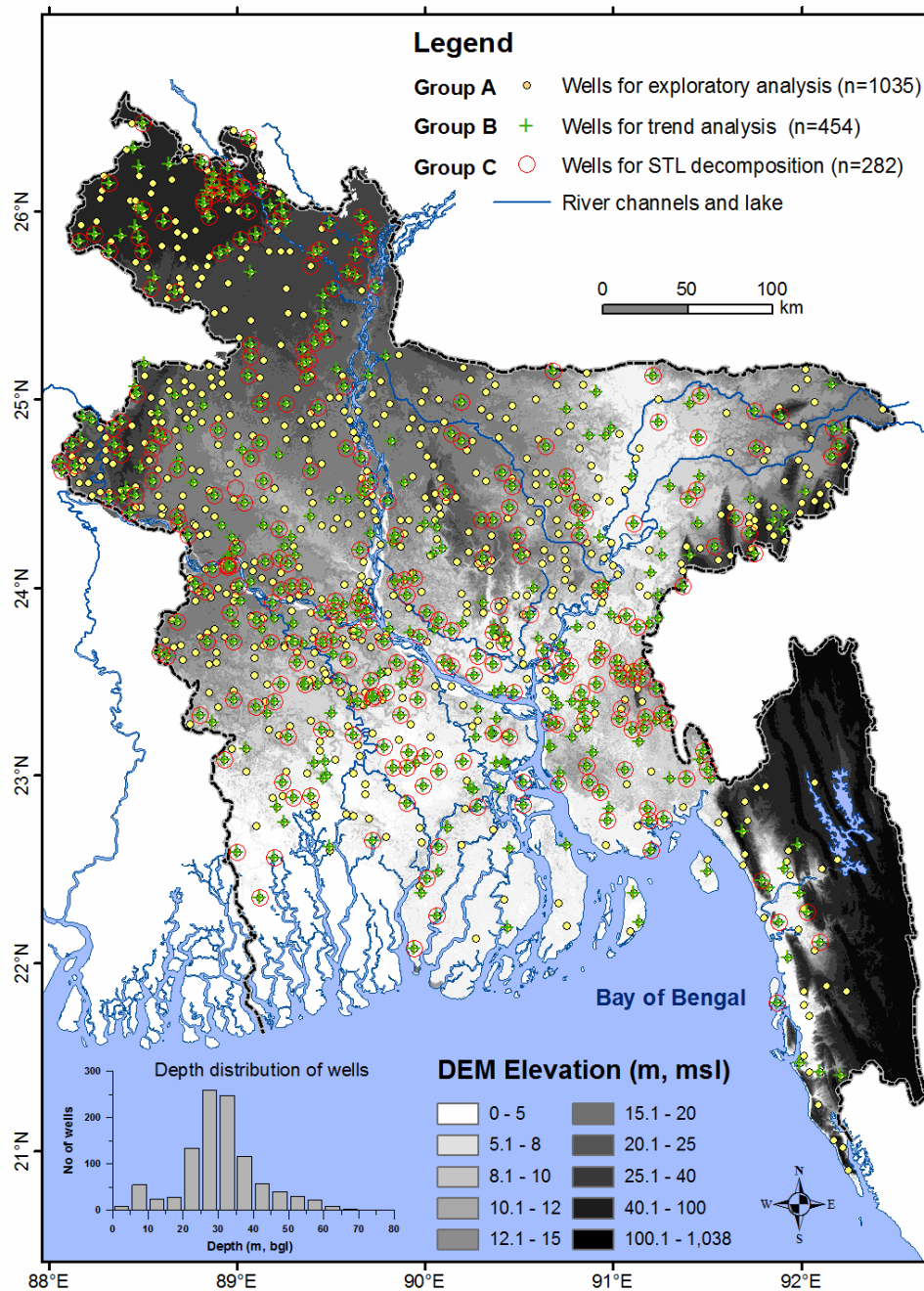


Figure 2.1 Distribution of groundwater level monitoring stations in Bangladesh (Group A, B and C) imposed on a 90-m resolution digital elevation model derived from the Shuttle Radar Topography Mission (SRTM). Depth distribution of monitoring wells is shown in the histogram (inset)

2.3.3 Linear Regression for Trend Analysis

The exploratory analyses of Group A wells provided an initial impression of seasonality and trends in the groundwater series. It is of particular interest to test for and characterise trends in the series, for example to examine the sustainability of current abstraction levels. To this end, an initial assessment of trends over the period from 1985 to 2005 was carried out using linear regression applied to annual time series at each Group B monitoring site for direct comparison of results. To investigate the possibility that trends may be seasonally varying, three different annual series were analysed at each site: the mean value, 5th and 95th percentiles of each year's observations. Trends in 5th percentiles correspond roughly to changes during the dry period, and trends in 95th percentiles to changes in the wet season groundwater levels. The use of percentiles, rather than annual maxima and minima, avoids problems associated with outliers and data errors.

2.3.4 Trend and Seasonality Decomposition with STL Method

Despite widespread application of linear regression for trend analysis, this procedure does not provide accurate assessments of nonlinear trends in borehole groundwater levels. In the analysis of linear trends in Group B wells, mean and seasonal extremes were treated separately yet it is preferable to develop an integrated description of change in groundwater levels over the entire time series. A nonparametric time series decomposition method known as “Seasonal-Trend decomposition procedure based on LOESS (STL)” (Cleveland et al. 1990) is applied to resolve trends and seasonality in groundwater levels at each Group C monitoring well. Each time series of groundwater level records was decomposed using the STL decomposition method (equation 2.1) in the R environment as:

$$Y_t = T_t + S_t + R_t \quad (2.1)$$

where Y_t is the groundwater level at time t , T_t is the trend component; S_t is the seasonal component; and R_t is an irregular (residual) component.

STL consists of a sequence of applications of the LOESS smoother to give a decomposition that is highly resistant to extreme observations. STL method consists of a series of smoothing operations with different moving window widths chosen to extract different frequencies within a time series, and can be regarded as an extension of classical methods for decomposing a series into its individual components (Chatfield 2003). STL

uses the locally weighted regression (LOESS; also known as LOWESS) technique that was first proposed in a study (Cleveland 1979) and later modified (Cleveland and Devlin 1988). The nonparametric nature of the STL decomposition technique enables detection of nonlinear patterns in long-term trends that cannot be assessed through linear trend analyses.

STL procedure consists of two loops: inner and outer (Yu et al. 2001). The inner loop consists of several steps where trend and seasonal components are separated from the original time series. The outer loop extracts the irregular or residual component of the time series. First, a detrended series is computed by subtracting the trend component estimated from the original data (see Yu et al. 2001 for details). A preliminary seasonal component is then formed by smoothing the detrended values. A moving average is applied to the preliminary seasonal component to filter out any trend cycle that may have affected the preliminary seasonal component. The seasonal component is estimated as the difference between the preliminary seasonal component of the second step and the seasonal component in of the third step. The resulting estimates of trend-cycle and seasonal components are then used to calculate the irregular component in the outer loop of the SLT decomposition procedure. For STL decomposition, it is necessary to choose values of smoothing parameters to extract trend and seasonal components. The choice of the seasonal smoothing parameter determines the extent to which the extracted seasonal component varies from year to year: a large value will lead to similar components in all years whereas a small value will allow the extracted component to track the observations more closely. Similar comments apply to the choice of smoothing parameter for the trend component. Several different choices of smoothing parameters were experimented with at a number of contrasting sites; visualisation of the results suggested that the overall structure of time series at all sites could be captured reasonably using window widths of 7 years for the seasonal component and 5 years for the trend. The smoothing parameters were therefore fixed at these values for all subsequent STL analyses.

2.4 Results

2.4.1 Spatial and Temporal Distribution of Groundwater Levels

Figure 2.2 shows groundwater levels for selected wells, along with the corresponding seasonal and annual distributions. These plots reveal both seasonality and long-term trends in groundwater levels. The results from all wells show that the relative magnitude

of each component varies considerably across the country. Long-term patterns include declining, stable, and rising trends in groundwater levels. Figure 2.2a shows data from a well (DH070-C) with a rapidly declining groundwater level and decreasing seasonality which is generally observed in the central part of Bangladesh in and around the capital city of Dhaka. The monthly boxplots at this location show that overall variability in groundwater levels is highest during the wet season. The groundwater-level plot is, however, dominated by the long-term trend.

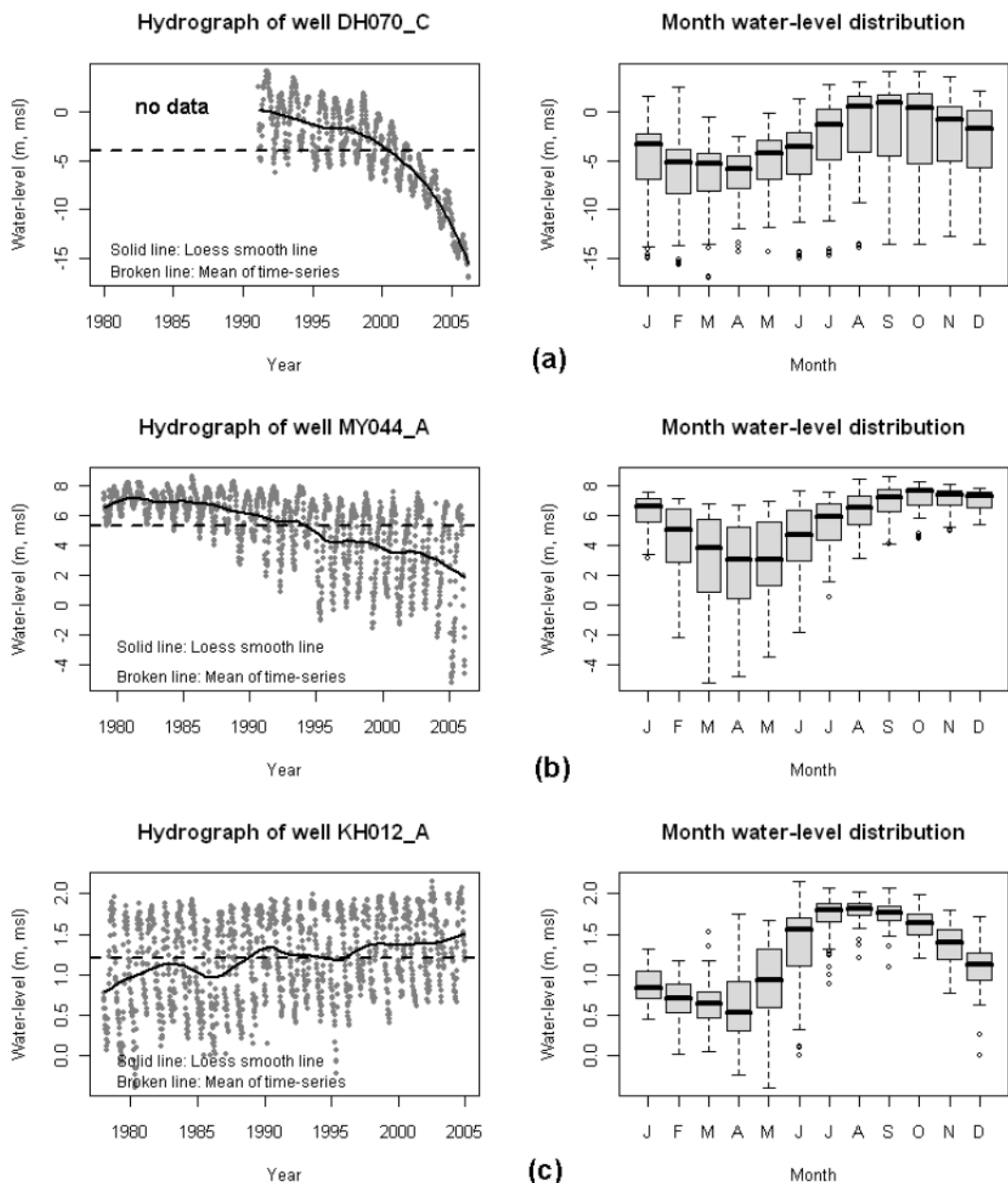


Figure 2.2 Groundwater levels and boxplots of monthly groundwater level distributions for three broadly representative monitoring wells in Bangladesh: a rapidly declining well (a), a steadily declining well (b), and a well with slightly rising trend (c). Seasonal (monthly) variations in groundwater levels of these three wells are shown as boxplots drawn next to the groundwater level plot of each well.

For another well (MY044-A) in the Old Brahmaputra river floodplain of the northeastern Bangladesh a steadily declining trend occurs mainly during the dry season (Figure 2.2b) and, in contrast to DH070-C, seasonality is the dominant component of the series. Site KH012-A reveals another distinct pattern (Figure 2.2c) consisting of a slightly rising trend with a smaller overall variation than other wells, and enhanced variability during the early monsoon. This site is located in a southern coastal area of the Bagerhat district. To visualise the regional structure of the groundwater levels, Figure 2.3 shows maps of the median levels from every monitoring well in Group A during the driest month (April) and the wettest month (September). General distributions of groundwater levels in the country broadly conform to topography. Figure 2.3 suggests that shallow groundwater flow in shallow aquifers occurs from the northwest and north-eastern areas towards the central region and subsequently in southern and southwestern directions where groundwater discharges into the Bay of Bengal (UNDP 1982).

Figure 2.3 shows that spatial distributions in monthly groundwater levels between April and September are very different in the western and north-central areas (where the annual fluctuations of water-tables are 6 to 9 m) from those in southern GBM delta and north-eastern floodplain areas (where fluctuations rarely exceed 3 m with a mean of 1.5 m).

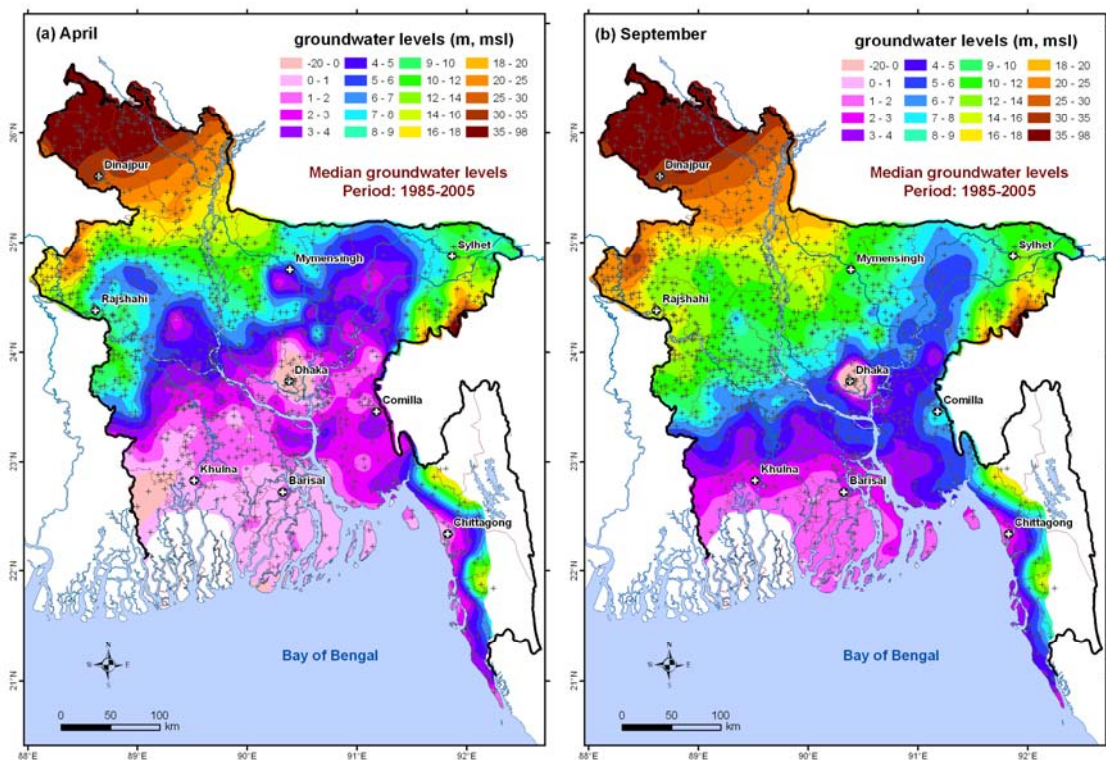


Figure 2.3 Median groundwater levels for April (end of the dry season) and September (end of the monsoon season) over a period of 21 years. Groundwater levels are referenced to the mean sea level (msl).

In the central part of the country (around Dhaka city) a regional cone of depression (~50 km in diameter) is observed throughout the year. During the dry season (see the April map in Figure 2.3), the cone expands northwards. Despite these general regional groundwater flow patterns, local-scale (50-100 km) variations are observed in the median monthly heads throughout the country (Appendix 1.1). Relatively higher levels are observed along the major rivers and close to their confluences, even during dry months when groundwater levels decline due to intensive abstraction for irrigation.

2.4.2 Trends in Shallow Groundwater Levels

Long-term (1985 to 2005) trends in groundwater levels of shallow aquifers across Bangladesh are shown in Figure 2.4. Panels (a-c) show contours of linear trends (cm/year) during the dry season (5th percentile), wet season (95th percentile), and in overall (annual mean) time series. Panel (d) will be discussed below. All of the maps show generally declining trends in most parts of Bangladesh, although the magnitudes of these trends vary spatially.

Strong declining trends (0.5 to 1 m/year) in dry-period groundwater levels are observed in the central part of the country surrounding the Dhaka city. Moderately declining trends (0.1 to 0.5 m/year) occur in western, northwestern, and northeastern areas. In the northern piedmont areas and floodplains of the major rivers, magnitudes of declining trends are low (0.01 to 0.05 m/year). Stable or slightly rising trends (0 to 0.1 m/year) are generally observed from the Meghna estuary to the southern coastal areas in the country. A similar overall pattern is seen during wet periods (Figure 2.4b) except in the northern piedmont areas, southwestern delta plains and southern coastal areas where wet period trends are slightly rising or stable.

Similar to long-term trends during dry and wet periods, declining trends in annual mean groundwater levels are observed in the central, northwestern, and northeastern parts (Figure 2.4c). Relatively stable to rising mean groundwater levels are detected in the northern piedmont, floodplains of major rivers, and deltaic plains. Generally declining groundwater levels are observed in the complex geological terrain of the eastern part of Bangladesh.

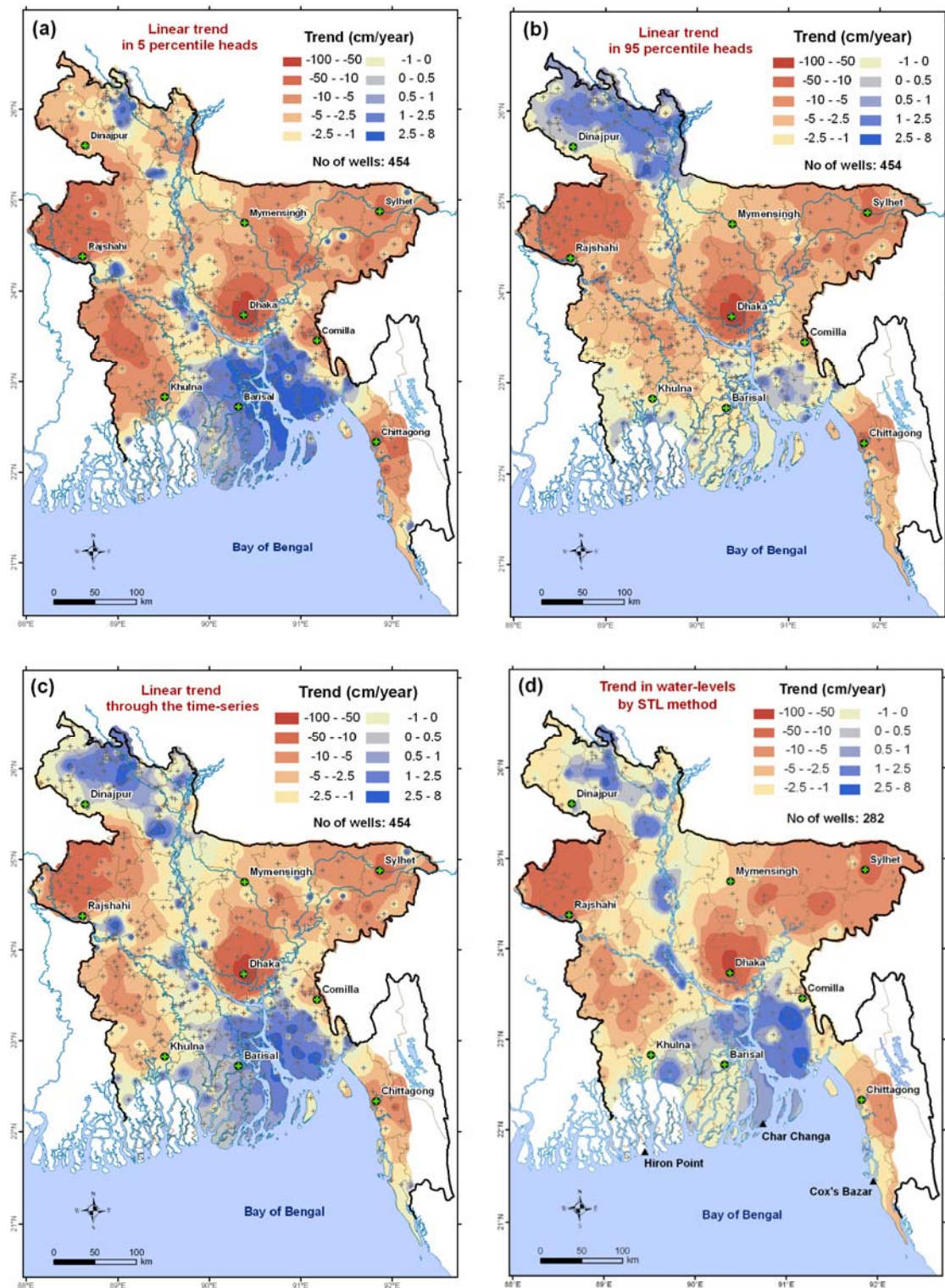


Figure 2.4 Trends in groundwater levels for the period of 1985 to 2005. Linear trends in the dry-period groundwater levels (5th percentiles of observations in each year) are shown in (a), trends in the wet-period groundwater levels (95th percentiles) are shown in (b), linear trends in annual means are shown in (c), and nonparametric trends calculated from the long-term trend component derived from an STL decomposition are shown in (d). Three locations in coastal regions of Bangladesh are shown in (d) where linear trends in sea levels were calculated by Singh (2002).

2.4.3 Spatial Variability in Trend and Seasonal Components

To obtain a more complete picture of the regional groundwater time series structure, this study focuses on the results of STL analyses. First, a representative STL decomposition (for monitoring well RJ039-B) is shown in (Figure 2.5). In this example, a decreasing seasonality is observed over time and a declining trend in the time series. The STL method improves on the previous linear regression analyses both by allowing a more flexible representation of the underlying trend, and by considering all aspects of the time series simultaneously.

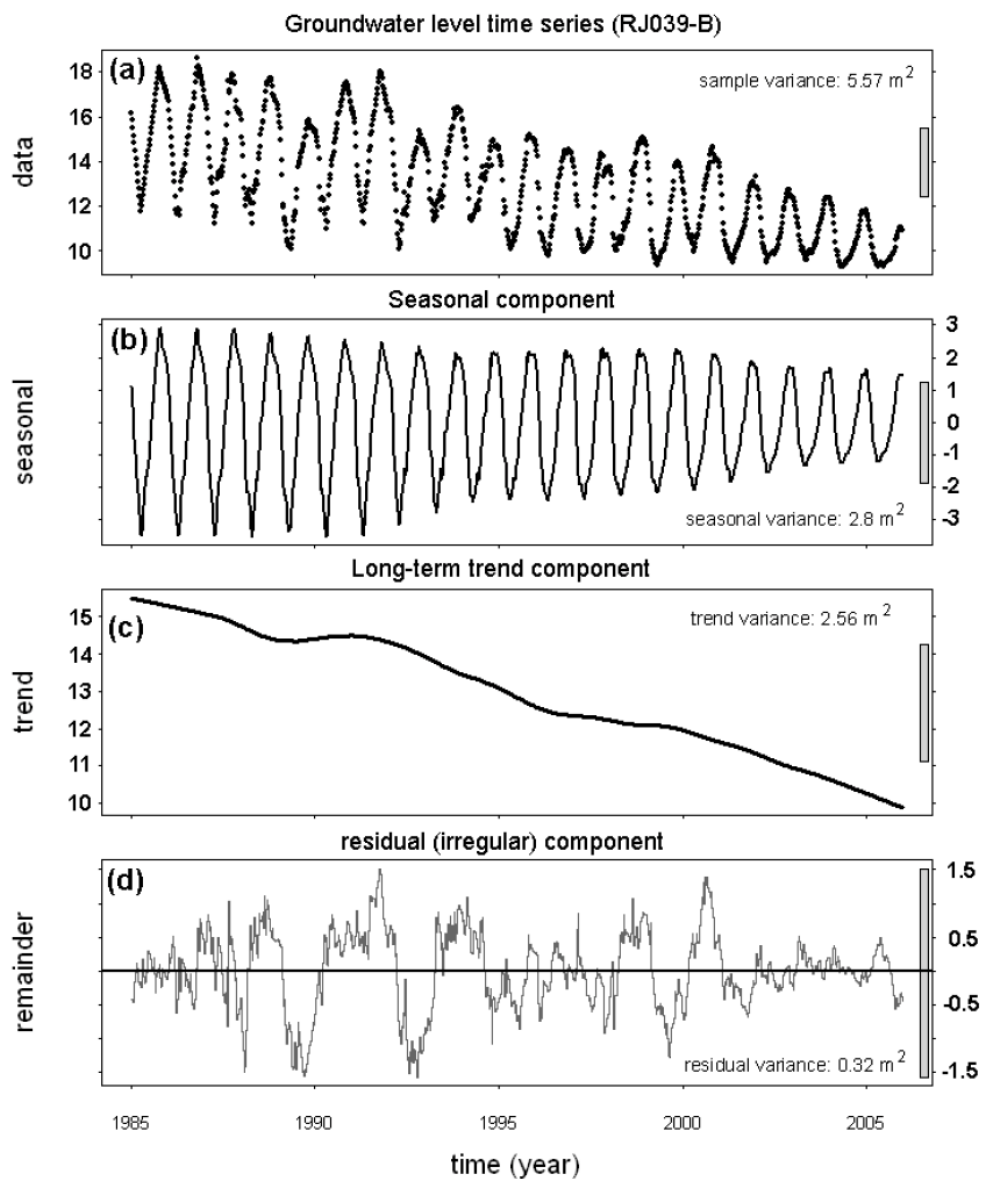


Figure 2.5 STL decomposition of the groundwater level time-series data (m, msl) for the monitoring well RJ039-B. The original time series of groundwater level data in (a). Seasonal and trend components as decomposed from time series by STL are shown in (b) and (c). Residual (irregular) component of the time-series is shown in (d). The bars at the right-hand ends of the plots provide a comparison of the vertical scales.

For the purpose of visualising the regional structure in STL-derived trends, it is convenient to reduce each one to a single number. Here, for each well an index of overall annual change has been defined as $52(T_n - T_1)/n$, where $n = 52 \times 21$ is the number of weeks of record in the analysis period 1985-2005 and T_t is the value of the STL trend component in the t^{th} week of the record as defined above. Figure 2.4d shows a map of the long-term trends calculated in this way. Overall, the pattern is very similar to that derived in Figure 2.4c using linear regression, although fewer wells ($n=282$) were used in the STL analysis due to more stringent data requirements. The STL trends are, however, more realistic than trends estimated by linear regression for the reasons given above.

To obtain further insight into the regional groundwater dynamics, it is of interest to compare the magnitudes of the trend, seasonal and irregular components at each monitoring location. To do this, the sample variance of each component is expressed as a percentage of the variance of the original groundwater level time series over the 1985-2005 period. Figure 2.6a shows maps of variances in the original time series. Higher variances in groundwater levels (5 to 30 m^2) are observed in the north-central, northwestern and southwestern parts where mean annual fluctuations of groundwater levels are high (3 to 8 m). Smaller variances are observed in the north, north-eastern, southern delta plains and estuarine areas.

Figure 2.6b shows the contribution of the STL seasonal components to the overall variance across the country. Generally, seasonality is the primary component of variance in groundwater levels except in northeastern and southeastern regions of the country. Groundwater level monitoring wells that are dominated by the seasonal component (>80% of variance) occur mainly in the upper Ganges and Brahmaputra floodplains. Seasonality explains 70 to 80% of the variance in groundwater levels in the northwestern and southeastern regions. Seasonality is the least important component in the central (surrounding Dhaka city), and eastern (Sylhet depression and Chittagong Hill Tracts) areas of Bangladesh.

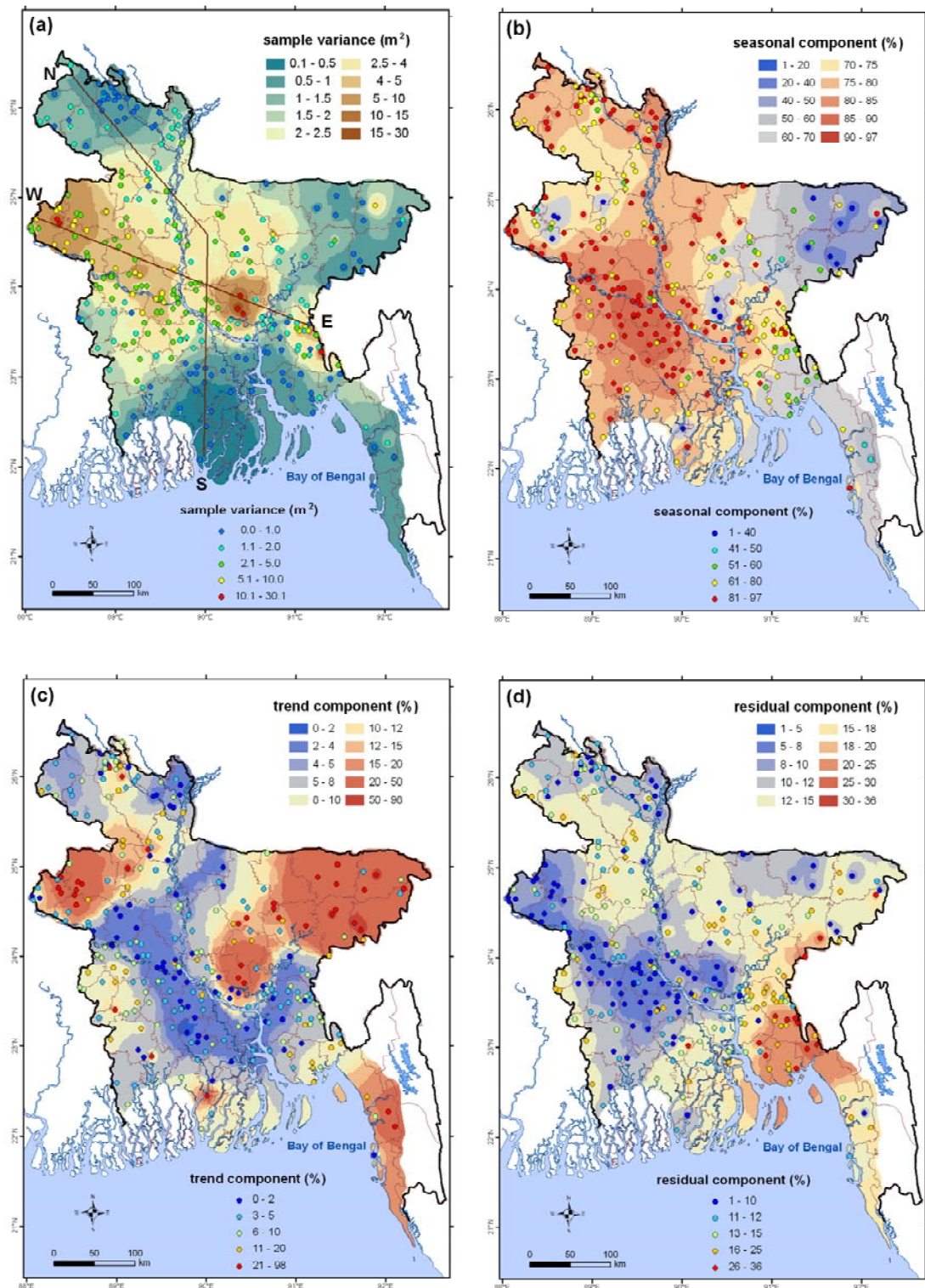


Figure 2.6 Variance of groundwater level time series for Group-C wells (a); relative proportions of groundwater level variance contributed by seasonal, trend and irregular components are shown in (b), (c), and (d) respectively. Relative proportion of variance in groundwater levels explained by all time series components along two profiles lines (N-S and W-E) on Figure 2.6a are shown in Figure 2.7.

Figure 2.6c shows the contribution of the STL trend components to the overall variance. Trend is the major component of variance in several locations. Higher percentages of trend components are concentrated in the central, northwestern, and north-eastern parts of Bangladesh. Although trends are detected in a large area of the north-east (Sylhet depression and Chittagong Hill Tracts), total variances of groundwater levels are rather small ($<0.6 \text{ m}^2$) here. In contrast, areas with elevated trend variances are also observed in the northwestern parts (higher or elevated Barind Tract in greater Rajshahi district) where mean annual groundwater fluctuations are high ($>5 \text{ m}$).

The median percentage of variance due to irregular components in groundwater levels is about 18% in the analysed 282 monitoring wells (Figure 2.6d). High irregular variances in groundwater levels coincide with anomalous seasonal extremes in groundwater levels that result from exceptional flood events and groundwater abstractions. Higher percentages of irregular components in groundwater levels are observed in the south-eastern and northern most parts of the country where annual fluctuations in groundwater levels are relatively smaller than the north-central and northwestern parts.

Spatial variations in groundwater level variance and its decomposition into various time series components are represented in two regional transects (Figures 2.6a and 2.7). The N-S transect shows variations in seasonality, trend and irregular components from piedmont areas down to the deltaic region, through central floodplains of the Brahmaputra river; and the W-E transect shows the variations from the northwestern irrigation districts to eastern parts through Dhaka city. Figure 2.7 shows that along both transects, seasonality is the major component of groundwater variance; however, trends dominate in the northwestern agricultural region and around Dhaka city. The irregular component explains approximately 15-20% of the variance in groundwater levels throughout the country. Irregular components are higher in the eastern hilly areas where aquifers are complex in nature.

2.5 Discussion

2.5.1 Trends in Groundwater Levels in the Ganges-Brahmaputra-Meghna Delta

These analyses show that shallow groundwater in the GBM Delta is highly dynamic with strong seasonality and trends of variable magnitude. Both parametric and nonparametric procedures reveal long-term trends in shallow groundwater levels throughout the country. Declining trends during the wet season, particularly in central (0.5 to 1 m/year) and northwestern (0.1 to 0.5 m/year) regions, indicate that shallow aquifers in these areas are not fully recharged each year during the monsoon season.

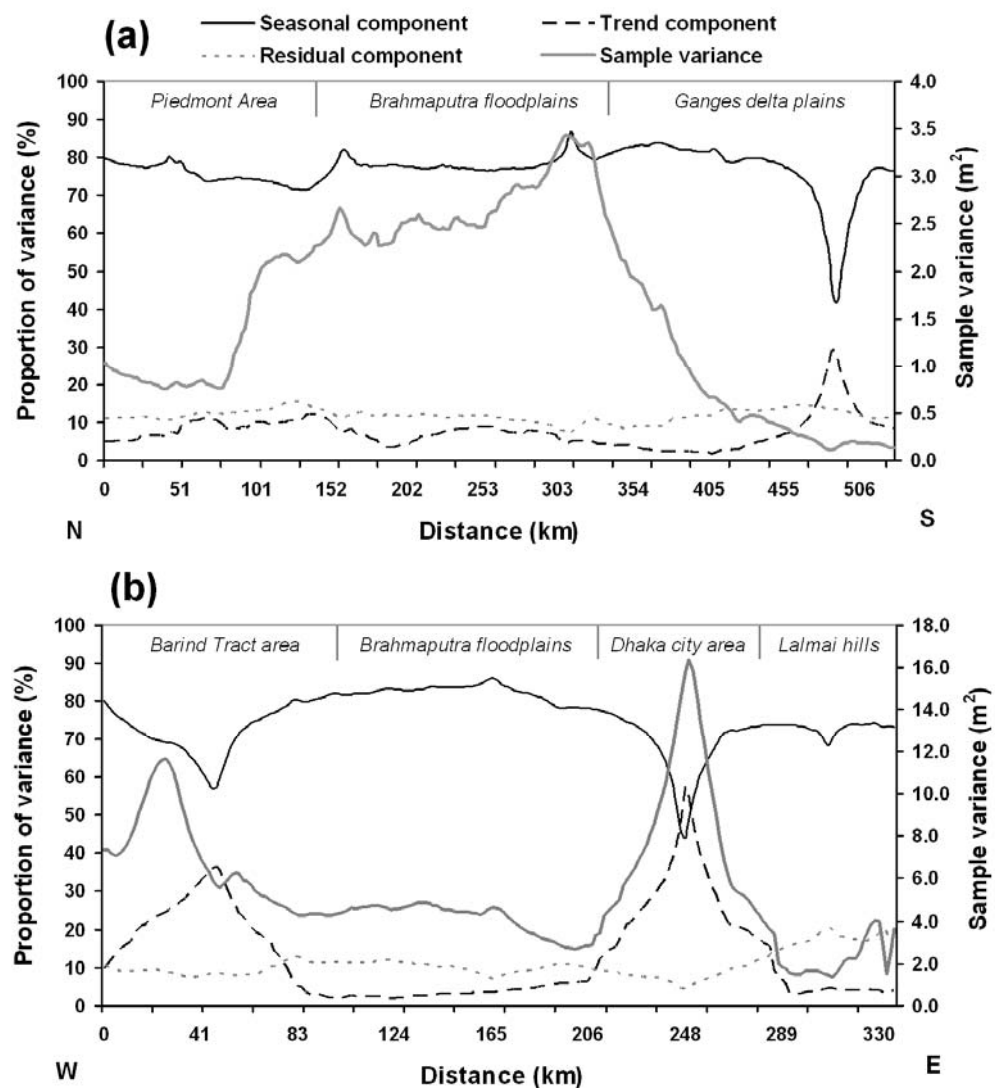


Figure 2.7 Sample variances and proportions of variances explained by various components of the groundwater level time series data along two transects as shown in Figure 2.6a; N-S profile shows variance in the groundwater level data (a); proportions of time series variances contributed by seasonality, trend and irregular components; seasonality is the dominating time series component in the Piedmont and Brahmaputra floodplain areas; W-E profile (b) shows that trend components in the Barind tract and central parts of Bangladesh are dominant where seasonal components are relatively less stronger.

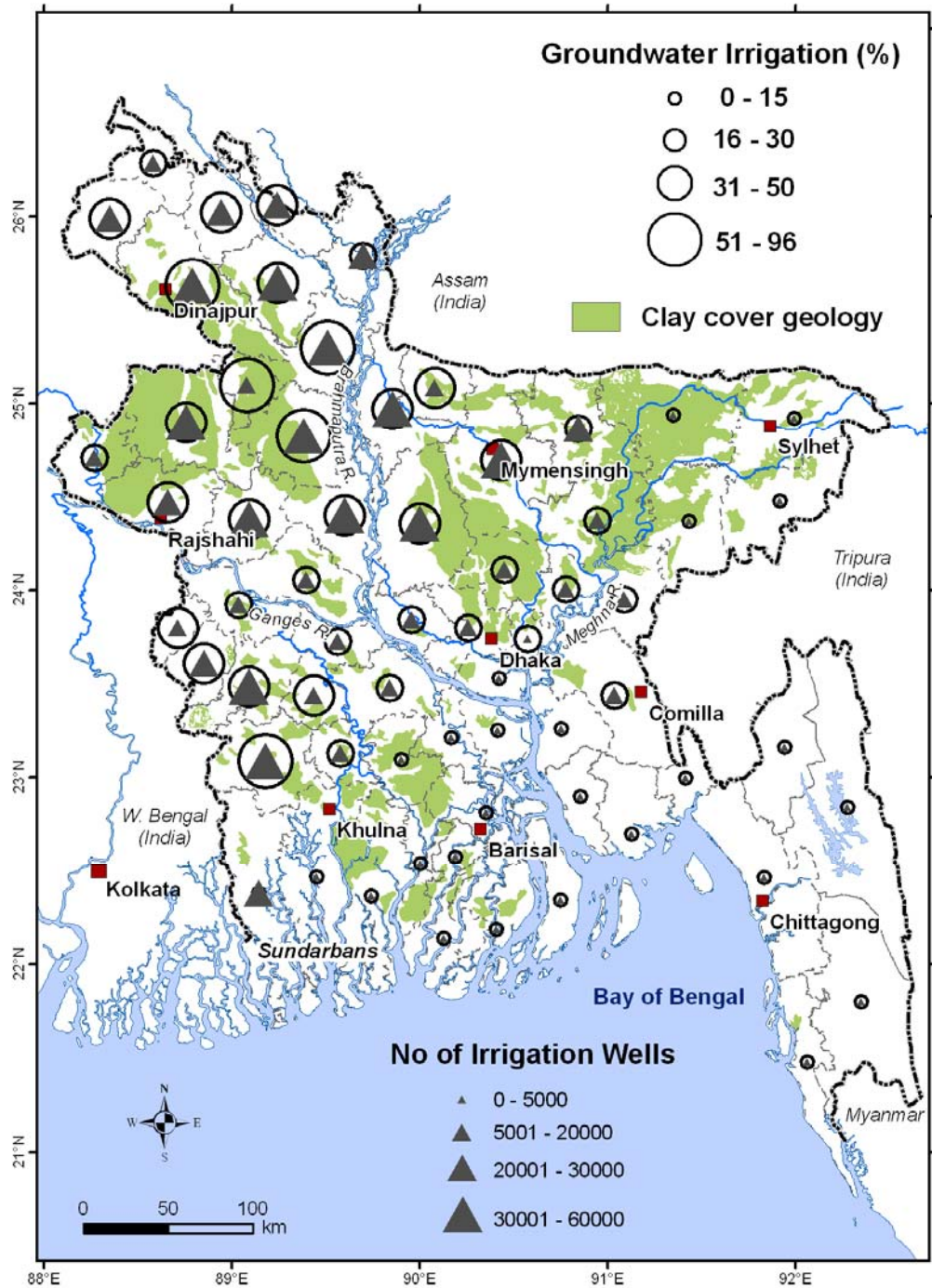


Figure 2.8 Percentage of land in each of the 64 districts (broken gray lines) in Bangladesh irrigated with groundwater in 2003 (BADC, 2003). Total numbers of shallow and deep tubewells operated in each district in 2003 are also shown. Low-permeable regionally extensive surface geological units are shown in the background.

As a result, shallow groundwater storage is declining. This critical observation falsifies the widely held assumption that shallow aquifers attain the so-called “full condition” every monsoon throughout Bangladesh (UNDP 1982; Aggarwal et al. 2000; WARPO 2000; BGS and DPHE 2001; Harvey et al. 2006).

The spatial structure of deduced trends reflects the balance between abstraction and surface geology which acts as a key control on the magnitude of groundwater recharge. From 1979 to 2003, groundwater-fed irrigation for dry season rice cultivation in Bangladesh increased by approximately 875 million cubic meters (MCM) each year (BADC 2003) elevating annual rice production from 11.9 megatonnes (Mt) in 1975 to 27.3 Mt in 2006-2007 (Bangladesh Bureau of Statistics 2008). Although records of groundwater usage for irrigation are not available, this study provides an approximation of the spatial distribution of groundwater abstraction based on the fraction (as a percentage) of land in each of the country's 64 districts that was irrigated by both shallow and deep irrigation pumps in 2003 (Figure 2.8). Nationally, a total of 924,023 STWs were used to irrigate about 24,094 km² of agricultural land accounting for approximately 60% of irrigated land whereas irrigation using DTWs comprised 15%.

Observations indicate that areas of intensive abstraction for irrigation exhibit declining trends in long-term groundwater levels in Bangladesh. A key exception is in the district of Dhaka where the shallow aquifer is overlain by the Madhupur clay formation (Ahmed et al. 1999). Here, there is little abstraction for irrigation in peri-urban areas but annual abstraction for domestic and industrial purposes is ~750 MCM (Hoque et al. 2007) and substantially exceeds total annual recharge of ~380 MCM in the Dhaka district (Karim 1984). This high groundwater deficit is responsible for the rapid decline (>1 m/year) in groundwater levels. Elsewhere in Bangladesh, the magnitude of declining shallow groundwater storage in northwestern (i.e., Barind Tract) and north-central (i.e., Madhupur Tract) regions (Figure 2.8) relates not only to the intensity of abstraction but also low to areas of clay cover where rates of rainfall-fed recharge are constrained by the low hydraulic conductivity (0.01 m/day) of this surface geology.

2.5.2 Rising Groundwater Levels and Sea-level Rise

Rising trends in groundwater levels (0.5 to 2.5 cm/year) observed from 1985 to 2005 in the Meghna estuary and coastal regions of Bangladesh, coincide with rising sea levels reported by several studies (Alam 1996; Singh et al. 2000; Singh 2002; Mohal et al. 2007). Observed sea levels from 1977 to 1998 at three locations (see Figure 2.4d) reveal that mean rates of sea-level rise range from 0.4 to 0.8 cm/year (Singh 2002). These rates are much higher than the average rate of global sea level rise of 0.18 cm/year for the 20th century (IPCC 2007) and arise from regional factors such as sediment load, basin tectonics and differential subsidence of the GBM Delta (Worm et al. 1998; Goodbred and

Kuehl 2000). As sea levels rise, shallow groundwater levels in coastal areas are elevated through an overall rise in the position of the freshwater-seawater interface (Barlow 2003; McCobb and Weiskel 2003). A rise in the groundwater level caused by sea-level rise could impact on river deltas up to 20-50 km inland (Barlow 2003). The magnitude of sea-level rise along the coast of the Bay of Bengal (0.4 to 0.8 cm/year) from 1977 to 1998 is comparable to the trends in rising groundwater levels (0.5 to 2.5 cm/year) observed in coastal aquifers between 1985 and 2005. Rising groundwater levels may additionally result from local recharge as the volume of rainfall-fed recharge exceeds abstraction in southern deltaic areas (BGS and DPHE 2001). Projected rises in sea level will accelerate the intrusion of saline water thereby impairing groundwater quality and threatening the world's largest mangrove forest in the Sundarbans (Alam, 2004) where groundwater plays a vital role in maintaining an intermediate salinity required for mangrove growth and survival (Agrawala et al. 2003). It is important to note that coastal defences (e.g., embankments, dykes) will not inhibit (subsurface) seawater intrusion.

2.6 Conclusions

This study resolves the recent (1985 to 2005) trends in groundwater levels within a highly seasonal hydrological system, the Ganges-Brahmaputra-Meghna (GBM) Delta, through the novel application of a robust seasonal-trend decomposition technique (STL). Seasonality dominates observed variance in groundwater levels but is shown, for the first time, that groundwater levels are declining by 0.1 to 0.5 m/year in north-central, northwestern, and southwestern areas of the GBM Delta where intensive abstraction of groundwater is conducted for dry-season rice cultivation. Unsustainable groundwater abstraction is especially pronounced in areas where the low hydraulic conductivity of surface geology inhibits rainfall-fed recharge. In Dhaka where abstraction has increased dramatically to meet domestic and industrial demands, rates of groundwater-level decline exceed 1 m/year. In the southern GBM Delta, rising groundwater levels (0.5 to 4 cm/year) are detected that are commensurate to, and coincident with, local trends in sea levels (0.4 to 0.8 cm/year). This analysis of the exceptional dataset of groundwater-level observations for the GBM Delta in Bangladesh provides insight into trends and seasonality in shallow groundwater levels expected in other Asian Mega-Deltas influenced by groundwater abstraction and global sea-level rise.

Chapter 3

Spatio-temporal Changes in Groundwater Storage

This chapter uses the national groundwater-level database of Bangladesh compiled and presented in the previous chapter and characterises spatio-temporal changes in groundwater storage. Borehole-derived estimates of groundwater storage changes are compared with estimates derived from GRACE satellite measurements. A rationale for investigating changes in groundwater storage in the Bengal Basin of Bangladesh is provided at the outset.

3.1 Introduction

As groundwater is the world's largest accessible store of freshwater (Shiklomanov and Rodda 2003), the quantification of changes in groundwater storage (ΔGWS) is critical to assessments of the sustainability of freshwater withdrawals in many parts of the world (Taylor 2009). Satellite measurements of changes in total terrestrial water storage (ΔTWS), provided by the Gravity Recovery and Climate Experiment (GRACE) since March 2002 (Tapley et al. 2004), constitute a global database to assess ΔGWS after accounting for and, if necessary, deducting from ΔTWS the contribution of changes in remaining terrestrial freshwater stores including soil moisture (ΔSMS) and surface water (ΔSWS) as well as ice and snow (ΔISS) using ground-based observations or simulations derived from Land Surface Models (LSMs) (Rodell et al. 2004; Wahr et al. 2004; Swenson et al. 2006). For example, basin-scale studies in the United States and Australia (Rodell et al. 2007; Leblanc et al. 2009; Strassberg et al. 2009) demonstrate that ground-based (in situ) observations of ΔGWS from borehole hydrographs compare well with estimates of ΔGWS derived from GRACE data.

Recent studies of GRACE-derived estimates of ΔGWS on the Indian subcontinent (Rodell et al. 2009; Tiwari et al. 2009) report substantial declining trends that are attributed to high rates of groundwater abstraction for irrigated agriculture. Trends range from $18 \pm 5 \text{ km}^3/\text{year}$ for northwestern India (Rodell et al. 2009) to $54 \pm 9 \text{ km}^3/\text{year}$ for the

entire Indo-Gangetic Plains (Tiwari et al. 2009) but neither estimate is well constrained by ground-based observations. Furthermore, trends in ΔGWS estimated by Tiwari et al. (2009) for the highly seasonal Indo-Gangetic Plains do not consider the contribution of river and flood storage to ΔTWS yet recent modelling study (Kim et al. 2009) shows that river storage, that includes an unresolved component of downslope movement of shallow groundwater, accounts for a substantial proportion (28–73%) of ΔTWS in highly seasonal hydrological systems such as Mississippi, Orinoco, and Amazon river basins.

This chapter quantifies ΔGWS in the Bengal Basin of Bangladesh from January 2003 to December 2007 using both gridded GRACE satellite data and a recently compiled database of ground-based observations from groundwater levels (i.e., borehole hydrographs) (see Chapter 2). Critically, this study resolves the contributions of ΔSWS and ΔSMS to ΔTWS in these calculations using ground-based observations of ΔSWS from a network of 298 monitoring stations across Bangladesh (Steckler et al. 2010) and simulations of ΔSMS from three LSMs (CLM, NOAH, VIC) provided by the Global Land Data Assimilation System (GLDAS) (Rodell et al. 2004). In doing so, this chapter tests the robustness of GRACE-derived estimates of ΔGWS in a highly seasonal hydrological system. Finally, estimates of recent trends in ΔGWS are placed in the context of long-term trends (1985 to 2007) derived from ground-based observations.

3.2 Datasets and Methods

3.2.1 Groundwater Level Dataset and Processing

This study assesses temporal trends in weekly groundwater levels (Δh) in a subset of 236 monitoring wells (mean depth of 30 m below ground level, bgl) for two periods (Jan. 2003 – Dec. 2007; Jan. 1985 – Dec. 2007). The first period represents the more recent changes in groundwater storage which is directly comparable with the duration of GRACE data period used in this study. The second period represents the longest period of groundwater storage changes for which observational records of sufficient quality (mean missing record <4.3%) and density are available. Interannual changes in wet-season groundwater levels each year represent net changes in groundwater storage after dry-season irrigation for rice (Boro) cultivation (Figure 3.1) and monsoon recharge have taken place. This study determines (i) linear trends in wet-season (July to September) groundwater levels, and (ii) multiple linear trends through annual means of time-series

records with covariates (sine and cosine functions of time) to account for the strong seasonality in groundwater levels.

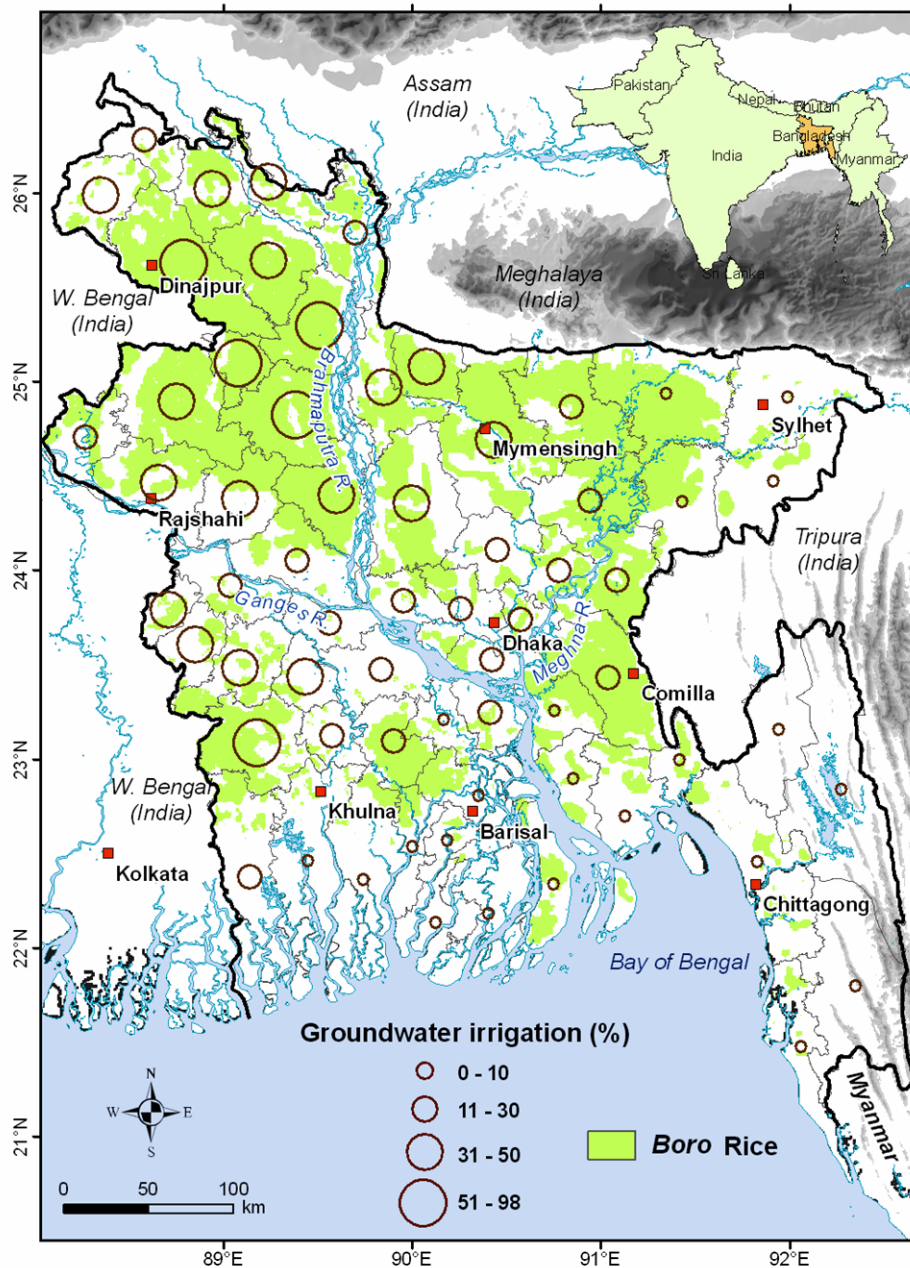


Figure 3.1 Map shows areas of dry-season Boro rice cultivation in 2007–2008 in Bangladesh (SPARRSO 2009) and percentage of land (brown circles) in each of the country’s 64 districts irrigated with groundwater using shallow and deep tubewells. Map also shows digital elevation (gray shades), river channels (blue polylines), district level boundaries (thin gray lines), and international boundary (dotted black lines).

To translate Δh for regionally unconfined shallow (<100 mbgl) aquifers (UNDP 1982) into an equivalent water depth (ΔGWS) for comparison with GRACE data, both spatially distributed values of specific yield (S_y) and an uniform value of 0.1 were applied. Spatially distributed values of S_y (mean 0.06, range 0.01 to 0.2) derive from 279 pumping test records (BWDB 1994) across Bangladesh (A detailed discussion on specific

yield is provided in Chapter 4). In light of uncertainty in observed values of S_y , a uniform, measure of S_y (0.1) is applied to represent the maximum potential groundwater-storage losses. High S_y (≥ 0.1) values were used in previous studies in the Bengal Basin (Michael and Voss, 2009b). Interpolated values of Δh and S_y were multiplied by the area (A) of the interpolated grid cell ($\sim 25 \text{ km}^2$) according to equation 3.1 for each time period (t):

$$\Delta GWS_t = \Delta h_t \times S_y \times A \quad (3.1)$$

3.2.2 GRACE-derived Terrestrial Water Storage

A total of four GRACE-derived ΔTWS datasets are used from two different sources: (i) 3 monthly gridded ($1^\circ \times 1^\circ$) time-series records of GRACE ΔTWS (Center for Space Research (CSR), version dpc-200711) (Chambers 2006); and (ii) a 10-day time series of GRACE ΔTWS (version RL02) provided by the GRGS (The Group de Recherche en Géodesie Spatiale) (Lemoine et al. 2007). All GRACE data sets are corrected for atmospheric mass variations, earth and ocean tides. The NASA GRACE-derived ΔTWS datasets were post-processed with zero, 300, and 500km half-width Gaussian filters after destriping and post-glacial rebound corrections were applied (Swenson and Wahr 2006). The GRGS GRACE time-series records are less noisy and do not require any additional filtering as gravity models were used to stabilize the original GRACE data (Lemoine et al. 2007; Ramillien et al. 2008).

3.2.3 GRACE Data Processing

Temporal changes in groundwater storage (ΔGWS) over the entire area of Bangladesh are separated from GRACE ΔTWS using the equation 3.2:

$$\Delta GWS = \Delta TWS - \Delta SMS - \Delta SWS - \Delta ISS \quad (3.2)$$

Note that ΔSMS represents changes in soil moisture storage in all soil horizons and ΔSWS includes river and flood water storage. Changes in freshwater storage derived from ice and snow (ΔISS) are negligible in Bangladesh and not considered in this study. ΔSMS derive from CLM (v. 2), NOAH and VIC LSMs (Rodell et al. 2004). The total depth of ΔSMS in CLM (10 layers), NOAH (4 layers), and VIC (3 layers) are 3.4 m, 2.0 m, and 1.9 m respectively. None of these LSMs includes groundwater storage (Rodell et al. 2004).

In these analyses, ΔSWS refers primarily to flood-water loads and river storage as there are no irrigation dams or reservoirs in Bangladesh (BGS and DPHE 2001). Areas of

up to one-third of the country ($\sim 48,000 \text{ km}^2$) are inundated by flood water each year and two-thirds of the country may be under water during extensive flood years (Steckler et al. 2010). Monthly estimates of ΔSWS were generated using daily river-stage observations from 298 monitoring stations throughout Bangladesh (Figure 3.2).

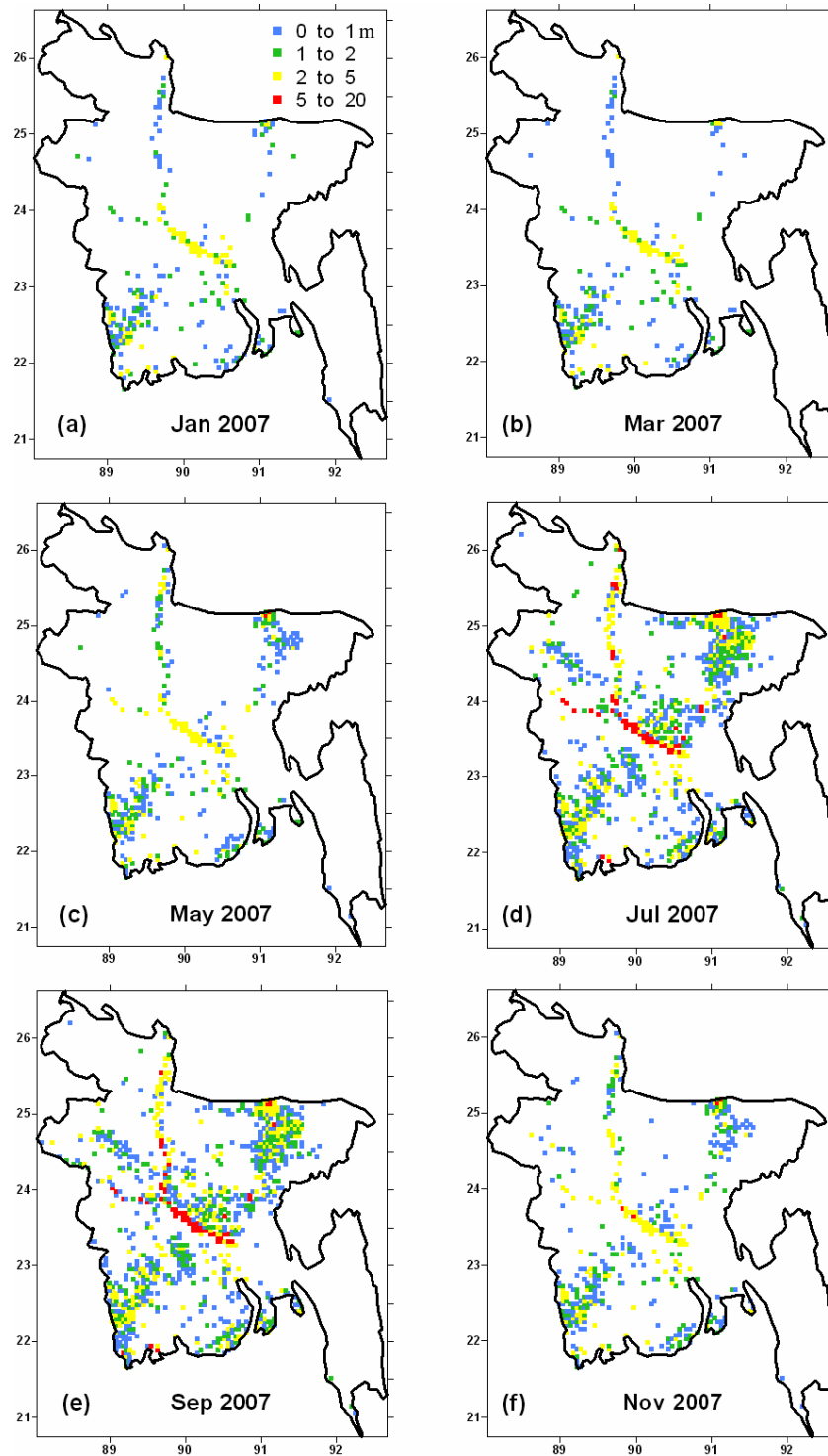


Figure 3.2 Maps show spatio-temporal distributions in surface water depth (m) in various months in 2007 across the entire Bangladesh. Surface water storage (ΔSWS) mapping includes (1) averaging of the daily observations (river and flood water storage) to a monthly time series and interpolating the point data over the entire Bangladesh, and (2) subtraction of the interpolated surface water levels from a digital elevation model to create monthly average surface water depth.

3.3 Results

3.3.1 Groundwater Storage from GRACE-TWS Data

Figure 3.3 shows monthly time-series anomalies in all GRACE derived ΔTWS , simulated ΔSMS from 3 LSMs and their average, observed groundwater and river levels, and average monthly rainfall in Bangladesh for the period of 2003 to 2007. Strong seasonality is observed in ΔTWS and various ΔSMS records (Figures 3a-b). Variations in individual water stores compares well with observed variability in monthly and interannual rainfall (Figure 3.3d). Average annual amplitudes in ΔTWS between 2003 and 2007 are 43 cm (CSR GRACE 300km) and 49 cm (GRGS GRACE). The amplitude in ΔSMS varies among the LSMs: 8 cm (CLM), 26 cm (NOAH) and 20 cm (VIC). At the outset of the monsoon season, river levels rise quickly whereas groundwater levels respond more slowly with a lag of approximately 1 month to river levels.

Estimates of ΔGWS over the period of 2003 to 2007 are derived from observed borehole hydrographs and 3 GRACE data sets (Figure 3.4, Tables 3.1 and 3.2). The GRGS GRACE solution and 2 CSR GRACE data sets (GRACE 0km and 300km) are used to estimate ΔGWS after separating simulated ΔSMS (3 LSMs and their average) and observed ΔSWS from ΔTWS (equation 3.2). The CSR GRACE 500km solution is found to be over-smoothed for the scale of the Bengal Basin ($\sim 144,000 \text{ km}^2$) and thus excluded from the estimation of ΔGWS . In the absence of validation data, the average of 3 LSMs is used to estimate ΔSMS . Changes in groundwater storage over the period of 2003 to 2007, estimated from GRACE data sets and borehole hydrographs, are strongly correlated (Figure 3.4). The highest correlation ($r=0.9$, $p<0.0001$) is observed for the GRGS GRACE dataset. Variability in GRACE-derived ΔGWS results from 12 possible estimates (3 GRACE solutions \times 4 SMS derived from 3 LSMs and an average) and is represented as an envelope in Figure 3.4.

3.3.2 Estimated Groundwater Storage from Borehole Data

Trends in ΔGWS averaged over the entire Bangladesh are summarised in Tables 3.1 and 3.2. Linear trends in wet-season (July to September) groundwater levels represent changes in ΔGWS as the wet-season water levels indicate recharge to aquifers. The linear trend (January 2003 to December 2007) in ΔGWS based on wet-season groundwater levels is $-0.75 \text{ km}^3/\text{year}$ using distributed S_y values whereas the rate of loss is 1.36

km³/year if a maximum S_y value of 0.1 is uniformly applied. Multiple linear trends in annual means represent net changes in ΔGWS that may be influenced by declining groundwater levels associated with increased dry-season irrigation. These estimates produce slightly higher rates of groundwater depletion (-0.85 to -1.53 km³/year). GRACE-derived trends of ΔGWS losses using a simulated mean ΔSMS range from 0.98 to 1.53 km³/year for wet-season and 0.49 to 2.81 km³/year based on annual means.

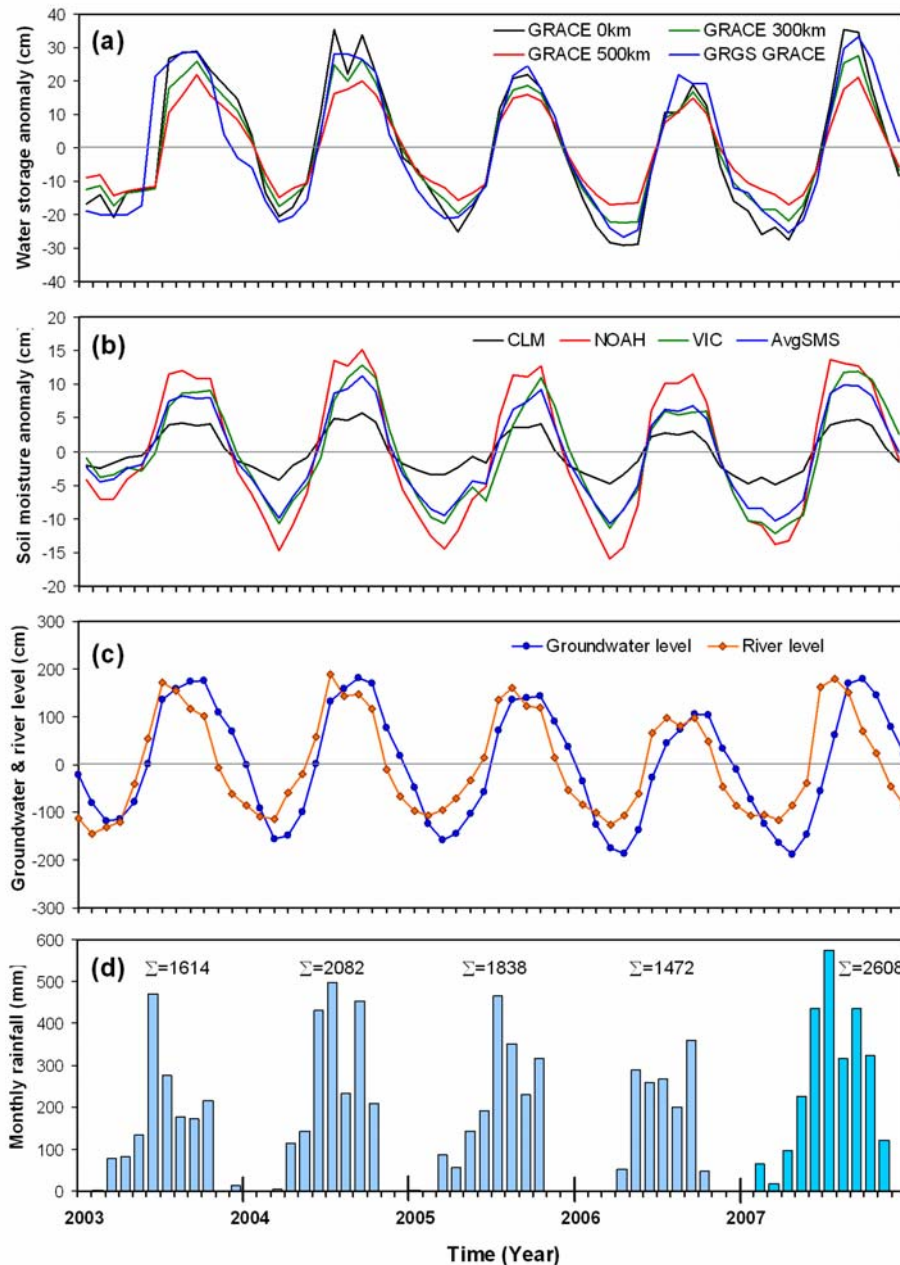


Figure 3.3 (a) Monthly time-series anomaly (cm) of 3 solutions of CSR GRACE and a GRGS GRACE derived ΔTWS for the period of January 2003 to December 2007; (b) 3 simulated soil moistures (CLM, NOAH, and VIC) and their average (AvgSMS); (c) monthly anomalies in groundwater levels averaged from a total of 236 monitoring locations and river levels averaged from a total of 298 gauging stations across Bangladesh; and (d) mean monthly rainfall for the same period averaged. Total annual rainfall for each year (2003 to 2007) is also shown in mm.

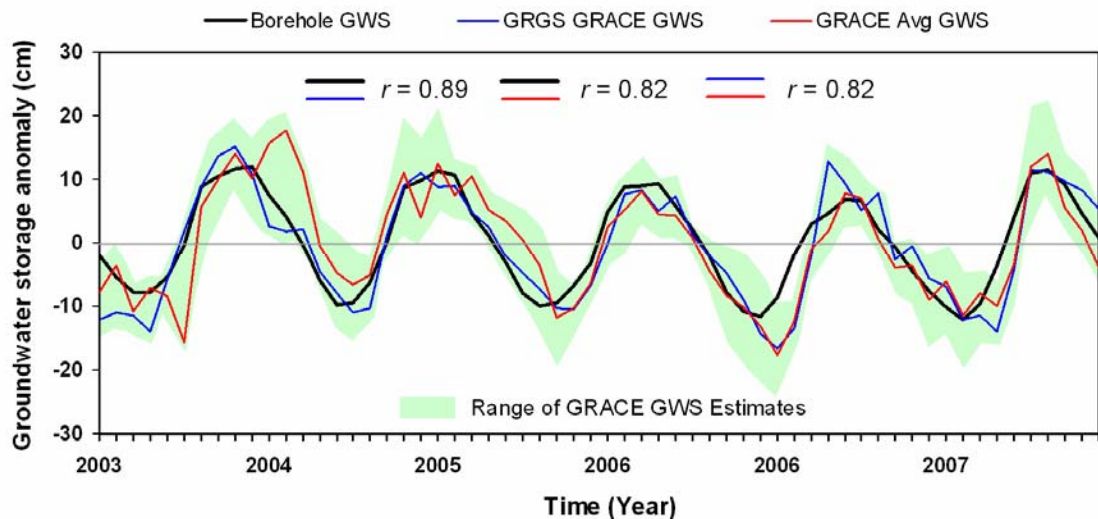


Figure 3.4 Monthly time-series anomaly (cm) in groundwater storage (ΔGWS) derived from borehole hydrograph (Borehole ΔGWS) and from GRACE solutions (GRGS GRACE derived ΔGWS , and an average of CSR GRACE 0km and 300km derived ΔGWS estimates) for the period of January 2003 to December 2007. Average soil moisture from 3 GLDAS LSMs, and monthly time-series records of surface water storage (ΔSWS) were used for these GRACE ΔGWS estimates. An envelope of range in GRACE-derived ΔGWS estimate was generated using the range of 12 different estimates of ΔGWS . Correlation coefficients between borehole and GRACE derived ΔGWS estimates are also given.

Short-term changes in ΔGWS estimates are sensitive to the length of the time series. Consequently, the resolution of trends in ΔGWS is problematic over short periods in the highly dynamic Bengal Basin where the seasonality in water storage is stronger than the trend component (shown in Chapter 2). For example, trends in ΔGWS estimated for a shorter (2003 to 2006) period, are nearly twice (Borehole ΔGWS : -1.53 to -2.8 km^3/year ; GRACE ΔGWS : -1.83 to -3.06 km^3/year) that calculated for the period of 2003 to 2007. In contrast to the estimates of short-term changes in ΔGWS , long-term (1985 to 2007) rates in ΔGWS using borehole hydrographs are considerably lower (-0.28 to -0.57 km^3/year).

Spatial distributions in ΔGWS derived from borehole hydrographs highlight areas of rising and falling groundwater storage over both short (2003 to 2007) and long (1985 to 2007) periods of observation (Figure 3.5). Over both periods, there are decreasing trends in ΔGWS in central and northwestern parts of Bangladesh and rising trends in coastal regions. Relative to long term terms, trends in groundwater storage have reversed in northern areas and intensified in central and northwestern regions. Due to the coarse resolution ($\sim 160,000$ km^2) of GRACE measurements compared to borehole-derived estimates (average density of 1 borehole per 100 km^2), spatial comparisons between

ground-based and satellite-derived ΔGWS are not possible for the Bengal Basin in Bangladesh (144,000 km²).

Table 3-1 Trends (km³/year) in groundwater storage changes (ΔGWS) in Bangladesh derived from borehole hydrographs. Linear trends were calculated in the wet-season groundwater levels and multiple linear trends through the annual means. Pumping-test derived distributed specific yield values and a maximum value of 0.1 were applied for these estimates.

Estimation period	Linear trends (wet season) with distributed S_y	Linear trends (wet season) with an uniform $S_y=0.1$	Multiple linear trends (time-series) with distributed S_y	Multiple linear trends (time-series) with an uniform $S_y=0.1$
2003-2006	-1.53	-2.80	-1.37	-2.54
2003-2007	-0.75	-1.36	-0.85	-1.53
1985-2007	-0.28	-0.57	-0.28	-0.55

Table 3-2 Trends (km³/year) in groundwater storage changes (ΔGWS) in Bangladesh derived from GRACE TWS data. Linear trends (wet-season levels) and multiple linear trends (annual means) were calculated after separating soil moisture (ΔSMS) and surface water (ΔSWS) storages from the ΔTWS .

GRACE solution/ Estimation period	Linear trends in wet-season levels				Multiple linear trends in annual means			
	CLM	NOAH	VIC	AVG	CLM	NOAH	VIC	AVG
GRACE 0km derived estimates								
2003-2006	-3.19	-3.19	-2.80	-3.06	-4.95	-3.83	-4.01	-4.27
2003-2007	-1.35	-1.54	-1.72	-1.53	-3.08	-2.67	-2.68	-2.81
GRACE 300km derived estimates								
2003-2006	-1.96	-1.96	-1.57	-1.83	-2.76	-1.64	-1.82	-2.07
2003-2007	-0.79	-0.98	-1.17	-0.98	-1.93	-1.51	-1.52	-1.65
GRGS GRACE derived estimates								
2003-2006	-2.56	-2.33	-1.72	-2.20	-2.00	-0.88	-1.06	-1.31
2003-2007	-1.09	-1.28	-1.46	-1.27	-0.76	-0.35	-0.36	-0.49

Note: CLM – Cumulative Land Model soil moisture model; NOAH – NOAH soil moisture model; and VIC – Variable Infiltration Capacity soil moisture model; AVG – Average of three LSMs.

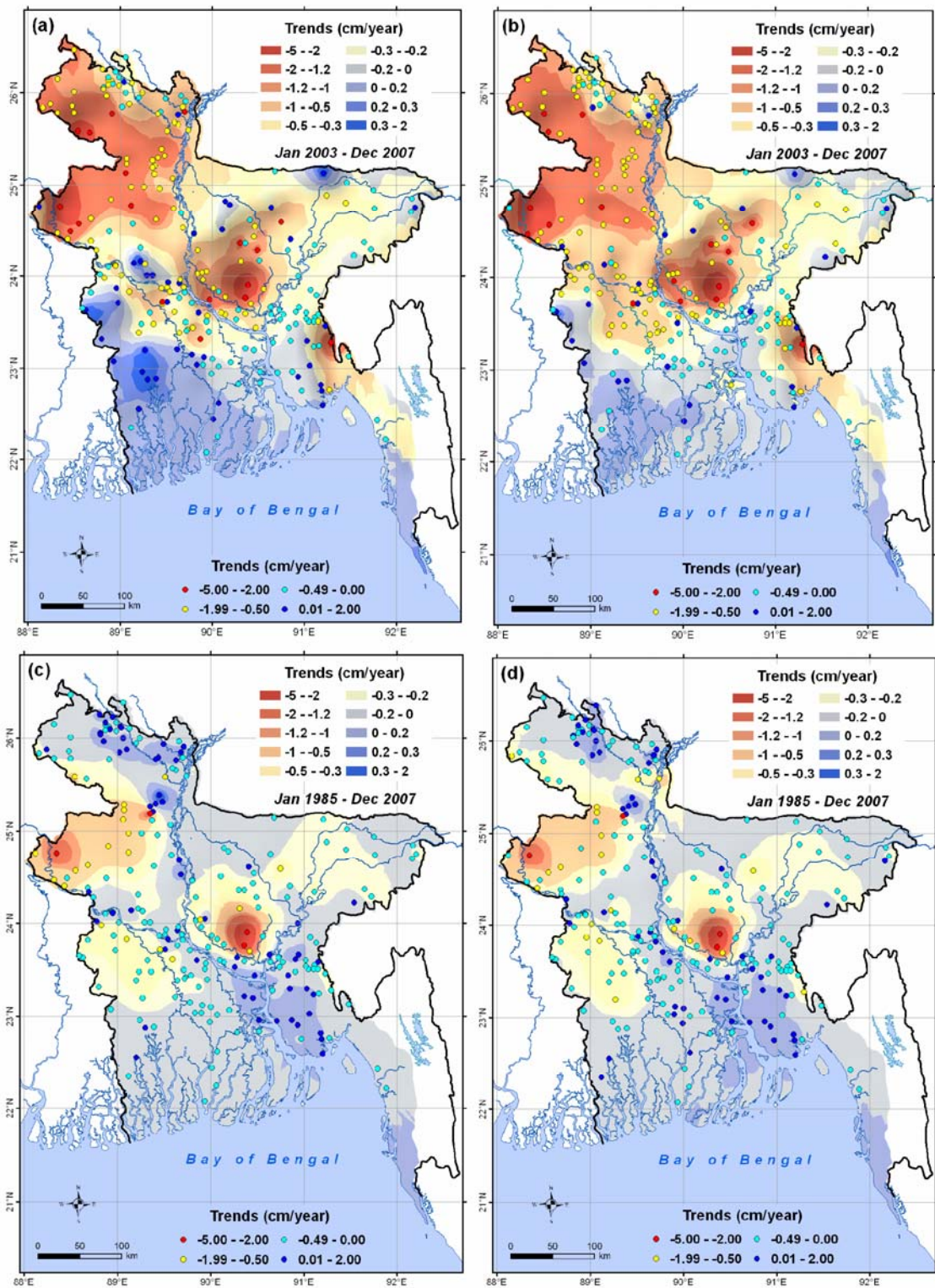


Figure 3.5 Trends (cm/year) in groundwater storage changes (ΔGWS) in Bangladesh derived from borehole hydrographs. Panels (a) and (b) show trends in ΔGWS from linear (wet-season) and multiple linear (annual means) estimates respectively for the period of 2007 to 2007; panels (c) and (d) show linear and multiple linear trends in ΔGWS for a longer period (1985 to 2007). Areas of recent groundwater storage losses are highlighted in top two panels.

3.4 Discussion

3.4.1 Comparison between Borehole and GRACE Estimates

The seasonality and trends in ΔGWS estimates derived from borehole hydrographs compare well with GRACE-derived ΔGWS (Figures 3.3, 3.4). There are, however, a number of sources of uncertainty and underlying assumptions that are inherent to both techniques. Estimation of borehole-derived ΔGWS assumes: (1) trends in groundwater levels do not result from inhomogeneities in observation records; and (2) applied values of specific yield (S_y), derived from pumping tests or applied as a worst-case scenario ($S_y=0.1$) in order to convert groundwater levels to an equivalent water depth, are representative of the monitored aquifer. Estimation of GRACE-derived ΔGWS assumes: (1) an accurate estimate of ΔSMS contribution from LSMs and (2) the sum of potential bias (underestimation from mass within the Bengal Basin) and leakage (contribution from areas adjacent to the Bengal Basin) is negligible (Longuevergne et al. 2010). S_y values derived from pumping tests can be biased toward low values in two ways. First, elastic storage often dominates short pumping tests where confined or semi-confined exist locally and water-table drainage has insufficient time to respond. Second, in situ estimates of S_y , that sample an area of $<0.5 \text{ km}^2$ but are scaled up to a $1^\circ \times 1^\circ$ grid cell (used in the analysis of in situ ΔGWS), do not represent the considerable variability in S_y that naturally exists in alluvial aquifers. The influence of low S_y values may be exaggerated at regional scales as abstraction and resultant groundwater depletion are biased to areas of higher S_y . These deductions highlight the current but under-explored uncertainty associated with the selection of storage coefficients to reconcile ΔGWS from GRACE, as an equivalent groundwater depth, with in situ monitoring observations from borehole hydrographs.

3.4.2 Importance of Surface Water Storage in GRACE Estimates

This study shows that accounting for the contribution of river and flood water stores in the Bengal Basin is critical to the estimation of ΔGWS from GRACE data. This contribution is, however, often ignored in flood-prone regions around the world (Swenson et al. 2006; Rodell et al. 2007; Tiwari et al. 2009) as flood water is mostly unregulated or its affect on ΔTWS is assumed to be negligible relative to ΔSWS . Surface water storage in the Bengal Basin accounts for 25% of the variation in ΔTWS . Exclusion of ΔSWS can lead to an overestimation of ΔGWS using GRACE data. For example, these estimates of

groundwater storage changes between 2003 and 2007 in Bangladesh show an overall decline in groundwater storage at rates (Borehole ΔGWS : $-0.75 \text{ km}^3/\text{year}$, mean GRACE ΔGWS : $-0.98 \text{ km}^3/\text{year}$) that are much lower than the value of $-4.0 \text{ km}^3/\text{year}$ recently reported by Tiwari et al. (2009) who disregard river and flood water storage in their analysis of GRACE data.

3.4.3 Changes in Groundwater Storage in Bangladesh

A curious observation is the more favourable comparison that is observed between wet-season trends in ΔGWS derived from GRACE (-0.98 to $-1.53 \text{ km}^3/\text{year}$) and groundwater levels using a high, uniform estimate (0.10) of S_y ($-1.36 \text{ km}^3/\text{year}$) rather than a spatially distributed value (mean: 0.06 ± 0.04) of S_y ($-0.75 \text{ km}^3/\text{year}$). The scaling up of pumping-test derived estimates of S_y , that sample an area of $<0.5 \text{ km}^2$, to a 25 km^2 grid cell used in this analysis of ground-based ΔGWS , does not represent the considerable variability in S_y that naturally exists in alluvial aquifers. Thus calculation may exaggerate the influence of low S_y values at regional scales as abstraction and resultant groundwater depletion are biased to areas of higher S_y . These deductions highlight the current but unexplored uncertainty associated with the selection of storage coefficients to reconcile ΔGWS from GRACE, as an equivalent water depth, with ground-based observations from borehole hydrographs.

The substantial increase in groundwater storage depletion estimated for the period 2003 to 2007, relative to 1985 to 2007, is attributed to rising groundwater abstraction for irrigation and urban water supplies in Bangladesh. Declining trends in groundwater storage arise from unsustainable abstraction for municipal and agricultural abstraction respectively (Hoque et al. 2007) in central (Dhaka city) and northwestern parts of Bangladesh (also discussed in Chapter 2 and 4) where a low-permeability surficial deposit (Madhupur Clay Formation) of variable thickness (6 to 40 m) inhibits direct rainfall-fed groundwater recharge (BGS and DPHE 2001).

3.5 Conclusions

In a highly seasonal hydrological system, the Bengal Basin, this study shows that recent (2003 to 2007) changes in groundwater storage (ΔGWS) derived from GRACE satellite measurements match well ground-based observations. Critical to this analysis is the resolution of ΔGWS from total water storage (ΔTWS) derived from GRACE using (1)

changes in observed surface water storage (ΔSWS) derived from river stage records monitored at 298 gauging stations; and (2) changes in simulated soil moisture storage (ΔSMS) using a series of Land Surface Models (LSMs) (CLM, NOAH, and VIC). The highest correlation ($r=0.89$, p -value <0.0001) between borehole and GRACE derived ΔGWS is found for the GRGS GRACE ΔTWS and mean ΔSMS estimated from the three LSMs. In the Bengal Basin, strong seasonality in individual water storages is reflected well in GRACE measurements and overall variations in the TWS are explained well by SWS storage (25%), SMS storage (37%), and by GWS storage (38%).

The rate of decline in ΔGWS observed in monitoring boreholes is $0.75 \text{ km}^3/\text{year}$ which is slightly less than the range of estimates (0.98 to $1.53 \text{ km}^3/\text{year}$) that derive from different GRACE data sets and representation of ΔSMS in 3 different LSMs. Ground-based and GRACE derived declining trends in ΔGWS are substantially lower than that ($4.0 \text{ km}^3/\text{year}$) recently estimated by Tiwari et al. (2009). Spatial variations in GRACE ΔGWS are not directly comparable with observed ΔGWS because of the coarse resolution ($\sim 400 \text{ km}$) of GRACE data and uncertainties associated with ΔSMS from 3 LSMs. The spatial resolution in ΔGWS provided by monitoring boreholes is therefore critical for local-scale (10s of km) groundwater resource management and highlights the continued need for ground-based monitoring. Long-term (1985 to 2007) trends in observed ΔGWS ($-0.28 \text{ km}^3/\text{year}$) are much less than recent trends indicating that higher rates of groundwater depletion result from increasing rates of groundwater abstraction for irrigation and urban water supplies.

Chapter 4

Groundwater Recharge and Impacts of Abstraction

Previous chapters present changes in shallow groundwater storage in Bangladesh and highlight the water balance between long-term groundwater abstraction and recharge to aquifers. This chapter uses the national groundwater-level database and estimates net groundwater recharge to the shallow aquifer and illustrates the impacts of long-term, intensive abstraction for dry-season irrigation and urban water supplies on recharge.

4.1 Introduction

Groundwater recharge is influenced not only by climate variability but also human interventions including most substantially groundwater abstraction. Globally, irrigation is responsible for more than 65% of all freshwater withdrawals. At present, one quarter of the world's irrigated land is supplied by groundwater and 75% of these lands are located in Asia (Shah et al. 2007). Groundwater-fed irrigation is conducted to cultivate high-yielding rice during the dry season in South Asia where India and Bangladesh represent the world's second and fourth biggest rice-producing nations respectively (Scott and Sharma 2009; IRRI 2010). Over the last 50 years, groundwater abstraction on the Indian subcontinent increased from about 10-20 km³/year to approximately 260 km³/year (Shah et al. 2003; Giordano 2009). Current abstraction exceeds potential groundwater recharge to the Ganges-Brahmaputra and Indus basins estimated to be ~246 km³/year (CGWB 2006). In Bangladesh, total annual (2004–2005) irrigation water use is estimated to be ~24 km³ of which 18 km³ comes from groundwater (Siebert et al. 2010) via a range of pumping technologies (Figure 4.1). Recent studies in India (Rodell et al. 2009; Tiwari et al. 2009) and Bangladesh (presented in Chapter 3) report declining trends in groundwater levels (0.1 to 0.5 m/year) that indicate reductions in aquifer storage from unsustainable groundwater abstraction for both irrigation and urban water supplies.

The regional-scale impacts of intensive groundwater abstraction on recharge have rarely been subject to direct examination yet are central to the arguments of several authors (Sophocleous 2000; Alley et al. 2002; Alley and Leake 2004) who challenge the

concept of ‘safe yield’ defined by the long-term balance between annual groundwater abstraction and recharge under natural (non-pumping) conditions advocated by others (Döll and Fiedler 2008; Döll 2009; Kundzewicz and Döll 2009).

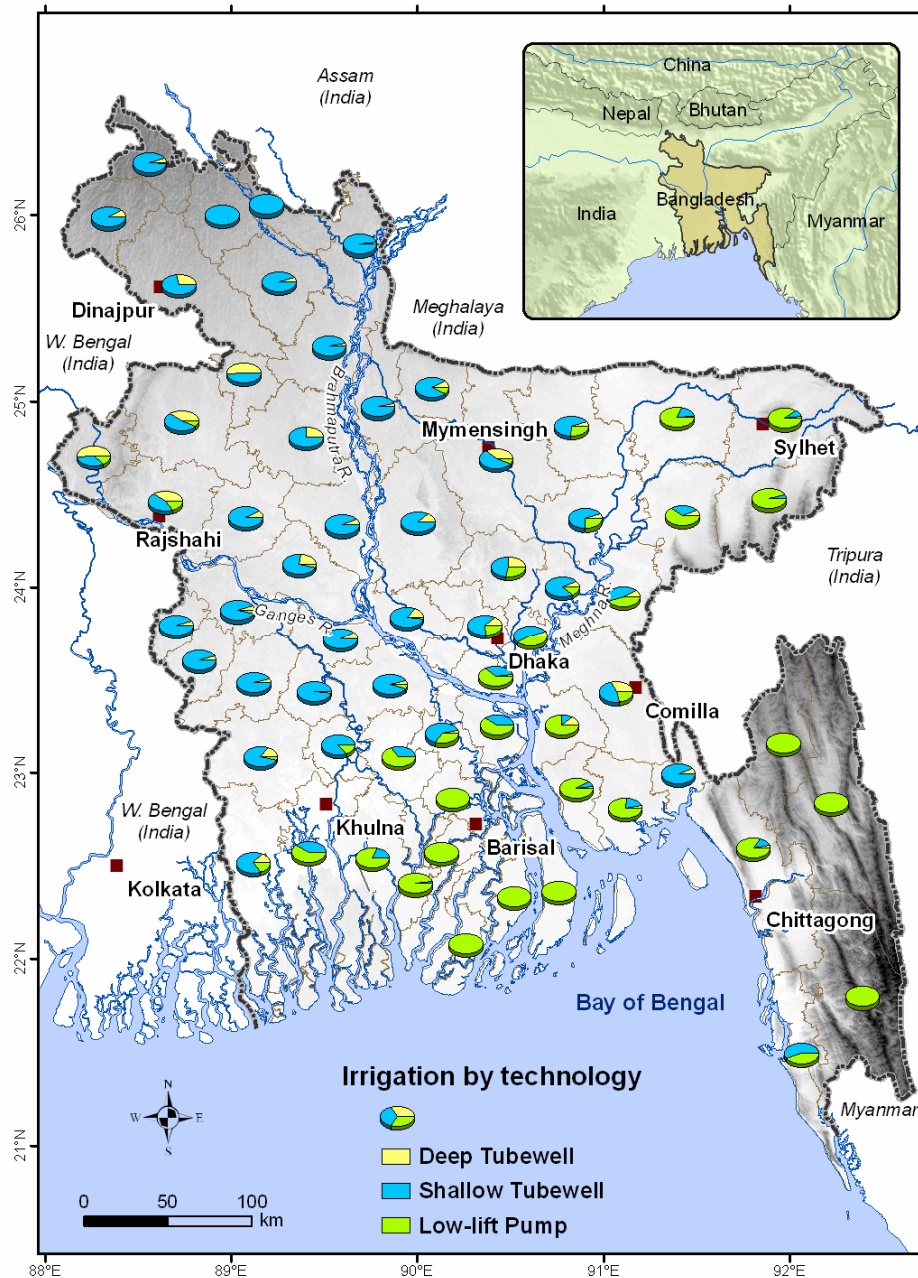


Figure 4.1 Relative proportion (percentage) of dry-season irrigation in 2006 by various pumping technologies in 64 districts in Bangladesh. Locations of the major district towns are given.

In the Bengal Basin, several localised studies of the mobilisation of arsenic in shallow groundwater (Harvey et al. 2006; Klump et al. 2006; Stute et al. 2007; Neumann et al. 2010) have speculated about a regional-scale perturbation of the shallow groundwater system caused by widespread pumping for irrigation. Abstraction, it is asserted, could induce groundwater recharge by either capturing surface water from rivers (Bredehoeft 2002) or increasing available aquifer storage through the dry season thereby

enhancing recharge during the subsequent wet (monsoon) season (MPO 1987). Recent, regional groundwater flow modelling in the Bengal Basin (Michael and Voss 2009a) provides support for this hypothesis. Here, spatio-temporal impacts of intensive groundwater abstraction on recharge to the shallow, alluvial aquifer system of Bangladesh are directly assessed using the compiled national database of water-level fluctuations and distributed estimates of specific yield. This study estimates actual (net) groundwater recharge to the shallow regional aquifer system for the period of 1975 to 2007 and compare changes in net groundwater recharge prior to the widespread adoption of groundwater-fed irrigation (1975 to 1980) to a more recent period (2002 to 2007).

4.1.1 Geomorphology and Aquifer Distribution

The alluvial plains of the Ganges-Brahmaputra-Meghna (GBM) Delta slope from north to south on a regional scale, but are interrupted locally by ridges and tectonically developed depressions, such as, Sylhet trough and Atrai depression (Figures 1.4 and 4.2). The Bengal Basin comprises of lowland floodplain and delta plain, and is surrounded by the Tertiary hills of various origins. Within the eastern Bengal Basin, the Madhupur Tract and Barind Tract are uplifted alluvial deposits of Pleistocene age interrupt the regional surface gradient of the central basin (Shamsudduha and Uddin 2007). Neotectonically uplifted Lalmai Hills located to the southeast of Madhupur Tract are composed of highly oxidized clay and sand of Pleistocene age. Underneath the Pleistocene tracts, there is yellowish-brown coloured sandy aquifer, formed within the Pliocene–Pleistocene Dupi Tila sand (Uddin and Lundberg 1998).

Groundwater in Bangladesh generally occurs at shallow depths within widespread alluvial deposits (MPO 1987). Shallow groundwater levels essentially follow surface topography. Groundwater levels are higher in northwestern parts of the country but generally low in the south and within large topographic lows such as Sylhet and Atrai depressions (Figure 4.2). Several classification schemes have been proposed to distinguish aquifers in Bangladesh; “Shallow” and “Deep” are the two most popularly used terms found in literature but the location of the contact between these two and the basis of hydrologic separation are not well defined (Michael and Voss 2009b). Aquifers that occur within the upper ~100 mbgl of the stratigraphic sequence are generally identified as the shallow aquifer, and the deep aquifer occurs at 100-150 mbgl (Ravenscroft 2003). Deep aquifers provide municipal and industrial water supplies in

urban areas and drinking water supplies in coastal areas where shallow groundwater is mostly saline (UNDP 1982; BGS and DPHE 2001).

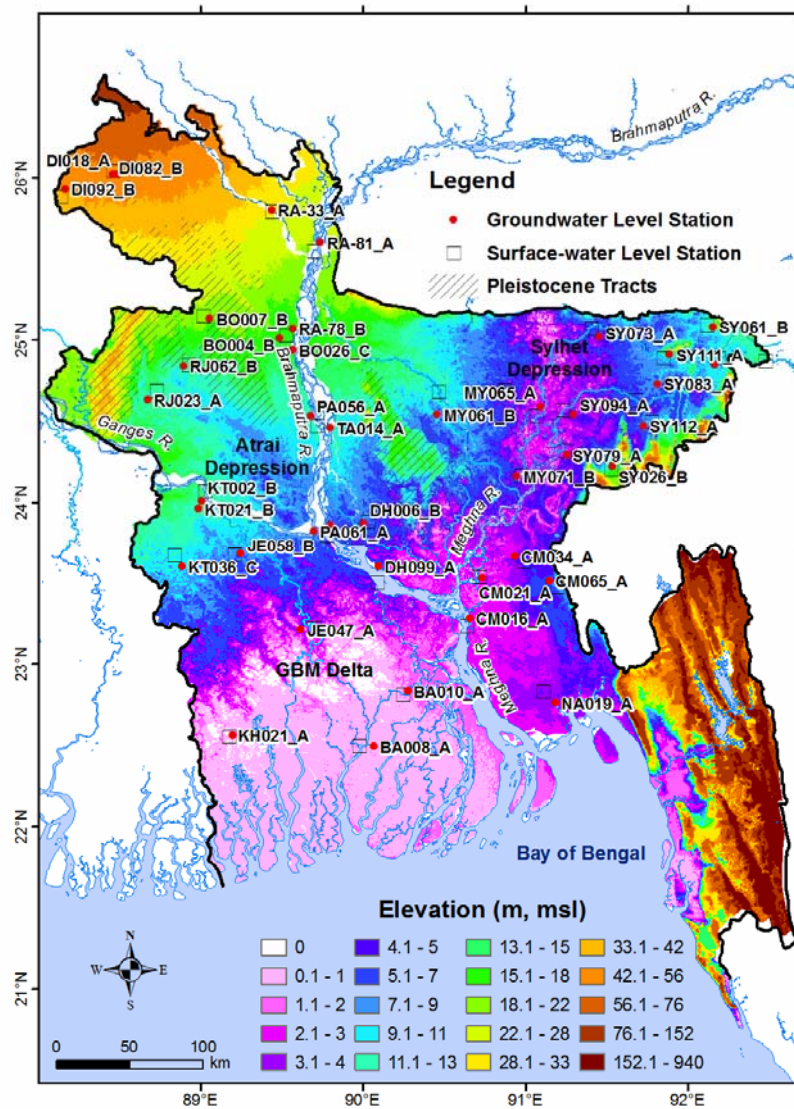


Figure 4.2 Digital elevation model (spatial resolution of 300m) of Bangladesh shows that topographic gradients are higher in the northwestern, northeastern, and southeastern parts of the country whereas gradients are low in southern GBM Delta and Sylhet depression of the upper Meghna catchment. The River Meghna runs through regionally topographic low areas where groundwater generally discharges. Pairs of selected groundwater (well IDs are shown) and surface water-level (IDs are not shown) monitoring stations are plotted on the DEM.

4.1.2 Previous Estimates of Groundwater Recharge in Bangladesh

There have been several efforts to estimate groundwater recharge to shallow aquifers in Bangladesh using different methods and datasets since the early 1970s (Figure 4.3). It is necessary to clarify terminology used in historical studies to define groundwater recharge. Actual (net) groundwater recharge is defined as the amount of water that infiltrates to the water-table through subsoil and is responsible for the net change in annual groundwater levels.

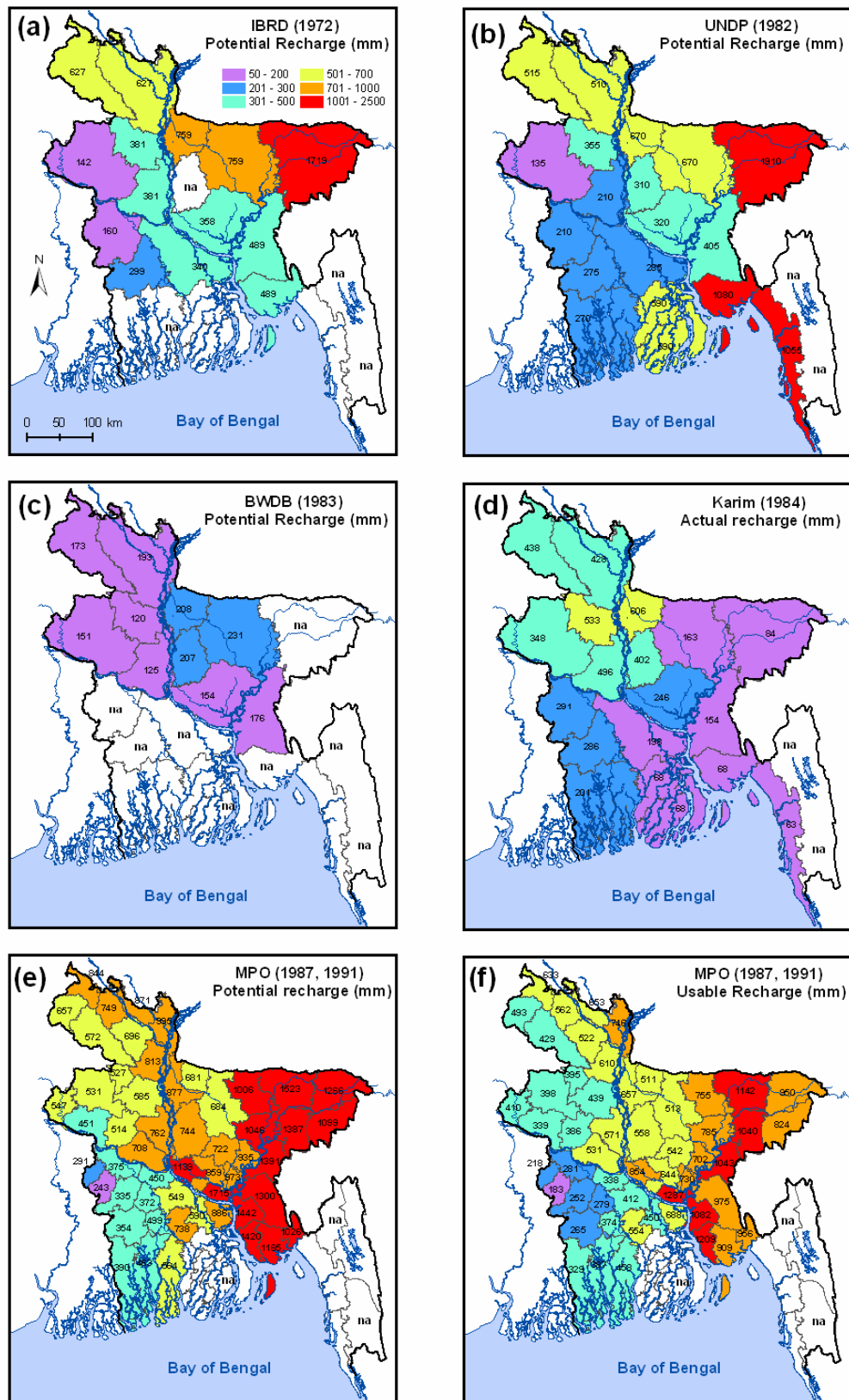


Figure 4.3 National-scale groundwater recharge estimates by various studies (a-f) between 1972 and 1991 in Bangladesh: panels (a-c, and e) show potential recharge; panel (d) shows estimates of actual recharge; and panel (f) shows usable recharge. Estimates are presented for aggregated districts (a-d) and individual districts (e-f). n.a. means no data available.

Potential recharge is defined as the total amount of water which could theoretically reach the water-table. Rejected recharge is the fraction of water available at the surface but unable to infiltrate and percolate down to aquifers because the aquifer is fully saturated and the water-table is at the ground surface. Usable recharge is the fraction (up to 75%) of potential recharge after accounting for uncertainties associated with the potential recharge due to poor model calibration, land-use, and flood control development. The “aquifer full” condition is achieved when the aquifer is fully replenished and potential recharge contributes to surface runoff (MPO 1987; Ravenscroft 2003).

The first study by the International Bank for Reconstruction and Development (IBRD 1972) estimated potential recharge from the difference between effective rainfall and potential evapotranspiration (Figure 4.3a). A more comprehensive study was later conducted by the United Nation Development Program (UNDP 1982) wherein potential recharge was defined as the excess amount of rainfall over the surface runoff and potential evapotranspiration (Figure 4.3b). During the 1980s, the Bangladesh Water Development Board and UNDP (BWDB and UNDP 1983) provided a more sophisticated estimate of potential recharge (Figure 4.3c) for northwestern and north-central parts of the country using a water balance method that considered both dry and wet percolation rates of aquifer units and variable recharge periods during the monsoon. Rates of groundwater recharge reported by BWDB and UNDP (1983) are much less than potential recharge since the rejected recharge was excluded from this estimate. Potential groundwater recharge mirrors rainfall is higher in the eastern Bangladesh but such estimates can greatly exceed actual recharge (Ravenscroft 2003). Karim (1984) used borehole hydrographs to estimate actual groundwater recharge to shallow aquifers between 1978 and 1983 (Figure 4.3d) and found recharge is lower in eastern Bangladesh compared to the western regions. Substantial uncertainty remains in these estimates due to the limited period of analysis and the use of tabulated specific yield values that are not reconciled to field conditions (Nishat et al. 2003). A more detailed analysis of potential and usable groundwater recharge (Figure 4.3e-f) at the nation-scale was conducted by the Master Plan Organisation (MPO 1987, 1991) using finite-difference recharge models that considered a large number of physical, hydrological and agricultural parameters. These estimates indicate higher potential for groundwater recharge in Rivers Brahmaputra (Jamuna) and Meghna, and in eastern parts of Bangladesh.

4.2 Data Sets and Methods

4.2.1 Groundwater Level Database

Weekly groundwater levels in monitoring boreholes are used to estimate groundwater recharge to shallow aquifers. Chapter 2 describes the national groundwater-level database compiled from a dense (one well per $\sim 100 \text{ km}^2$) network of 1267 monitoring wells for the period of 1965 to 2007 operated by the Bangladesh Water Development Board. The mean depth of monitoring wells is approximately 30 mbgl with a standard deviation of 15 mbgl. These wells represent spatio-temporal groundwater dynamics of the shallow aquifer (<100 mbgl) in Bangladesh.

4.2.2 Water-table Fluctuation Method

The water-table fluctuation (WTF) technique (Healy and Cook 2002) is applied to estimate net groundwater recharge. The principal assumption of the WTF method is that rises in the water level of an unconfined aquifer result from recharge arriving at the water-table (Healy and Cook 2002). In Bangladesh, the overwhelming majority ($>90\%$) of recharge to regionally unconfined (UNDP 1982) shallow aquifers occurs during the annual monsoon season (May to September) (MPO 1987; WARPO 2000) though recharge can also take place during the dry season indirectly via ponds and return flow from irrigation (Harvey et al. 2006). The annual range in groundwater levels is used to estimate annual recharge at each monitoring location. This study first decomposes the groundwater level time-series at each monitoring site into seasonal, trend and irregular components using a nonparametric seasonal-trend decomposition (STL) technique (described in Chapter 2). The annual fluctuation in groundwater levels is represented by the seasonal component of the time series. Specifically, the annual range of weekly-measured groundwater levels (Δh) between the maxima (during wet season) and minima (during dry season) was calculated at each monitoring location. This approach differs slightly from the typical WTF method where Δh is the difference between the peak water level and the theoretical lowest level which has been extrapolated along the antecedent recession-curve to the time of the peak water level (see Figure 1 in Healy and Cook 2002). Therefore, this approach derives the minimum annual recharge estimate to the aquifer. The calculation of net annual recharge for the pre-developed groundwater-fed irrigation (PGI) period (1975 to 1980) involves 177 monitoring wells of which there are 60 piezometers and 117 dug wells. The developed groundwater-fed irrigation (DGI)

period (2002 to 2007) involves 236 monitoring wells which include a total of 202 piezometers and 34 dug wells (Appendix 1.2). Lastly, the estimate of recharge for the long-term groundwater-fed irrigation (LGI) period (1985 to 2007) (LGI) is used to derive trends in net recharge rates and involves the same monitoring wells as DGI period.

4.2.2.1 Recharge Estimate for PGI Period

Under natural or pre-developed groundwater-fed irrigation condition (PGI period) net groundwater recharge to aquifers can be estimated using the equation (4.1) where R is net annual recharge, ΔS^{gw} is change in groundwater storage, Q^{bf} is baseflow to river channels, ET^{gw} is evapotranspiration from groundwater, and $Q_{out}^{gw} - Q_{in}^{gw}$ is the net groundwater flow from the study area.

$$R = \Delta S^{gw} + Q^{bf} + ET^{gw} + (Q_{out}^{gw} - Q_{in}^{gw}) \quad (4.1)$$

ΔS^{gw} estimated using the WTF method over long time-intervals (seasonal or annual), is sometimes referred to as “net” recharge (Healy and Cook 2002). In Bangladesh, Q^{bf} is inhibited during the monsoon period when river stages are universally higher than the water-table (Appendix 1.3) and the shallow aquifer adjacent to major rivers experiences induced recharge through bank infiltration. Baseflow is restricted to the early part of the dry season (i.e., descending limb of the groundwater hydrograph) which does not affect annual water-table rises. ET^{gw} is assumed to be negligible throughout Bangladesh where land cover is dominated (>80%) by crops (e.g., rice paddy) with shallow <2 m rooting depths (Mishra et al. 1997) and dry-season water tables are >2 mbgl (Chapter 2). During the monsoon (ascending limb of groundwater hydrograph) soil moisture sustaining ET is predominantly supplied by rainfall and flood water, and ET^{gw} via capillary flow is inhibited by direct and indirect recharge fluxes to aquifers. The magnitude of ET^{gw} via capillary flow during the dry season is unclear. Net groundwater flow ($Q_{out}^{gw} - Q_{in}^{gw}$) during the monsoon period is assumed to be negligible throughout the study area due to the absence of substantial hydraulic gradients in the water-table of the shallow aquifer (Harvey et al. 2006; Shamsudduha et al. 2009). Additionally, net groundwater flow ($Q_{out}^{gw} - Q_{in}^{gw}$) from the shallow system through the submarine groundwater discharge is negligible since groundwater flux to the Bay of Bengal is likely to be controlled by the deep flow system that is driven by regional head gradients (Michael and Voss 2009a). Eq.

(1) can, therefore, be simplified for the PGI period to the equation (4.2) where S_y is specific yield, Δh is water-table height between annual maxima and minima, and Δt is time period (a year).

$$R = \Delta S^{gw} = S_y \partial h / \partial t = S_y \Delta h / \Delta t \quad (4.2)$$

Equation (4.2) is used to estimate annual net groundwater recharge at each monitoring well location (n=177) for the PGI period.

4.2.2.2 Recharge Estimate for DGI and LGI Periods

Groundwater abstraction can both amplify (Figure 4.4a-b) and suppress (Figure 4.4c) seasonal fluctuations in groundwater levels. For the former, pumping increases greater available storage in the aquifer over time (Figure 4.5). Net recharge increases due to this rise in available storage and the capture of potential recharge that was previously rejected due to limited available storage. For the DGI period, actual (net) recharge estimated via the equation (4.2) includes both natural and abstraction-induced recharge ($R_{actual} = R_{natural} + R_{induced}$). Where groundwater abstraction is perennial (e.g., public water supplies in Dhaka city) and the capture of potential recharge is inhibited by low-permeability of surficial deposits (e.g., Madhupur and Barind Tracts), seasonality in groundwater fluctuation is suppressed (Figure 4.4c) by the long-term trend associated with intensive abstraction. The annual groundwater fluctuation no longer effectively represents the total recharge fluxes and estimation of recharge requires the additional inclusion of abstracted groundwater. Net groundwater recharge in this case is estimated with equation (4.3) where Q^p is annual groundwater abstraction.

$$R = Q^p + \Delta S^{gw} \quad (4.3)$$

The suppression of seasonality in the groundwater-level time series is observed at four locations (Figure 4.6) that include Dhaka city and a part of the Barind Tract. These locations were distinguished from rest of the monitoring sites based on the following criteria: (i) seasonality in groundwater hydrograph represents <30% of the total variance in the time-series (see Chapter 2), and (ii) groundwater abstraction is intensive. Recent studies (Hoque et al. 2007) report that increased abstraction for urban and irrigation water supplies in Dhaka city and Barind Tract region draws groundwater from storage. Q^p was estimated in Dhaka city using abstraction data recorded at a total of 421 boreholes

managed by Dhaka Water Supply and Sewerage Authority (DWASA) (Hoque et al. 2007; Akther et al. 2009). In addition to DWASA wells, there are approximately 1000 private boreholes where no systematic monitoring exists. Q^p in Barind Tract was estimated for the period of 2002 to 2007 using irrigated area (BADC 2008) and water requirements for rice and non-rice plants (MPO 1987; Ravenscroft 2003).

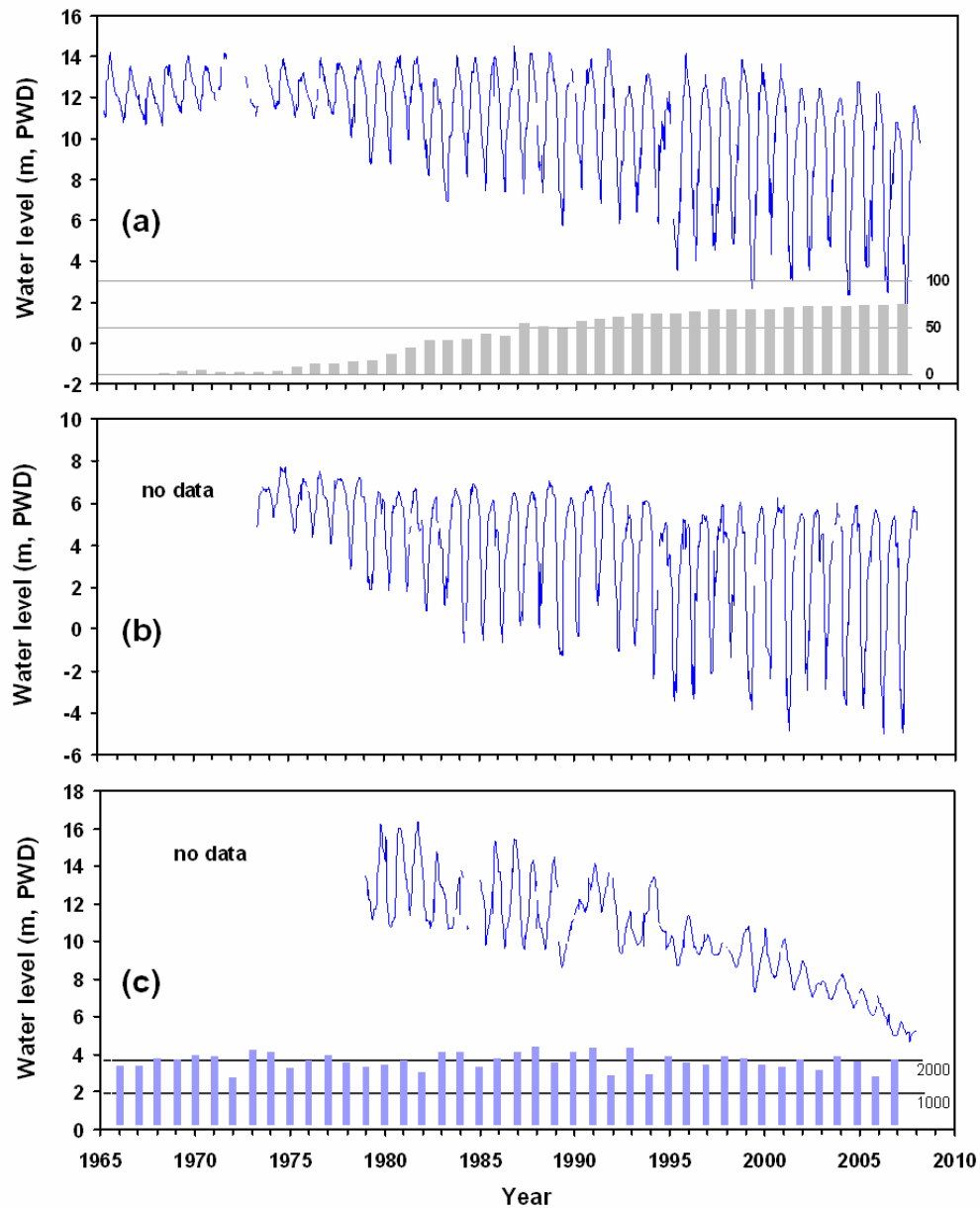


Figure 4.4 Borehole hydrographs showing long-term changes in groundwater levels in areas of intensive groundwater-fed irrigation under different geological conditions: (a) shows the hydrograph of a dug well (RJ023_A) located in the alluvial silt and clay (“asc”) geological unit where the upper silt and clay (USC) unit is thin (<10 m); (b) shows groundwater levels in a piezometer (CM004_A) of shallow depth (20 mbgl) where surface geology is permeable alluvial silt (“asl”) where thickness of the USC unit ranges from 10 to 15 m; and (c) shows rapidly declining trend and reduced seasonality in groundwater levels in RJ086_AB. Surface geology at this location is the Barind residuum (“rb”) of low vertical permeability and thickness of the USC unit is approximately 18 m. Percentage of areas in Bangladesh irrigated with groundwater is shown in (a); mean annual rainfall (mm) from 1965 to 2007 is shown in (c).

Net groundwater recharge at each of the monitoring locations was estimated using a programming routine in R language (R Development Core Team 2009) and interpolated at the national-scale using the geostatistical kriging technique with a modelled semivariogram available on ArcGIS (v.9.2) to generate the contoured map.

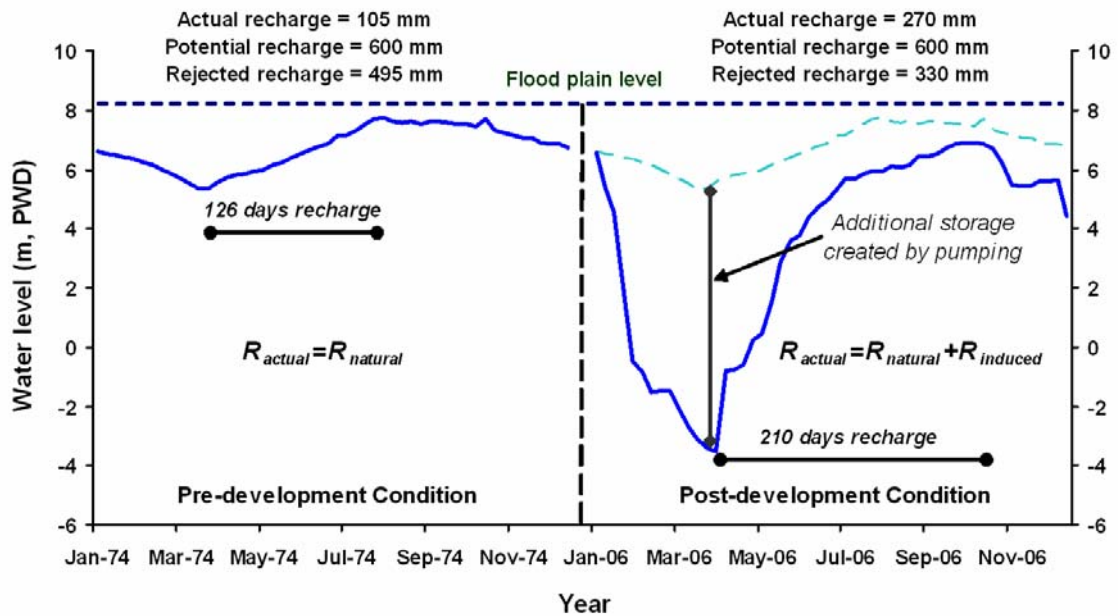


Figure 4.5 Hydrograph shows increase in groundwater recharge due to rise in available storage created by long-term abstraction for groundwater-fed irrigation. The monitoring well (CM004_A) is located in Burichang Thana of Comilla district in eastern Bangladesh where 82% cultivable lands are under groundwater-fed irrigation schemes. Recently, increase in available storage captures potential recharge that was previously rejected due to “aquifer full” condition. The aquifer in this location takes about 7 months to fully recharge following a water-table drop to its deepest level following the dry-season irrigation.

4.2.3 Specific Yield of Shallow Aquifers

Specific yield (S_y) is a measure of the release of groundwater from storage in an unconfined aquifer as the water-table drops during an event of abstraction or natural discharge (WARPO 2000). Specific yield values at sites of groundwater-level monitoring were derived from pumping tests conducted at 279 locations by the Ground Water Circle of Bangladesh Water Development Board between 1972 and 1992 as part of the national groundwater survey and investigations (UNDP 1982; BWDB 1989, 1994). The majority of these pumping tests were performed between 1976 and 1985 in a total of 188 monitoring locations. Hydraulic testing occurred during a period when groundwater-fed irrigation was not fully developed in most part of the country (BWDB 1989). These tests derived different hydraulic parameters of shallow aquifers including transmissivity (T), hydraulic conductivity (K), and specific yield (S_y) or storativity in alluvial aquifers.

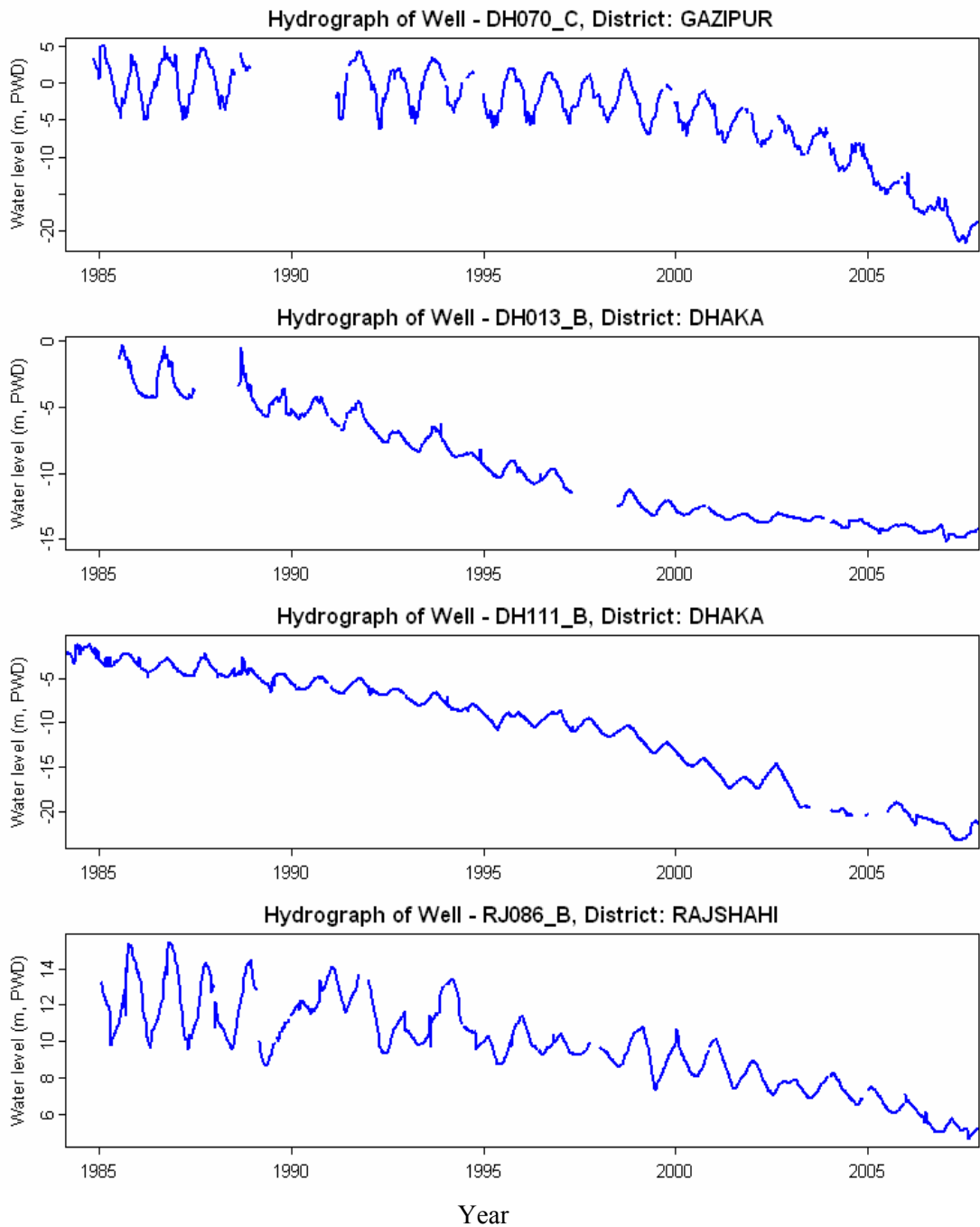


Figure 4.6 Hydrograph of groundwater-level monitoring wells where seasonality (annual fluctuation) has recently been suppressed (reduced) with declining trends. These wells are located in areas of intensive groundwater abstraction for urban and industrial (Dhaka and Gazipur districts) and irrigation water supplies (Gazipur and Rajshahi districts). Long-term declining trends in groundwater levels resulted from recent rise in abstraction which essentially draws water from the aquifer storage.

Pumping tests were primarily conducted in Bangladesh Agricultural Development Corporation (BADC) irrigation wells and newly installed boreholes ranging in depth from 50 to 100 mbgl. Pumping tests reported that the alluvial aquifer system in most parts of Bangladesh is primarily composed of a number of stratified and unconfined aquifers with

greater transmissivity (mean $1270 \pm 770 \text{ m}^2/\text{day}$) and specific yield ranging from 0.01 to 0.20 (Figure 4.7) with a national average of 0.06 ± 0.04 (mean with one standard deviation of the data) (UNDP 1982; BWDB 1994).

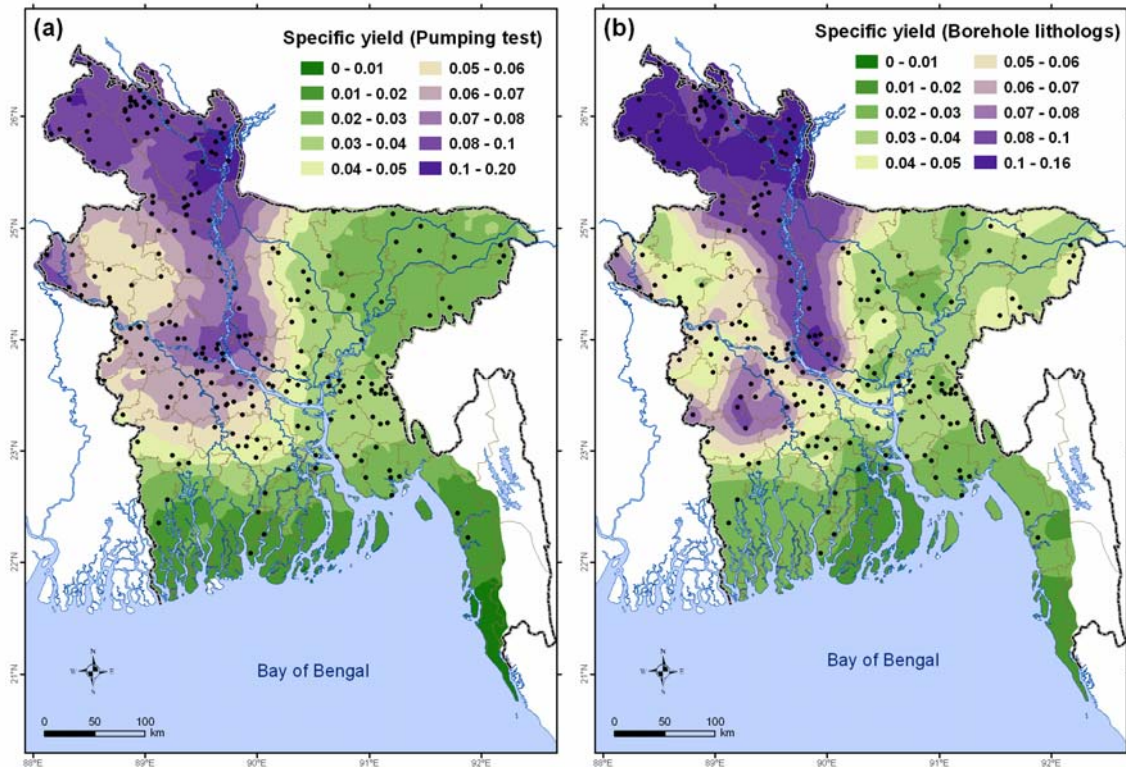


Figure 4.7 National-scale distribution of estimates of specific yield values for shallow aquifers in Bangladesh by (a) pumping tests in shallow aquifers (BWDB 1989, 1994) and (b) analysis of borehole lithologs (MPO 1987). Locations of BWDB groundwater-level monitoring wells (n=236) used in this study for recharge estimates are also shown as black dots on both maps. Note that colour shaded classes are discrete and values do not overlap between classes.

The geographic locations of pumping-test wells and BWDB groundwater-level monitoring wells are not the same. The spatial join function is used in the ESRI ArcGIS (v.9.2) environment with a set of selection criteria to extract specific yield values at each of the 236 well locations. Specific yield values from the national pumping-test database were chosen for each groundwater-level well following two conditions: (i) each pair of wells are located in the same geological unit; and (ii) maximum distance between the pumping-test well and groundwater-level well in each pair is $<50 \text{ km}$. Extracted data sets of pair of wells show that the mean distance between each pair of groundwater-level and pumping-test wells is $<10 \text{ km}$ and wells are located in the same geological unit. Derived S_y values at 236 locations show a mean value of 0.06 with a standard deviation of 0.03.

Pumping-test derived specific yield values represent well the stratigraphy of shallow aquifers from the upper 20 m down to a depth of 90 mbgl. Groundwater

fluctuations in most monitoring wells often occur within a depth of 10 mbgl. To include a depth-variable S_y value, specific to the zone of water-table fluctuations (0-10 mbgl) within the upper part of the aquifer, another set of S_y data was applied which was derived from borehole lithological records throughout Bangladesh (MPO 1987). At the national-scale S_y values derived from both pumping tests (Figure 4.7a) and borehole lithology (Figure 4.7b) show a similar pattern with the highest values concentrating in alluvial fans and Brahmaputra River valley and lowest in southern parts of the GBM Delta and most of Sylhet depression as well as Madhupur and Barind Tracts. When estimating groundwater recharge at each monitoring site, a programming routine is used in R which allows every well to choose depth-specific S_y values depending on the occurrence of groundwater fluctuation in the stratigraphic column. For example, some groundwater-level monitoring wells in level Barind region where thickness of the upper silt and clay (USC) unit is <10 m, show abrupt changes in mean water-table between two consecutive years. In these wells, the mean water-table occurred within the USC zone for most of the 1990s but recently dropped below the clay layer and water level occurs in the aquifer sand unit where S_y is almost an order magnitude higher than that of the overlying aquitard (WARPO 2000). This approach of using depth-variable S_y values is able to consider such abrupt but significant variation in aquifer storage capacity to provide reasonable estimates of net groundwater recharge.

4.3 Results

4.3.1 Groundwater Recharge Estimates

Estimates of mean annual groundwater recharge are shown in Figure 4.8 for three time periods: (i) pre-developed groundwater-fed irrigation (PGI) period (1975 to 1980), (ii) post-developed groundwater-fed irrigation (DGI) period (2002 to 2007), and (iii) long-term mean recharge (LGI) period (1985 to 2007). In this study, annual mean values are expressed in mm whereas temporal trends in mean annual recharge are expressed as mm/year to indicate the rate of changes over a period of time. The results show that actual (net) recharge is higher in northwestern (Dinajpur district) and western parts (Rajshahi district) of Bangladesh than in southern (Khulna district) and eastern parts except for Comilla district (Figure 4.8). The magnitude of groundwater recharge varies substantially between the PGI and DGI periods. Greater increases in the net recharge are observed in northwestern regions and along the Rivers Brahmaputra and Ganges; changes in recharge

are limited in the rest of the country. The net recharge also increased recently in Jessore (north of Khulna district), Mymensingh and Comilla regions. Recent mean annual recharge (2002 to 2007) is greater than the long-term (1985 to 2007) mean recharge in some parts of the northwestern Bangladesh and in the River Brahmaputra floodplains.

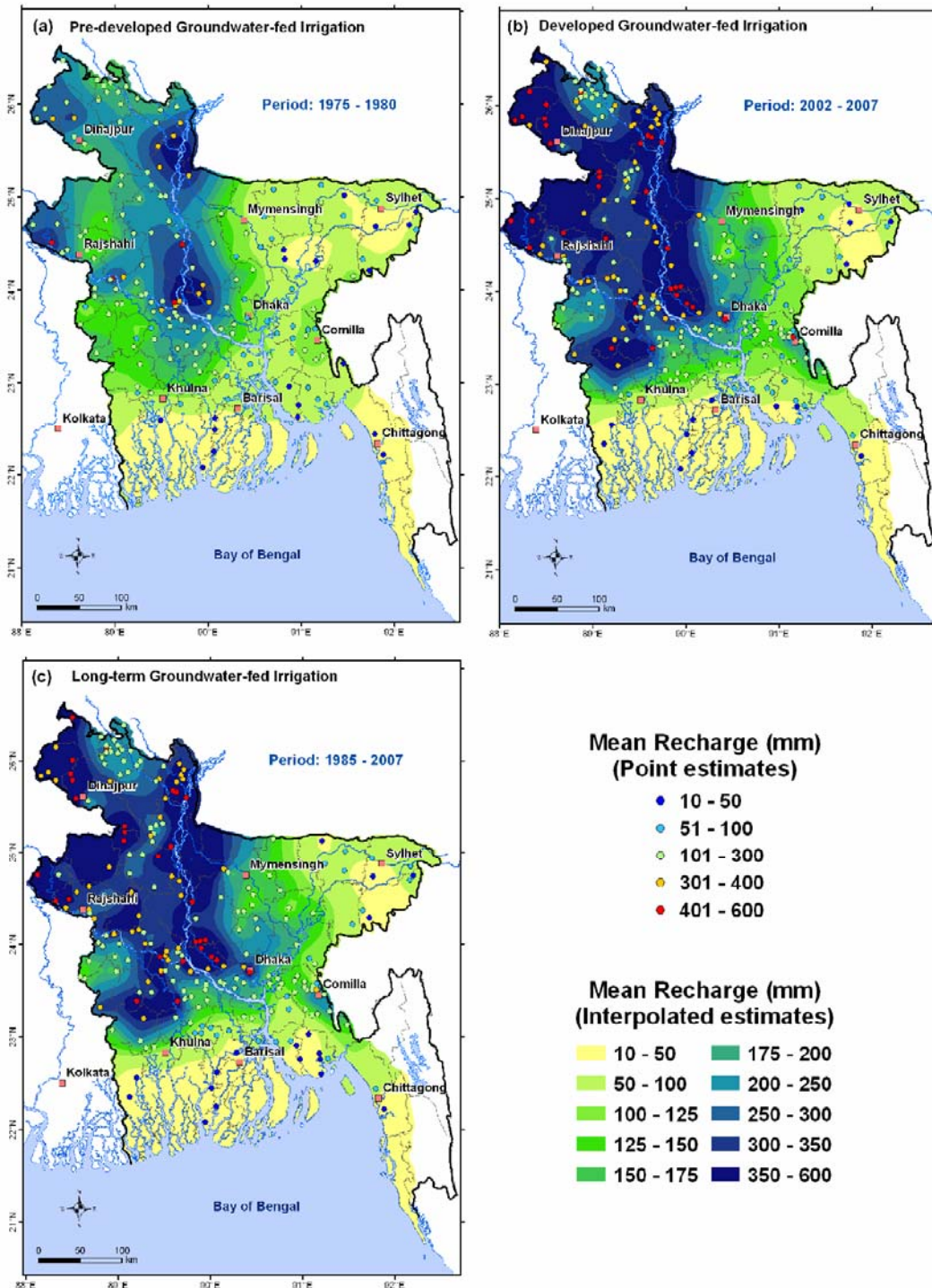


Figure 4.8 Map of estimated mean annual actual (net) groundwater recharge (in mm) to shallow aquifers in Bangladesh using the water-table fluctuation method for three time periods: (a) mean annual recharge for a 6-year period of 1975 to 1980 related to the pre-developed or underdeveloped groundwater-fed irrigation period in Bangladesh, (b) mean annual recharge for the period of 2002 to 2007 showing higher recharge in fully-developed irrigation era, (c) mean annual recharge over a period of 23 years (1985 to 2007) in Bangladesh.

4.3.2 Spatio-temporal Trends in Groundwater Recharge

Figure 4.9 shows the rate of changes (mm/year) in mean annual groundwater recharge for the period of 1985 to 2007. Mean annual recharge has increased substantially (5 to 15 mm/year) in northwestern and western districts (Bogra, Dinajpur, Gaibandha, Jessore, Jhenaidah, Rangpur, and Rajshahi), north-central districts (Dhaka, Jamalpur, Mymensingh, Tangail districts), and Comilla district in the east but has slightly decreased (-0.5 to -1 mm/year) or remained unchanged in the rest of Bangladesh (Figure 4.9a). Decreases in the net groundwater recharge are observed in southern GBM Delta and Sylhet depression. Spatial variations in changes to net annual recharge (absolute difference) between the PGI and DGI periods are shown in Figure 4.9b at the national-scale. Annual recharge in many places has increased by 100 to 350 mm between these two observation periods. A reduction in the net annual groundwater recharge (10 to 50 mm) is observed mainly in the tidal GBM Delta, and some parts of northeastern region in Bangladesh. Greatest increases in net groundwater recharge between the PGI and DGI periods coincide with areas of intensive groundwater-fed irrigation in Figure 4.9b.

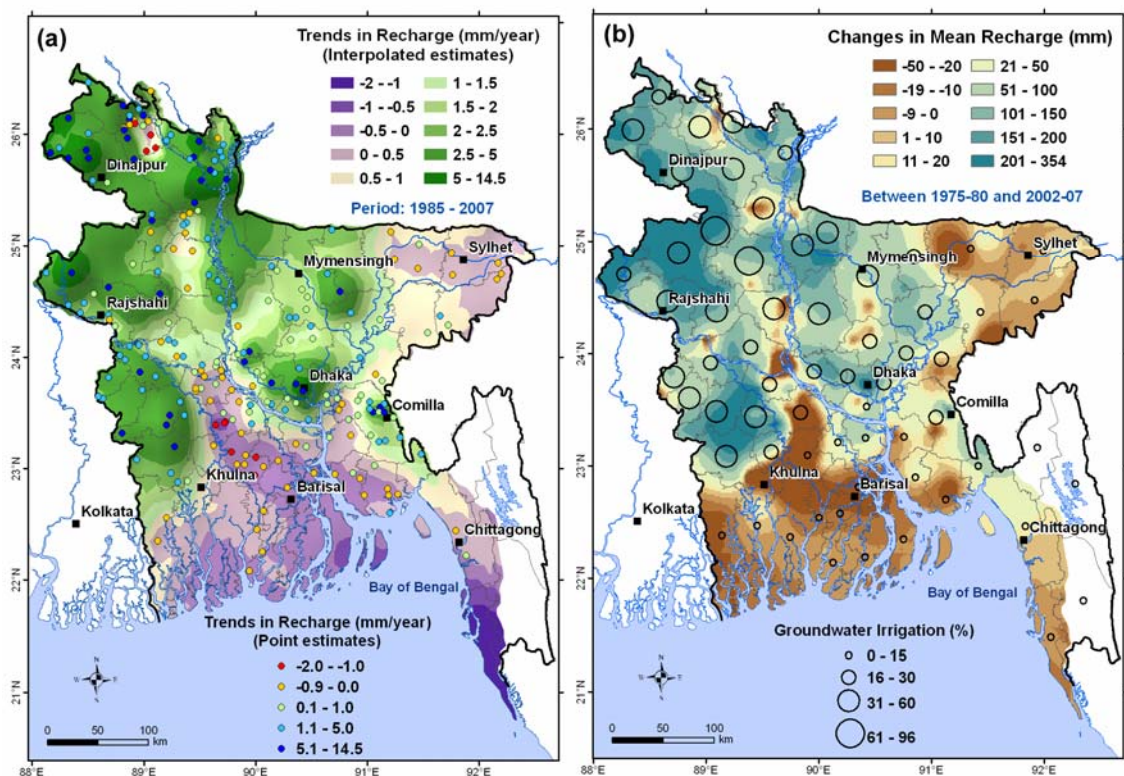


Figure 4.9 Spatio-temporal trends (mm/year) in the mean annual groundwater recharge across the shallow aquifer in Bangladesh in terms of (a) long-term trends in groundwater recharge between 1985 and 2007 and (b) absolute changes (mm) in net recharge between two periods, 1975 to 1980 and 2002 to 2007. Percentage of groundwater-fed irrigated areas (2005-2006) in each of the country's 64 districts is shown as graduated circles. Areas with higher groundwater-fed irrigation experience greater rise in actual recharge with time.

4.4 Discussion

4.4.1 Relationship between Actual (Net) and Potential Groundwater Recharge

Increases in groundwater recharge may be possible where actual (net) recharge is less than potential recharge estimated previously (section 4.1.2). These estimates of net annual recharge in northwestern and western parts of Bangladesh are much greater than in eastern parts where potential recharge is higher due to greater annual rainfall (>2000 mm). Net annual recharge in western parts of the country has substantially increased since the 1980s and now approximates potential recharge. Net recharge is high (300 to 600 mm) along the Rivers Brahmaputra and Ganges where potential recharge was previously estimated to be 500 to 700 mm (MPO 1991). Net recharge in northwestern parts of the GBM Delta ranges from 250 to 600 mm and similarly approximates potential recharge. In southeastern GBM Delta and Sylhet regions where estimated potential recharge is high (400-2000 mm) (UNDP 1982; MPO 1991), the net annual recharge is considerably lower (<150 mm). The substantial difference between actual and potential recharge in these areas suggests that a major fraction of the available recharge is lost through surface runoff and evapotranspiration. UNDP (1982) calculated potential recharge using a hydrological balance where runoff was estimated to be 20-40% of the annual precipitation. However, annual runoff in northeastern parts of Bangladesh (Sylhet) can be as high as ~3000 mm (75% of annual rainfall) (Fekete et al. 1999). Therefore, much of the monsoon rainfall is converted to surface runoff and routinely generates floods in low-lying areas (WARPO 2000). Net annual recharge in coastal areas is also much lower than potential recharge. Shallow water-tables in southeastern GBM Delta, floodplains of Rivers Meghna and Brahmaputra reach peak levels during the early (July-August) part of the monsoon season indicating that aquifers are fully recharged (Figure 4.10). In contrast, shallow aquifers in the north-central and western parts of the country experience longer period of recharge following a substantial drawdown during the dry-season groundwater-fed irrigation.

4.4.2 Impacts of Groundwater Abstraction on Recharge

Net groundwater recharge has increased in many areas of Bangladesh since the 1980s where intensive dry-season irrigation sustains Boro rice cultivation. Previous groundwater studies in Bangladesh (UNDP 1982; MPO 1991; WARPO 2000) suggest that greater groundwater-fed irrigation will increase net recharge in areas where surface geology and soil properties are permeable and thereby favour recharge. Numerical modelling of

regional groundwater flow suggests that actual (net) recharge increased from around 70 mm/year prior to widespread groundwater-fed irrigation (before 1970s) to around 250 mm/year more recently (Michael and Voss 2009a). Estimates of net recharge show that the mean recharge in Bangladesh has increased from 132 mm/year over a period from 1975 to 1980 to approximately 190 mm/year for the period 2002 to 2007.

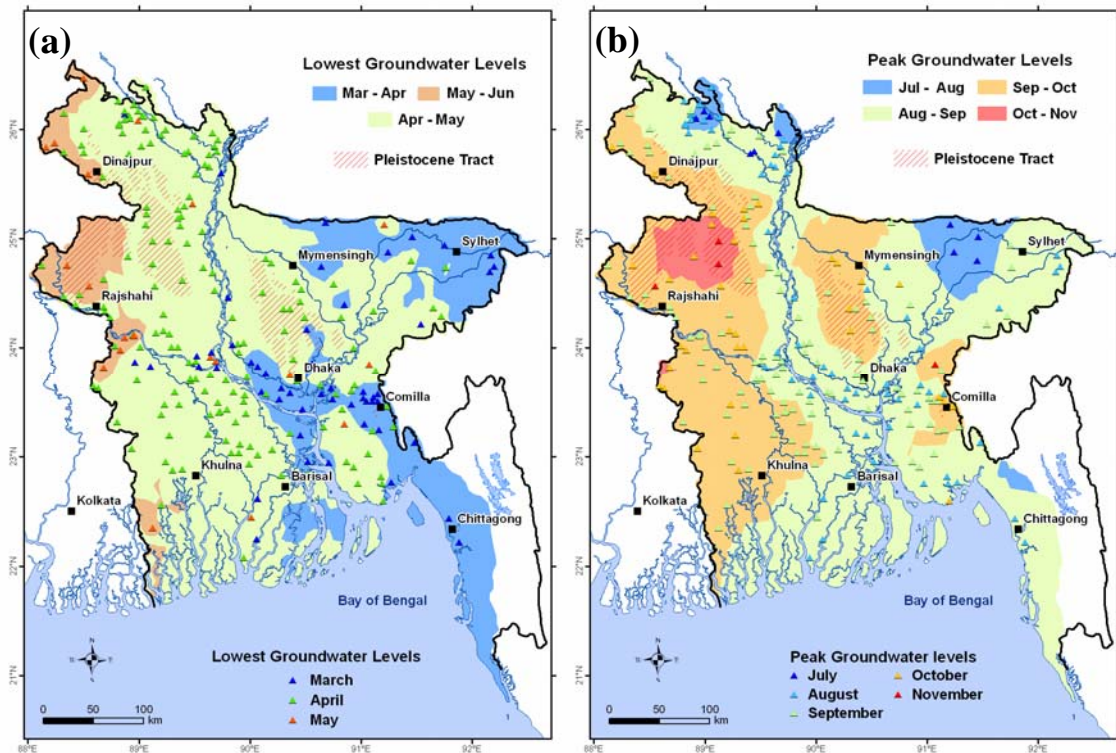


Figure 4.10 Timing of the occurrence of (a) lowest and (b) peak groundwater levels in shallow aquifers across Bangladesh. Occurrence of the lowest groundwater levels coincides with the end of groundwater-fed irrigation for Boro rice cultivation. Groundwater levels reach the annual minima early in areas with low groundwater-fed irrigation (northeastern and southeastern parts and lower Meghna floodplains) whereas it takes longer time for shallow water tables to reach their lowest levels in north-central and western parts of the country. The shallowest (i.e., wet-season peak) levels in shallow groundwater levels reach early in the monsoon season within Sylhet depression and some parts of the northern Bangladesh whereas it takes longer time in the north-central and western parts where groundwater-fed irrigation is highest in the country. The delay in reaching the peak levels indicates that aquifers are recharged over a longer period of time following a substantial drawdown during the dry-season irrigation. Note that colour shaded legend shows interpolated values whereas triangular colour legend shows point observations.

Net groundwater recharge can rise if greater dry-season abstraction increases the available aquifer storage capacity where a large difference (positive) difference exists between actual and potential recharge. In Bangladesh, the proportion of arable land irrigated by groundwater increased from <1% in 1965 to approximately 78% in 2007. Recharge has increased in areas where dry-season groundwater levels have declined 5 to 10 m since the pre-irrigation period but where wet-season water levels have remained

more or less unchanged over the period of observation. This steady rise in net recharge has occurred without any increasing trend in annual rainfall. Available groundwater storage has increased to accommodate greater recharge that previously had been rejected during the pre-irrigation period after reaching the “aquifer full” condition. For example, net recharge at the monitoring well RJ023_A in Mohanpur Thana (this being the third level of administrative unit in Bangladesh, of an average area of ~296 km²) of Rajshahi district increased from 125 mm in 1965 to ~430 mm in 2007 where potential recharge is estimated to be 450 mm (MPO 1991). Although net groundwater recharge increased substantially at this location a steady decline in wet-season groundwater levels suggests recent depletion in storage. The borehole hydrograph for monitoring well CM004_A (Comilla district) indicates that net recharge has recently increased to 270 mm from 105 mm during the PGI period; potential recharge is estimated to be ~600 mm (MPO 1987).

Increases in actual groundwater recharge are limited in areas of intensive abstraction where direct rain-fed recharge is inhibited by low-permeable surface geology and net recharge is approaching or has reached potential recharge. At monitoring well RJ086_AB in the higher Barind Tract (low-permeable geology), net groundwater recharge has only marginally increased (200 to 230 mm from PGI to DGI periods) yet groundwater-fed irrigation in this area (Tanore Thana) has increased from <50 mm to 375 mm over the period of 1985 to 2007.

Reductions in net groundwater recharge are observed in several areas of Bangladesh including Sylhet depression, lower Ganges floodplains, and tidal deltaic areas. Abstraction for groundwater-fed irrigation in these areas are lower (<30%) than the rest of Bangladesh. Groundwater-fed irrigation has slightly decreased (–0.5 to –1 mm/year between 1985 and 2007) in some areas in Sylhet and coastal regions. Recently, many agricultural lands (rice fields) in the coastal areas of the country have been transformed into brackish-water shrimp farms (Ahmed et al. 2010). Actual recharge to shallow aquifers in these areas has declined, in part, from a reduction in groundwater abstraction for dry-season irrigation.

4.4.3 Indirect Recharge: Interactions between Groundwater and Surface Water

Net groundwater recharge along the Rivers Brahmaputra (Jamuna) and Ganges (Padma) (350 to 600 mm) is much higher than that in the River Meghna and the GBM Delta (<150 mm). Sediments in floodplains of the River Brahmaputra are generally sandy and the

storage capacity of adjacent aquifers is higher than the deltaic plains. In addition to a high specific yield, the transmissivity of shallow aquifers in the Brahmaputra floodplains are greater (3,500 to 7,000 m²/day) than those in Ganges and Meghna floodplains (3,000 to 5,000 m²/day), and terrace and deltaic aquifers (300 to 3,000 m²/day) in Bangladesh (UNDP 1982; BGS and DPHE 2001). Interactions between groundwater levels and water levels in the River Brahmaputra are highly dynamic showing similar magnitudes (6 to 8 m) of annual fluctuation between dry and wet seasons. Analysis of groundwater level and river-stage hydrographs reveals that water levels in almost all river channels rise above groundwater levels in adjacent aquifers during the monsoon season (May to September); indirect recharge is restricted to lateral river-bank infiltration during the early monsoon time (April to June). Shallow aquifers adjacent to the River Brahmaputra mostly experience greater indirect groundwater recharge. Water levels in the River Brahmaputra generally rise earlier (March to April) than those of the Rivers Ganges and Meghna due to increased fluxes from snowmelt water in the Himalayas (WARPO 2000). Additionally, stable isotope (¹⁸O and ²H) data and geochemical analyses of river and groundwater compositions suggest close interactions between the River Brahmaputra and adjacent shallow aquifers whereas indirect recharge from the River Ganges is much lower (MPO 1987). Aquifers adjacent to the River Meghna receive the least indirect groundwater recharge as hydrographs shows that water levels both in the shallow aquifers and river-channel respond coincidentally to the monsoon pulse. Baseflow discharges from groundwater to upper reaches of the River Surma-Meghna during the dry season are negligible (MPO 1991; WARPO 2000). Additionally, in lower reaches of the River Meghna at Bhairab Bazar station (near the confluence with the River Old Brahmaputra) dry-season discharge is also extremely low similarly suggesting negligible baseflow from groundwater (WMO and GWP 2003).

4.4.4 Constraints of Groundwater Recharge: Further Development

The national-scale analysis of net groundwater recharge in Bangladesh shows areas where recharge to shallow aquifers has generally increased following widespread groundwater abstraction for irrigation and urban water supplies. Net recharge to aquifers in western and southwestern parts of the country is nearly equal to potential recharge. Potential recharge is, however, much greater than the current rates of net recharge in eastern and southern parts of the country where annual rainfall is high (>2500 mm/year). Further increases in groundwater abstraction in western and southwestern parts of Bangladesh

may further lower dry-season groundwater levels but not increase net recharge because current recharge rate has reached estimated potential recharge.

In Bangladesh, shallow aquifers can reach the “aquifer full” condition by monsoon recharge but greater abstraction in many places can reduce dry-season groundwater levels so that irrigation is no longer possible by low-cost pumping technologies (Figure 4.11a). For instance, dry-season groundwater levels in many areas have recently dropped below 15 mbgl which prevents abstraction of groundwater by hand pumps and peristaltic pumps. Figure 4.11b shows areas where (Comilla, Dhaka, Gazipur, Mymensingh, Nawabganj, and Rajshahi districts) dry-season groundwater abstraction is restricted to more expensive, high-capacity pumps (e.g., submersible, super Tara pumps).

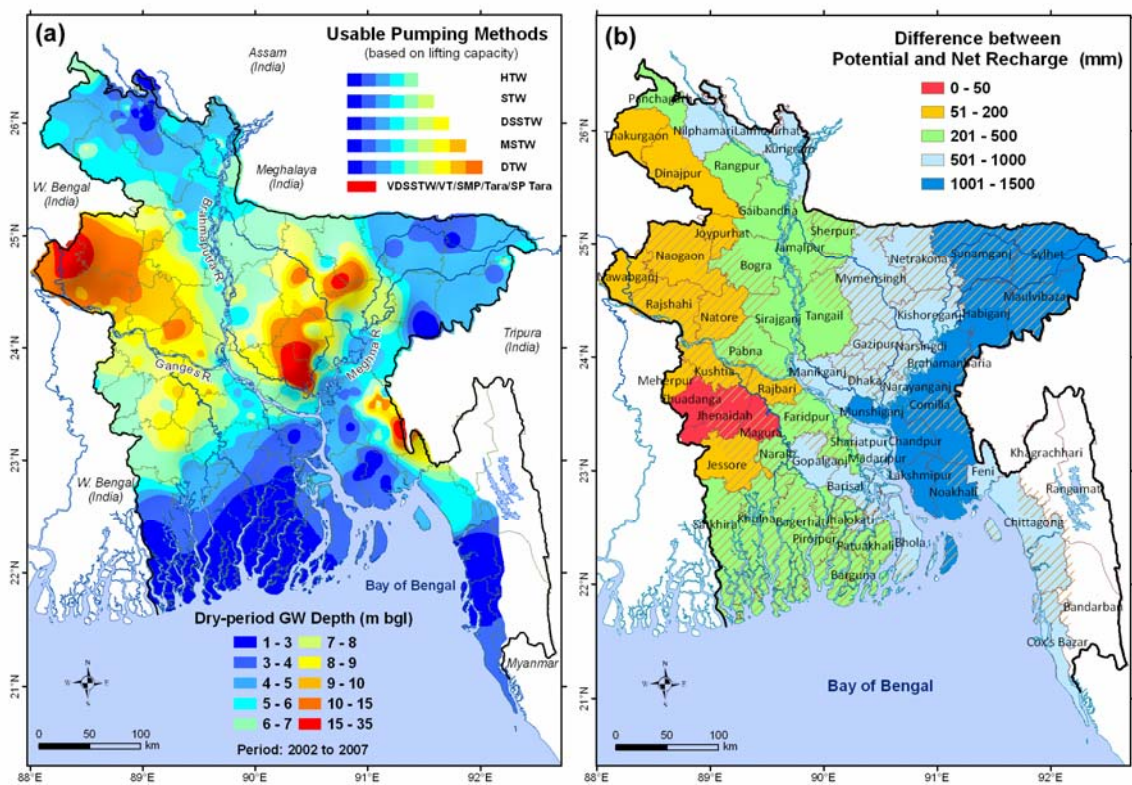


Figure 4.11 (a) Map shows the maximum depth (mbgl) to the recent (2002 to 2007) static water table in aquifers in Bangladesh. This map highlights the areas where currently available pumping technologies for drinking and irrigation water supplies are unusable during the dry season. HTW-hand tubewell, STW-shallow tubewell, DSSTW-deep set shallow tubewell, MSTW- mini-submersible shallow tubewell, DTW-deep tubewell, VDSSTW-very deep-set shallow tubewell, VT-vertical turbine pump, SMP-submersible pump, Tara-Tara pump, SP Tara-super Tara pump; (b) Map shows part of the potential recharge available for further groundwater development in 64 districts in Bangladesh. Further increase in net recharge due to increased abstraction in western parts of Bangladesh is constrained by the limited quantity of potential recharge and surface geology. Hatch lines show areas where the thickness of the upper silt and clay unit is >15 m.

4.4.5 Groundwater Abstraction and “Safe Yield” of Aquifer

The national-scale analysis of groundwater recharge provides a clear quantitative illustration of the fallacy of the concept of “safe yield”. Previous criticisms of this concept (Sophocleous 2000; Alley and Leake 2004; Zhou 2009) have been based solely on theoretical arguments. This study presents direct evidence of regional changes in net recharge in response to abstraction. The assertion that the sustainability of groundwater abstraction is based on long-term average recharge (Döll and Fiedler 2008; Döll 2009; Kundzewicz and Döll 2009), fails to recognise the critical influence of abstraction on recharge rates. This analysis also highlights the necessity of reconciling recharge estimates to local geology and soil permeability as these properties play a fundamental role in determining recharge. To sustain groundwater development, it is critical to distinguish areas (such as Bogra, Brahmanbaria, Chandpur, Comilla, Gaibandha, Kishoreganj, Manikganj, Munshiganj, Rangpur, Sirajganj and Tangail districts; Figure 4.11b) where further abstraction may induce greater recharge (i.e., soils and geology are favourable and potential recharge is much greater than current recharge rates) from areas (such as Chuadanga, Dhaka, Gazipur, Jaypurhat, Jessore, Jhenaidah, Kushtia, Magura, Naogaon, Natore and Rajshahi districts; Figure 4.11b) where it will not.

4.5 Conclusions

Groundwater recharge has increased substantially in north-central, northwestern, and parts of southwestern Bangladesh following the widespread adoption of groundwater-fed irrigation for dry-season Boro rice cultivation in the 1980s. Groundwater-fed irrigation lowers the water table in shallow aquifers during the dry season which induces greater recharge by increasing available groundwater storage during the subsequent monsoon. This study shows that the greatest increases in groundwater recharge have occurred where the density of groundwater-fed irrigation is highest. Anomalous reductions (–0.5 to –1 mm/year between 1985 and 2007) in groundwater recharge have taken place in areas of low groundwater abstraction for irrigation. The national-scale distribution of actual (net) groundwater recharge differs substantially from estimates of potential recharge reported by previous studies which show greater potential recharge in eastern Bangladesh where rainfall is highest. These national-scale dynamics of groundwater recharge in Bangladesh highlight three fundamental points regarding the relationship between groundwater recharge and abstraction: (1) rates of groundwater recharge can change substantially (5 to

15 mm/year; 1985 to 2007) in response to abstraction; (2) estimates of potential recharge can greatly exceed actual groundwater recharge; and (3) the magnitude of the difference between potential and actual recharge provides a measure of possible increases in groundwater recharge that may be realised through greater groundwater abstraction. The first observation illustrates well the fundamental flaw in definitions of “safe yield” based on estimates of groundwater recharge under static (non-pumping) conditions. The second shows how values of (potential) recharge derived from current macro-scale hydrological and land-surface models, unreconciled to the transmissivity and storage of the underlying soils and geology, can substantially overestimate net groundwater recharge fluxes. The third enables areas where further abstraction may induce greater groundwater recharge to be distinguished from areas where increases in net recharge are limited and any further rises in abstraction may deplete groundwater storage and lower the water table (i.e., actual recharge is nearly equal to potential recharge). Falling groundwater tables in some areas in Bangladesh (Rajshahi, Jessore and Dhaka districts) have already restricted access to groundwater via shallow irrigation and hand-operated tubewells for food production and drinking water supplies. Water-use policies should, therefore, recognise the dynamic nature of groundwater recharge and consider the spatio-temporal changes in water levels and abstraction to promote the sustainable use of groundwater resources in Bangladesh.

Part C:

Groundwater Arsenic Mobilisation

Chapter 5

Groundwater Dynamics and Arsenic Mobilisation

This chapter develops statistical models based on information generated/compiled in the previous chapters of this thesis as well as from previous research to describe the national-scale variability in As concentrations in shallow groundwater of Bangladesh.

5.1 Introduction

Nearly 100 million people in lowland basins and mega deltas in South and Southeast Asia are currently exposed to elevated groundwater arsenic (As) concentrations in drinking water supplies (Ravenscroft et al. 2009). The public health impact of As contamination in groundwater of the Ganges-Brahmaputra-Meghna (GBM) Delta in the Bengal Basin of Bangladesh and West Bengal (India) has been described as the largest mass poisoning in history (Smith et al., 2000). Between one quarter and one half of Bangladesh's population of 145 million are estimated to be chronically exposed to elevated concentrations of As ($>10 \mu\text{g/L}$; WHO drinking water As standard is $10 \mu\text{g/L}$ whereas Bangladesh standard is $50 \mu\text{g/L}$) in drinking water (BGS and DPHE 2001; Gaus et al. 2003; Yu et al. 2003). A recent study (Argos et al. 2010) in an As-affected area of central Bangladesh attributes more than a fifth (21.4%) of all deaths to exposure to elevated As concentrations ($>10 \mu\text{g/L}$) in drinking water supplied by hand-operated tubewells. Despite public health concerns associated with regular consumption of high concentrations of As in drinking water, current understanding of the hydrogeological conditions under which As is mobilised in groundwater are unclear.

Over the last few decades, studies in the GBM Delta (Bhattacharya et al. 1997; Nickson et al. 1998; BGS and DPHE 2001; Islam et al. 2004; McArthur et al. 2004; Swartz et al. 2004; Saunders et al. 2005; Zheng et al. 2005; Harvey et al. 2006; Shamsudduha et al. 2008; Burgess et al. 2010; McArthur et al. 2011) and other Asian Mega-Deltas (Berg et al. 2007; Benner et al. 2008; Berg et al. 2008; Polizzotto et al. 2008; Winkel et al. 2008a; Winkel et al. 2008b; Fendorf et al. 2010) have reached a

general consensus that As derives naturally from source rocks in the Himalayas and is primarily released to groundwater by microbially-mediated reductive dissolution of iron-oxhydroxide minerals in the presence of organic matter. Alternative hypotheses attribute the widespread occurrence of As in groundwater to chemical weathering that involves the dissolution of specific minerals including biotite (Seddiq et al. 2008), magnetite (Horneman et al. 2004; Shamsudduha 2007a; Neumann et al. 2010), and sulphide minerals (Swartz et al. 2004; Polizzotto et al. 2006).

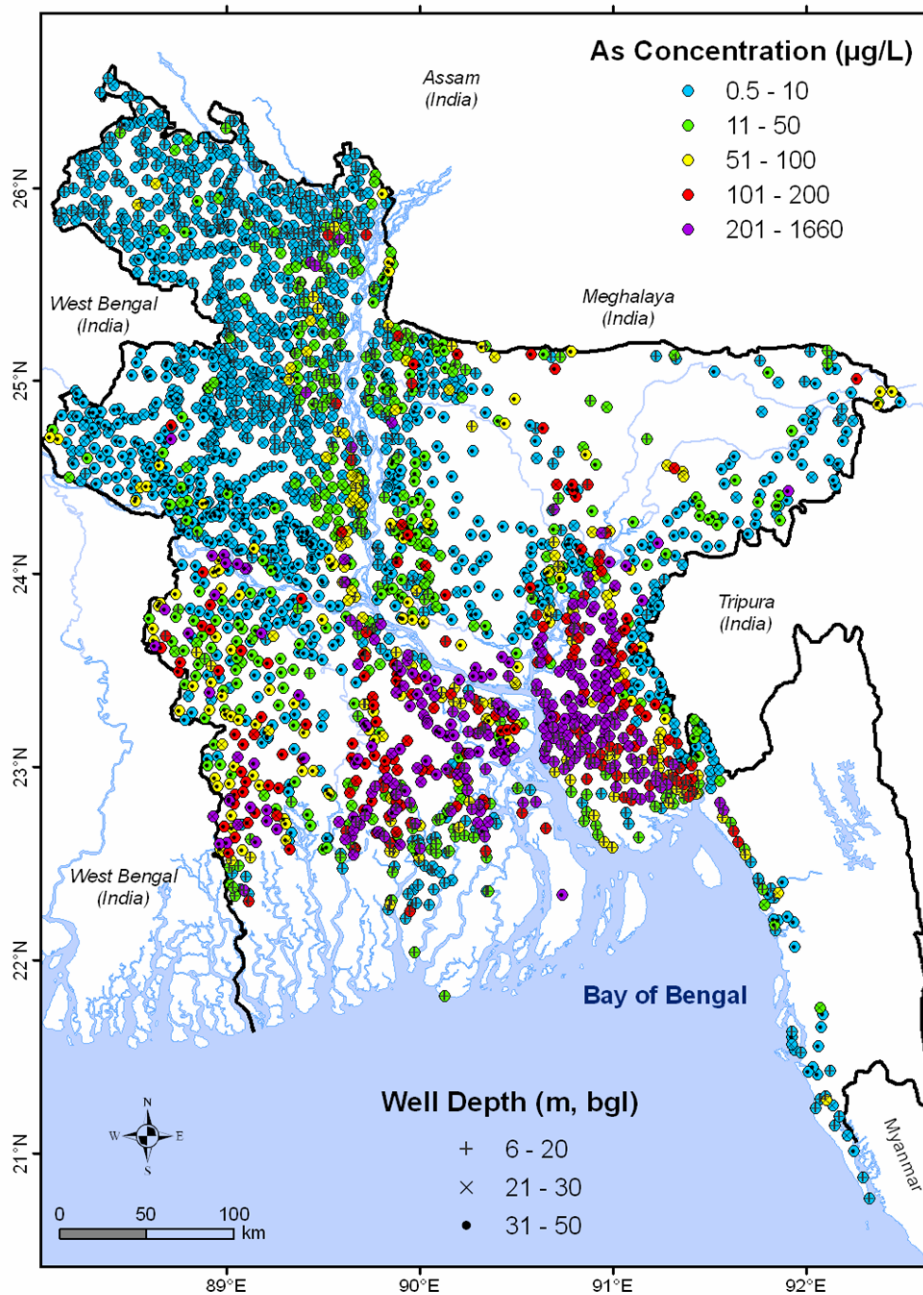


Figure 5.1 National-scale variations in the distribution of As concentrations in shallow (≤ 50 m bgl) groundwater throughout Bangladesh. Map shows both As concentrations and depth of sampled wells (n=2140). Data collected as part of the National Hydrochemical Survey in Bangladesh (BGS and DPHE, 2001).

Despite agreement on the geogenic origin of As, hypotheses concerning the hydrogeological conditions under which As is mobilised and transported, vary considerably. The highly variable distribution of As at regional (Figure 5.1) (BGS and DPHE 2001; Yu et al. 2003) and local scales (van Geen et al. 2003b) has been attributed to differences in both groundwater flow paths (Harvey et al. 2002; Harvey et al. 2006; Klump et al. 2006; Stute et al. 2007; Polizzotto et al. 2008) and variations in groundwater recharge to shallow aquifers (Stute et al. 2007; Aziz et al. 2008; van Geen et al. 2008; Neumann et al. 2010). The central disagreement that follows from the adoption of either of these hypotheses is whether greater recharge (1) increases As concentrations in groundwater by transporting reactive organic carbon (OC) from near-surface sources to sites of As release from the aquifer substrate or (2) decreases As concentrations in groundwater by flushing As from the aquifer.

Groundwater flow and recharge pathways to the shallow aquifer in the Bengal Basin has, in many places, been substantially altered by widespread, intensive abstraction for dry-season irrigation (MPO 1987, 1991; Harvey et al. 2006; Michael and Voss 2009a). Groundwater recharge to shallow aquifers has substantially increased with time due to intensive abstraction for irrigation (discussed in Chapter 4). Several localized studies of As contamination of groundwater (Harvey et al. 2006; Klump et al. 2006; Neumann et al. 2010) show that increased rates of groundwater recharge via return flow from irrigation and ponds modify local groundwater flow patterns and enhance As concentrations. In contrast, several studies (McArthur et al. 2004; Stute et al. 2007; van Geen et al. 2008) suggest that low As concentrations in groundwater stem from high rates of groundwater recharge that flush As from the aquifer. Such observations are further supported by other studies (Aziz et al. 2008; Weinman et al. 2008) that reveal rapid groundwater recharge in shallow aquifers covered with sandy soils of high hydraulic conductivity that locally inhibits the release of As either by dilution (through flushing) or by sustaining an aerobic conditions in the aquifer. Conclusions drawn from these localised studies primarily derive from correlation analysis or simple linear regressions where the effects of individual factors (e.g., recharge, groundwater abstraction) were examined in isolation. However, multiple hydrogeological factors are expected to operate simultaneously to influence the distribution of As concentrations in groundwater but their combined effects were not investigated in these studies. The present study applies, for the first time, generalised regression techniques to investigate the associations of multiple hydrogeological factors,

surface geology and irrigation abstraction on the variation of As concentrations in the shallow groundwater in the Bengal Basin.

5.2 Modelling Approach and Datasets

To investigate simultaneously the response of groundwater As mobilisation to the effects of multiple factors is a challenging problem requiring the use of advanced statistical methods. It is conventional in statistics to refer to the primary variable of interest (As concentration here) as the ‘response variable’, and to the potential influencing factors as ‘covariates’. In general, the choice of method for this type of problem will depend on specific features of the data involved in the analysis. In the current study, the main features that need to be taken into account are (i) the skewed distribution of As concentrations, (ii) the presence of As concentrations below instrumental detection limits, and (iii) the potential for correlation between observations from neighbouring spatial locations. The process therefore starts by describing the response variable and covariate datasets used in this study and outlining the issues that need to be addressed in any convincing statistical analysis. This provides a context for the discussion of statistical methodologies applied in this study in the following sections.

5.2.1 Groundwater Arsenic Dataset

This study uses 2410 single observations of As concentrations from shallow (depth ≤ 50 m below ground level, bgl) groundwater (Figure 5.1). The observations were sampled under the National Hydrochemical Survey (NHS) in Bangladesh jointly by the British Geological Survey (BGS) and the Department of Public Health Engineering, Bangladesh (DPHE) at different times during the period of 1998 to 1999 (BGS and DPHE 2001). Groundwater samples were analysed for As concentrations by two different techniques: hydride generation-atomic fluorescence spectrometry (HG-AFS) and hydride generation-ICP AES (Inductively-Coupled Plasma Atomic Emission Spectroscopy). The minimum detection limit of As concentrations for the HG-AFS method was 0.5 $\mu\text{g/L}$ and for HG-ICP-AES method was 6.0 $\mu\text{g/L}$ (BGS and DPHE 2001).

The distribution of observed As concentrations in Bangladesh is highly (positively) skewed, with values ranging from <0.5 to 1660 $\mu\text{g/L}$. The spatial distribution of groundwater As concentrations is also highly variable throughout the country (Gaus et al. 2003; van Geen et al. 2003b; Yu et al. 2003; Shamsudduha 2007b) (Figure 5.1). High As

concentrations ($>50 \mu\text{g/L}$) are observed in most parts of southern Bangladesh at depths $<100 \text{ mbgl}$ (BGS and DPHE 2001). Groundwater tapped from northwestern alluvial fans, Madhupur and Barind Tracts, and eastern hilly terrains generally features low As concentrations ($<10 \mu\text{g/L}$).

Vertically, groundwater As concentrations reach the peak levels at a depth between 20 and 40 mbgl in most As-affected areas in Bangladesh but concentration decreases with increasing depth thereafter (BGS and DPHE 2001; Ravenscroft et al. 2005; Harvey et al. 2006). However, at very shallow depths ($<20 \text{ mbgl}$), groundwater As concentrations increase (linearly) with increasing depths (Stute et al. 2007; Aziz et al. 2008). Linear regression analysis of the NHS As data (BGS and DPHE 2001) with sampling depth shows that groundwater As concentrations increase downward at a rate of $6.3 \mu\text{g/L/m}$ (p -value 0.01) up to a depth of 25-35 mbgl. From the peak levels, As concentrations then decrease along the profile at a rate of $1.5 \mu\text{g/L/m}$ (p -value <0.001) with increasing depths in the aquifer.

Of the 2410 As measurements, 743 (31%) are reported as below the detection limit of the measuring instruments. In the statistical literature, such values are described as being “censored”. The presence of censored data values requires care in any statistical analysis. In environmental applications, non-detects in skewed data are most commonly handled by replacing each value with one-half of the detection limit and then using a logarithmic transformation to normalise the distribution (Helsel 2005). However, this approach can lead to substantial bias in estimates of descriptive statistics (Helsel 2006; Antweiler and Taylor 2008; Helsel 2010). For example, Helsel (2010) considers a data set (his Figure 1 and 2) in which this approach leads to serious underestimation of the correlation between two variables: in his example, when 58% of the data are censored and replaced with half detection limits the sample correlation coefficient is estimated as 0.55, whereas its true value prior to censoring is known to be 0.81. Therefore, to calculate the basic statistics of As data which have censored observations the Regression on Order Statistics (ROS) and the Kaplan-Meier (K-M) methods are applied (Helsel 2005; Lee and Helsel 2007). This present study is particularly interested in assessing the dependence of As concentrations upon potential covariates. It is therefore important to avoid using approaches that may lead to biased estimates of this dependence, and to apply a robust statistical technique where censored As data are handled within a framework of the probability distribution.

A further feature of this As dataset, that must be accounted for properly in any statistical analysis, is the potential for dependence between observations from the neighbouring sites. The need to account for spatial dependence (i.e. inter-site correlation) in statistical modelling has previously been recognised (Chandler 2005). The presence of such dependence in the response variable invalidates the usual standard errors and confidence intervals for model parameters, which must therefore be corrected before interpreting results. The present study demonstrates a method for resolving the issue of inter-site dependence in statistical modelling using the NHS As dataset of Bangladesh.

5.2.2 Covariate Datasets: Rationale and Description

Several covariates were considered in the development of a statistical model for As variations in shallow groundwaters in Bangladesh. These are surficial geology, groundwater irrigation, and hydrogeological variables representing groundwater dynamics, aquifer properties, groundwater recharge processes and spatio-temporal changes in recharge. This section provides the rationale for considering these variables, and gives details of the datasets and their processing. Table 5.1 summarises the factors that have been discussed in the literature to explain As mobilisation in the Bengal Basin.

Previous studies (DPHE 1999; BGS and DPHE 2001; Fazal et al. 2001; Ravenscroft et al. 2005) examined statistical relationships between groundwater As and many of these geological and hydrogeological factors in isolation. Ravenscroft (2001) correlated As concentrations with mean groundwater levels and found that low As concentrations (<10 µg/L) are associated with deepest groundwater levels. High As concentrations (>50 µg/L) in tubewells are, however, associated with shallow (<3 mbgl) water table in aquifers (Shamsudduha et al. 2009). Several other studies (Ravenscroft, 2001; McArthur et al., 2004; Harvey et al., 2006; Klump et al., 2006; Stute et al., 2007; Polizzotto et al., 2008; Neumann et al., 2010) relate the distribution of As in groundwater with recharge to aquifers and long-term changes in recharge rates. However, it is currently a matter of some controversy as to whether rises in groundwater recharge are associated with decreased or increased As concentrations over time.

The controls of geology and geomorphology upon the regional-scale distribution of groundwater As have been suggested in several studies (DPHE, 1999; BGS and DPHE, 2001; Ahmed et al., 2004; Ravenscroft et al., 2005; Stute et al., 2007; Aziz et al., 2008; van Geen et al., 2008). Ravenscroft (2001) demonstrated associations between

groundwater As, surface geology, and geomorphology in Bangladesh through descriptive statistics and linear regression analysis. Among the surface geological units the Chandina alluvium (ac), estuarine deposits (de), deltaic silt (dsl), and alluvial silt and clay (asc) are the most As-affected, groundwater-bearing units (Figures 5.2 and 5.3). The Meghna River floodplains feature high (>50 µg/L) As concentrations in tubewells whereas the Teesta and Brahmaputra River floodplains have the lowest As concentrations in shallow groundwaters (BGS and DPHE 2001; Ravenscroft 2001).

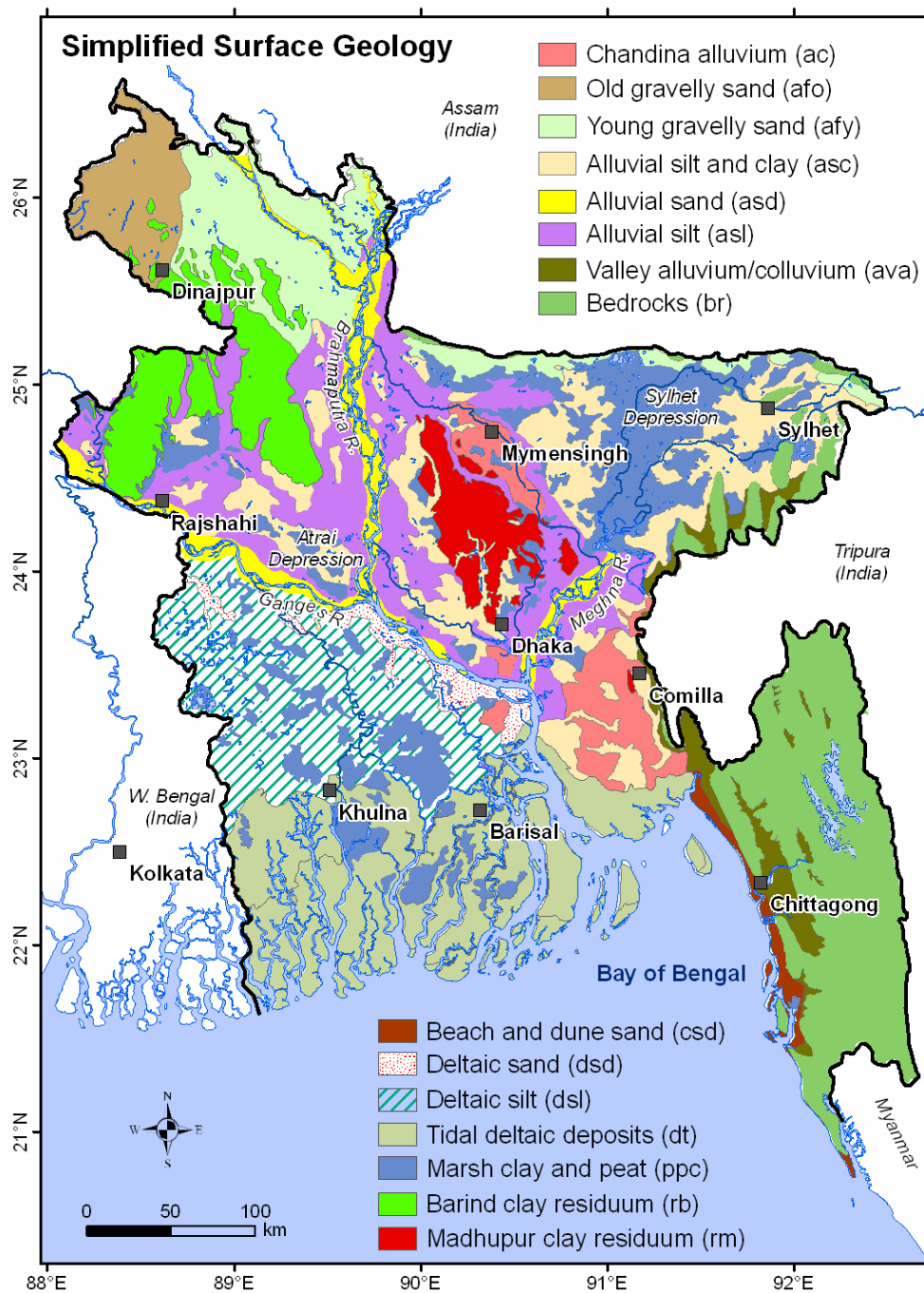


Figure 5.2 Simplified surface geological units in Bangladesh (modified from Alam et al., 1990). Major physiographic units and rivers are also shown.

Table 5-1 Covariate datasets used in this study to explain As variations in groundwater, along with summary of conclusions of previous studies regarding their effects on As concentration. Units of measurement are given in Table 5.3.

Group	Predictor variable	Association with arsenic	Reference
Geology and hydrogeology	Surface geological cover	Mobilisation of groundwater As is largely geologically controlled	DPHE (1999), Ravenscroft (2001), BGS and DPHE (2001), Ahmed et al. (2004)
	Surficial (upper) silt and clay cover (USC)	Properties of near-surface deposits are related to As mobilisation	DPHE (1999), Ravenscroft (2001), BGS and DPHE (2001)
	Hydraulic conductivity of aquifer	Hydraulic conductivity is associated with aquifer flushing and thus As in groundwater	Aziz et al. (2008)
	Specific yield of aquifer	Groundwater recharge is associated with specific yield and thereby control As mobilisation	Harvey et al. (2006), Klump et al. (2006); Stute et al. (2007)
	Darcy flux (groundwater flow velocity)	Groundwater flow moves As from the site of release (distribution of As controlled by preferential flow paths)	BGS and DPHE (2001), Ravenscroft et al. (2005)
	Depth to sampling well	Distribution of As is strongly related to depth (low As at greater depths)	BGS and DPHE (2001)
Groundwater dynamics and recharge process	Dry-season groundwater table	Low As concentrations in areas where dry-season groundwater table is deep	Ravenscroft et al. (2005)
	Wet-season groundwater table	High As concentrations in areas where wet-season groundwater table is shallow	Shamsudduha et al. (2009)
	Trend in mean annual groundwater levels	Low As in areas of declining groundwater levels	Shamsudduha et al. (2009)
	Mean groundwater fluctuation	Low As concentrations in areas of limited groundwater fluctuations (annual range in groundwater levels)	DPHE (1999)
	Net annual groundwater recharge	Role of recharge in As mobilisation is controversial (recharge can either decrease or increase As in groundwater)	DPHE (1999), Harvey et al. (2006), Stute et al. (2007); van Geen et al. (2008)
	Trend in annual recharge	Role of long-term recharge trends in As mobilisation is controversial (recharge can either decrease or increase As in groundwater)	Klump et al. (2006)
Geography and seasonality	Geographic position (latitude and longitude)	There are regional trends in groundwater As variations	Shamsudduha (2007b)
	Surface elevation	Low As concentrations in elevated areas; high As in low-lying areas	Shamsudduha et al. (2009)
	Seasonality (water sampling season)	No discernible seasonal pattern of As has been detected at the national scale	This study
Groundwater abstraction	Trends in groundwater-fed irrigation	Role of irrigation to As mobilisation is also controversial	Ravenscroft et al. (2005), Harvey et al. (2006), Klump et al. (2006)

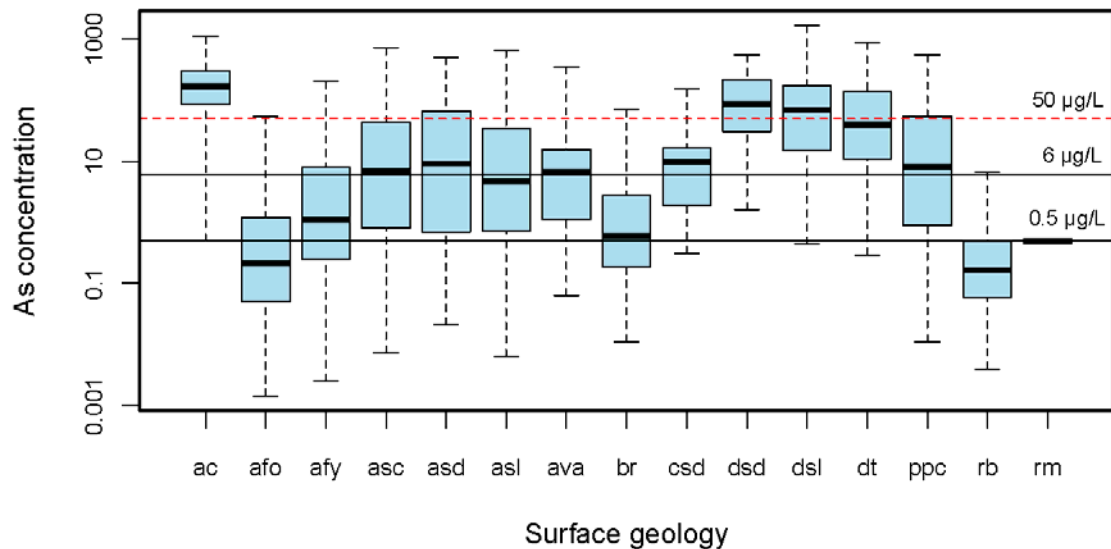


Figure 5.3 Boxplots showing As variations within various surface geological units in Bangladesh. The vertical axis is in log scale. The horizontal lines on the plot represent different threshold As concentrations; the black lines represent the minimum detection limits (6 and 0.5 µg/L) of As measurements by two different methods (see BGS and DPHE, 2001 for details), and the broken red line represents the Bangladesh standard limit (50 µg/L) of As in drinking water. Values below the detection limits are approximated using the regression on order statistics (ROS) technique designed for multiply censored analytical chemistry data (see Helsel, 2005). The NADA package under the “R” environment (Lee and Helsel, 2007) was used for the analysis and plot.

The influence of soil permeability and properties of near-surface deposits on groundwater As distribution have also been examined previously (van Geen et al. 2006; Stute et al. 2007; Aziz et al. 2008; van Geen et al. 2008; Hoque et al. 2009). These studies reveal that low-As concentrations in groundwater are associated with areas of highly permeable soils and near-surface geology. It is hypothesised that shallow aquifers that underlie sandy soils receive rapid recharge from rainwater (and surface water bodies) that flushes As in groundwater by dilution. Recharge also supplies oxidants (dissolved oxygen and nitrate) that inhibit the reductive dissolution of iron oxy-hydroxides and thus As mobilisation in groundwater (Aziz et al. 2008). In contrast, low-permeability surface geology is thought to inhibit vertical recharge to the underlying aquifer where As is mobilized in groundwater under sustained reducing (iron-oxyhydroxide) conditions. This hypothesis is supported by Stute et al. (2007) who showed that As concentration in very shallow (<20 mbgl) aquifers is linearly correlated with groundwater residence time.

Several studies (Aggarwal et al. 2000; Harvey et al. 2002; Klump et al. 2006; Michael and Voss 2009a) have asserted that shallow groundwater flow regime has been substantially modified by recent, intensive dry-season irrigation abstraction in

Bangladesh. Some studies link the distribution of As concentrations with increased abstraction for irrigation both at national (Ravenscroft et al. 2005) and local (Harvey et al. 2006; Klump et al. 2006) scales. However, how and to what extent recent irrigation abstraction has influenced As distribution in shallow groundwaters is unexplained.

5.2.2.1 Seasonal Groundwater Levels and Trends

A newly compiled national database of shallow groundwater levels (see Chapter 2) is used in this study. Statistics of weekly groundwater levels (i.e., mean depth to dry- and wet-season groundwater levels below ground level; hereafter dry- or wet-season water table) were calculated for the period 1985 to 1999 at each monitoring site, and interpolated over the entire country using geostatistical techniques with appropriate model variograms. Values of each interpolated surface at each As observation location (n=2410) were extracted using the spatial extraction function within the ArcGIS (v. 9.2) environment. Small-scale spatial variations in groundwater levels are expected to be smoothed due to spatial interpolation of these variables representing seasonal groundwater dynamics. The root mean square error (RMSE) for the interpolated (Ordinary Kriging with a fitted variogram) mean dry-season water table is small (1.7 m) compared to the observed mean dry-season groundwater level with one standard deviation of 5.4 ± 2.8 m throughout Bangladesh. Similarly, the RMSE for the mean wet-season interpolation is 1.3 m whereas the observed mean wet-season groundwater level is 1.5 ± 2.0 m. In addition to the seasonal water tables, values of long-term (1985-1999) trends in mean annual groundwater levels at each As location were extracted from the interpolated surface. The RMSE of the interpolated groundwater-level trends is 0.64 cm/year whereas the mean value over the entire country is -3.6 ± 5.7 cm/year.

To examine the effect of the seasonal water-table and groundwater-level trends on the national-scale As variations, this study uses mean dry and wet-season shallow water tables as well as the linear trends in mean annual groundwater levels for the period 1985-1999 (datasets and method described in Chapter 2). This time period is particularly chosen as this represents a period over which groundwater-fed abstraction for irrigation developed throughout Bangladesh that could affect As concentrations in the tubewells during the 1998-1999 sampling period (BGS and DPHE 2001).

5.2.2.2 Mean Groundwater Recharge and Trends

Mean annual (net) groundwater recharge and trends in mean recharge are used for the period of 1985 to 1999 as potentially important covariates in the statistical model to explain As variations in the shallow groundwater. Mean annual groundwater recharge and long-term trends in net recharge to shallow aquifers in Bangladesh have recently been estimated at the national scale in Bangladesh (see Chapter 4) using the water-table fluctuation method with distributed specific yield values. Values of mean annual recharge and their temporal trends at each As observation site have been estimated using a similar procedure to that described in section 5.2.2.1.

5.2.2.3 Surface Geology

The surface geology of Bangladesh is used as an important covariate in constructing the statistical model to explain As variations in shallow groundwater. Information on surface geology was extracted at each of the 2410 As sampling locations (DPHE 1999; BGS and DPHE 2001) from the geological map of Bangladesh (Figure 5.2) (Alam et al. 1990). Occurrence and spatial extent of shallow aquifers in Bangladesh follow the general distribution of the surface geology. A detailed description of surface geology and the aquifer systems in Bangladesh can be found in, for example, UNDP (1982), MPO (1987), BGS and DPHE (2001) and Burgess et al. (2010).

Descriptive statistics of As concentrations within these geological units are summarised in Table 5.2 that show that mean groundwater As concentrations are highest ($>100 \mu\text{g/L}$) in Chandina alluvium (as), deltaic sand (dsd), deltaic silt (dsl), and tidal deltaic deposits (dt) in Bangladesh (Figure 5.2). Mean As concentrations are lowest ($<10 \mu\text{g/L}$) in older alluvial fan (afo), bedrocks (br), Barind (rb) and Madhupur clay residuum (rm) in Bangladesh.

To represent the effect of the distinct geological units upon As concentrations within a statistical model, it is convenient to regard the surface geology as a categorical covariate (Davison 2003). Such covariates are conventionally handled in statistical models by using appropriate indicator or dummy variables (Hardy and Reynolds 2009). Surface geology is consisting of a total of 15 levels ($K=15$). In the model, it takes the value 1 if a certain geological unit is present in the dataset or 0 when it is absent. Therefore, the fitted model only provides $K-1$ coefficients (14 in this case) after adjusting them against the first level of the covariate.

Table 5-2 Descriptive statistics of the NHS As data (n=2410) within different geological units in Bangladesh. Mean, median, and standard deviation of As observations are estimated using the ROS method (Helsel, 2005) in the R statistical programme.

Geology	No of data	Censored	%Censored	Median	Mean	Std. deviation	Minimum	Maximum
ac	121	2	1.6	182.0	221.6	185.4	<0.5	1090.0
afo	109	68	62.4	0.3	2.2	7.3	<0.5	54.2
afy	281	108	38.4	1.5	15.7	57.3	<0.5	708.0
asc	285	92	32.3	9.1	77.5	147.4	<0.5	704.0
asd	91	28	30.8	5.8	68.3	128.9	<0.5	665.0
asl	496	141	28.2	5.1	45.1	102.7	<0.5	735.0
ava	56	10	17.9	6.6	30.5	68.3	<0.5	344.0
br	53	28	52.8	0.6	6.0	17.7	<0.5	108.0
csd	18	3	16.7	9.7	23.6	38.4	<0.5	151.0
dsd	43	4	9.3	72.0	123.6	145.2	<0.5	540.0
dsl	280	34	12.1	67.9	134.2	187.0	<0.5	1660.0
dt	192	15	8.0	48.0	118.9	163.3	<0.5	862.0
ppc	159	50	31.4	9.1	65.5	111.9	<0.5	538.0
rb	194	135	69.6	0.3	0.7	1.1	<0.5	7.7
rm	31	25	80.6	0.4	0.4	0.1	<0.5	6.0
National	2410	743	30.8	5.7	66.7	134.3	<0.5	1660.0

5.2.2.4 Upper Silt & Clay Unit (USC)

Groundwater As concentrations vary with depth to the shallow (<100 mbgl) aquifers in Bangladesh (BGS and DPHE 2001). Shallow aquifers are generally overlain by a silt/clay deposit, commonly known as the upper silt & clay (USC) unit, throughout the country (MPO 1987). The thickness of the USC unit ranges from <5 to 50 m (see Figure 4.2 in Chapter 4) (MPO 1987). In the alluvial fan deposits of northwestern Bangladesh, the USC unit is thin (<5 m) where fine sands occur at the surface. In contrast, shallow aquifers occur at greater depths beneath the Madhupur and Barind Tracts, Sylhet depression, and southern GBM Delta where the USC unit is thicker (>15 m). The thickness of the USC unit is used as a potentially important numerical covariate to explain the spatial As distribution in shallow aquifers.

5.2.2.5 Hydraulic Conductivity, Storage Coefficient, and Darcy Flux

At each sampling location, the hydraulic conductivity, storage coefficient (specific yield), and Darcy flow velocity of the aquifer are also considered as numerical covariates in the statistical model. Bangladesh Water Development Board (BWDB 1989, 1994) conducted pumping tests in shallow aquifers throughout Bangladesh and calculated horizontal hydraulic conductivity and specific yield. This study compiles pumping-test-derived hydraulic properties of shallow aquifers and generated geographical information system

(GIS) maps at the national scale (see Chapter 4). Values of hydraulic conductivity and specific yield at the 2410 As sampling locations were extracted using the procedure described in section 5.2.2.1 after interpolating these aquifer properties at the national scale in the country using geostatistical method. In addition, groundwater flow velocity (Figure 5.4) (also known as the Darcy flux), which is a function of hydraulic conductivity and groundwater-level gradient (Hiscock 2005), has been calculated using hydraulic parameters compiled in this study. Values of Darcy flux at each of the As sampling locations have been estimated using the same interpolation procedure as for other hydraulic parameters.

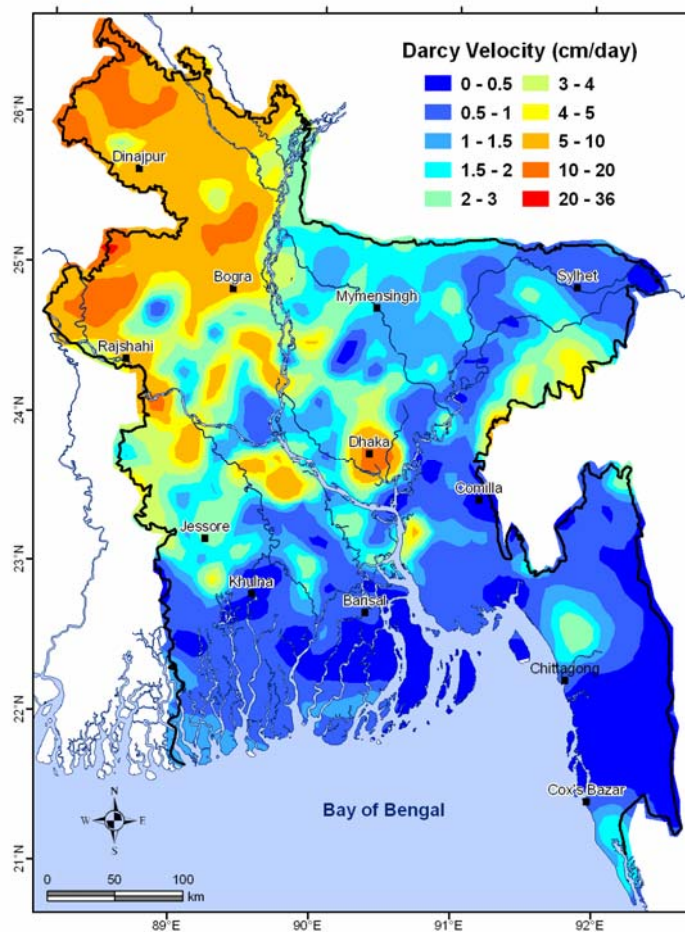


Figure 5.4 Groundwater flow velocity (Darcy flux) of shallow aquifers throughout Bangladesh. The Darcy flux map is created within the ArcGIS environment using spatial information on aquifer's hydraulic conductivity and groundwater-level gradients compiled in this study.

5.2.2.6 Abstraction for Groundwater-fed Irrigation

Groundwater irrigation trend (i.e., changes in annual irrigation) is used as a numerical covariate in the statistical model to explain groundwater As variations in Bangladesh. Dry-season (December to April) irrigation for Boro rice cultivation consumes ~80% of the total groundwater abstraction in Bangladesh (see Chapter 4). The Bangladesh

Agricultural Development Corporation (BADC) has been maintaining a database of annual groundwater abstraction for irrigation since 2001. This database is recorded at the Thana level. However, no systematic record for irrigation existed before 2000 although groundwater-fed irrigation in Bangladesh started during the early 1970s. Several studies (UNDP 1982; MPO 1987, 1991; WARPO 2000) estimated groundwater abstraction for irrigation for some years (e.g., 1986, 1991, and 1996) at the national scale using information on number of irrigation pumps, discharge capacity and pumping hours, or from agro-climatic records (BADC 2003; Ravenscroft 2003). This study has compiled all available datasets on groundwater abstraction for irrigation in Bangladesh and calculated linear trends (rate of change in annual irrigation) (Figure 5.5) for the period of 1985 to 1999. An interpolated spatial map showing linear trends in groundwater-fed irrigation is generated at the national scale and values are extracted at each of the 2410 As sampling locations using the geostatistical interpolation procedure described in section 5.2.2.1.

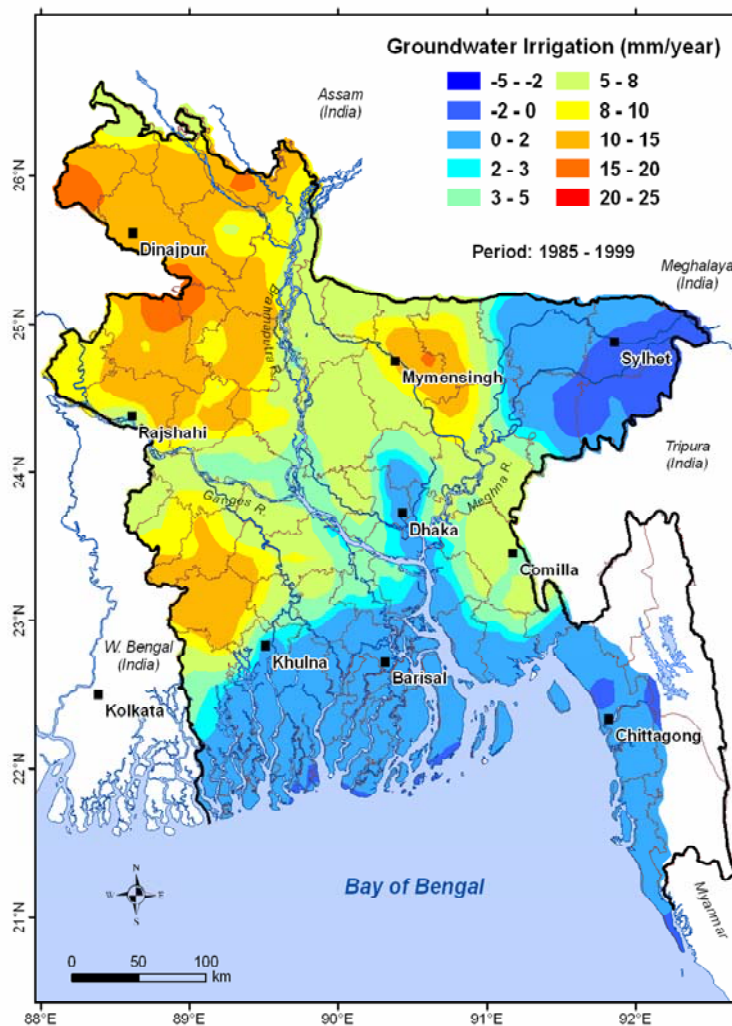


Figure 5.5 Linear trends (mm/year) in spatio-temporal groundwater-fed irrigation over the period from 1985 to 1999 in Bangladesh.

5.2.2.7 Geographical, Altitudinal and Seasonal Effects

Geostatistical analysis of groundwater As dataset in Bangladesh reveals that the concentration tends to increase from north to south which follows a decreasing gradient in surface elevation (Shamsudduha 2007b; Shamsudduha et al. 2009). To capture this effect, this study uses covariates in the model that represent the regional variation. Systematic regional variation is represented using surface elevation, along with Legendre polynomial transformation of the geographic coordinates of As observations (Chandler 2005). These polynomial bases are likely to provide a reasonable approximation to the regional structure of the dataset (Chandler and Scott 2011); groundwater As dataset shows a increasing north-south gradient in Bangladesh. The degree of polynomials considered here is restricted to a maximum of two which can adequately capture the regional-scale variation in As concentrations. The coordinates for sampling locations were taken by the hand-held Global Positioning System (BGS and DPHE 2001). Elevation information at each As location was derived from a digital elevation model of 300m spatial resolution (Shamsudduha et al. 2009). Additionally, in order to adjust for any potential seasonal variation in groundwater As concentrations (because the sampling was conducted over a period from January 1998 to December 1999) the sampling dates are used as a covariate. Seasonality in As concentrations may arise due to dependence on one or more seasonally varying covariates although no clear seasonal variation in As concentration has been reported in Bangladesh (Dhar et al. 2008). Seasonality is, however, represented via Fourier covariates (see Section 3.2 of Chandler and Scott, 2011), specifically $\cos(2\pi \times \text{day of sampling}/365)$ and $\sin(2\pi \times \text{day of sampling}/365)$.

5.3 Statistical Modelling Strategy

To investigate the simultaneous effect of the preceding factors upon groundwater As distribution at the national scale a statistical model is developed which can be regarded as a generalised regression technique. In the statistical literature, the most common candidate for modelling a skewed dataset like the groundwater As concentrations in Bangladesh is the generalised linear model (GLM) with a gamma distribution (Chandler 2005; Yan et al. 2006). GLMs extend the classical linear regression model (McCullagh and Nelder 1989) and apply a probability distribution to relate the response variable to a linear combination of covariates (Chandler 2005). However, in the presence of censored (non-detect) observations in the As dataset a GLM cannot be applied as it is computationally intensive to handle censored data correctly in the context of gamma

distributions (Chandler and Wheeler 2002). Instead, censoring in the skewed dataset can be dealt with regression-like techniques from the survival analysis which are well developed and widely accepted (Klein and Moeschberger 2003). From this perspective, the Weibull family of distributions is much more tractable (Aiken and West 1991). The Weibull distribution is generally used to model highly skewed (extreme) observations in the response variable (Yan et al., 2006).

5.3.1 Modelling Framework

Survival regression models (analogous to GLMs) are widely used in the biomedical sciences to model the survival time for individuals to experience a particular event. In this context, censoring can occur if an individual has already experienced the event before the start of the experiment (leading to a left-censored observation) or if the individual does not experience the event at all during the study. For example, in a study of survival time in malaria infected population, some individuals may already have malaria at the outset of the experiment but the exact timing (i.e., age) of contracting the disease is unknown. This particular situation produces a left-censored observation, which is directly analogous to an observation recorded as “below detection limits” in the context of As dataset. Survival regression models with a suitable family of distributions (e.g., the Weibull) are designed for use in this type of situation and to enable parameters to be estimated by maximum likelihood (ML) (Aitkin and Clayton 1980). To date however, these techniques have not been used widely in the environmental sciences (Helsel 2006; Ryberg and Vecchia 2006). This study develops a generalised regression model with the Weibull distribution for describing the influence of hydrogeology and groundwater dynamics on the variation of As concentrations in Bangladesh.

Similar to the gamma distribution, the Weibull is a two-parameter continuous probability distribution with parameters α and λ representing “shape” and “scale” respectively. The probability density function (PDF) of the distribution is

$$f(y; \alpha, \lambda) = \frac{\alpha}{\lambda} \left(\frac{y}{\lambda} \right)^{\alpha-1} \cdot e^{-\left(\frac{y}{\lambda} \right)^{\alpha}} \quad \text{when } y \geq 0; \alpha, \lambda > 0 \quad (5.1)$$

and the corresponding cumulative distribution function (CDF) is

$$F(y; \alpha, \lambda) = 1 - e^{-\left(\frac{y}{\lambda} \right)^{\alpha}} \quad \text{when } y \geq 0; \quad F(y; \alpha, \lambda) = 0 \quad \text{when } y < 0 \quad (5.2)$$

The mean and variance of the Weibull distribution are $\mu = \lambda\Gamma(1 + \alpha^{-1})$ and $\lambda^2\Gamma(1 + 2/\alpha) - \mu^2$ respectively.

In the statistical modelling framework used here, the vector of all groundwater As observations, $Y = (y_1, \dots, y_n)$ say, are all considered to be generated from Weibull distributions with a common shape parameter α (Yan et al., 2006). The common shape parameter implies that the coefficient of variation is constant across all point observations of As concentrations in groundwater. The scale parameters are however covariate-dependent: scale parameter for the i^{th} observation is λ_i so that $y_i \sim \text{Wei}(\alpha, \lambda_i)$.

Suppose groundwater As concentration at each location, y_i is to be predicted from values of J covariates, and denote the values of these covariates by $\{x_i(j) : j = 1, \dots, J\}$. It is common practice in survival analysis (Klein and Moeschberger 2003) to use a logarithmic link between the covariates and the mean, μ_i , of the distribution:

$$\ln \mu_i = \beta_0 + \sum_j \beta_j x_i(j) \quad (5.3),$$

where $\{\beta_j\}$ are model coefficients. The use of logarithmic link is adopted primarily as a convenient device to guarantee that As concentrations have positive means (Yan et al., 2006). It also ensures that the model coefficients are easily interpretable. In this model the coefficients $\{\beta_j\}$ have a convenient interpretation, since e^{β_j} is the average multiplicative effect of the j th predictor upon the expected groundwater As concentration. Replacing the mean value in the formula, then equation (5.3) takes the new form, $\ln \lambda_i = \ln \mu_i - \ln \Gamma(1 + \alpha^{-1})$, which implies that the mean value depends on the scale parameter of the distribution as the latter, $[\ln \Gamma(1 + \alpha^{-1})]$, is a constant because of the assumption of a common shape parameter. So equation (5.3) can equivalently be regarded as specifying a model for covariate effects directly upon the scale parameters.

A convenient feature of the Weibull model is that a tractable expression (equation 5.2) is available for the CDF. Given the parameters of the distribution, it is easy therefore to calculate the probability of any observation falling above or below a particular threshold. In particular, the probability of an observation being censored (i.e. falling below the relevant detection limit) can be calculated using a likelihood function.

Let δ_i be an indicator variable in the likelihood function taking the value 1 if the As observation at the i^{th} location is uncensored, and 0 if it is censored. Moreover, let τ_i be the detection threshold for the observation. Then, if the groundwater As observations were mutually independent, the likelihood function (L) for the model parameters given the data is

$$L = \prod_{i=1}^n [f(y_i)]^{\delta_i} [F_i(\tau_i)]^{1-\delta_i}. \quad (5.4)$$

The logarithm of (equation 5.4) can be maximised numerically to estimate the model parameters (Aitkin and Clayton 1980); standard large-sample theory can then be used to calculate standard errors for the parameters and to test hypotheses about them. However, in this example, groundwater As observations are obtained from the neighbouring spatial locations and are therefore unlikely to be independent. The approach to deal with this difficulty is described below.

To fit the Weibull model to describe As variation in shallow groundwater in Bangladesh, this study uses routines for survival analysis in the “R” environment (version 2.10.0) (R Development Core Team 2009). The `survreg()` function within the “survival” package (Therneau et al. 1990; Therneau 2009) and `psm()` function from the “Design” package (Harrell 2001; Harrell 2009) are applied for modelling the groundwater As data.

5.3.2 Model Checking and Testing

To check the fitting of the model and unexplained structure the standardised deviance residuals are computed in this case since the original residuals (observed – fitted) are not suitable for diagnostic purposes because they all have different variances under the model (Chandler and Scott 2011). For many models of this type it is also common to use standardised deviance residuals to assess model fit which provides an idea of the extent to which individual observations contribute to the lack of the model fit. Detailed description of deviance residuals for the survival regression model can be found in literature (McCullagh and Nelder 1989; Therneau et al. 1990). Under the assumed model, the deviance residuals should be symmetrically distributed around a mean 0 and a standard deviation of 1 although heavy censoring in the dataset can however distort the normal approximation (Davison and Gigli, 1989). Additionally, if the fitting of the model is

correct the standardised deviance residuals (approximately 95%) should fall within a range of -2 to 2 (Chandler 2005).

Statistical significance of covariates is tested with a log-likelihood ratio (LR) test (similar to the ANOVA test) where statistics are adjusted for the inter-site dependence (see Chandler and Bate, 2007 for detailed description). Description of how the inter-site dependence is accounted for is given in section 5.3.3 below. Significance of each term (associated with covariates) in the fitted model is checked using the adjusted LR test statistics which provide the p -value for each deleted term in both naïve (unadjusted) and adjusted tests.

In addition to the LR test, this study also uses a generalised R^2 statistic (Harrell 2001) to measure the proportion of variation in the data explained by the covariate data. R^2 is defined by the following formula:

$$R^2 = (1 - \exp(-LL/n)) / (1 - \exp(-L^0/n)) \quad (5.5)$$

where LL is the global log likelihood ratio statistics, L^0 is the -2 log likelihood for the null (intercept) model, and n is the number of observations in the model.

5.3.3 Inter-site Spatial Dependence

In section 5.3.1 it was indicated how model parameters could be estimated using ML under the assumption that observations in the dataset are independent. It is, however, highly unlikely that groundwater As observations from neighbouring spatial locations are independent. To compare models and interpret results it becomes necessary to adjust the standard errors of the estimates and likelihood ratios for the inter-site dependence (Chandler 2005). The required adjustments can be calculated relatively straightforwardly if the observations can be separated into a large number of distinct clusters that can be considered as independent (Chandler and Bate 2007). To achieve this for the As observations, a hierarchical clustering method is applied based on the site locations to partition the observations into spatially compact clusters by imposing a minimum separation distance between sites in different clusters. The observations which were not used to form these clusters were subsequently used for validation of the fitted model.

To investigate the possibility of inter-site dependence a preliminary model similar to that discussed below is fitted, and the variogram of the residuals is calculated from this

model. This variogram (shown later in section 5.4.1) indicated that spatial dependence was relatively localised and observations separated by more than ~25km could be considered as effectively independent.

Ideally, the aim of this exercise is to obtain clusters that are separated from each other as widely as possible; thus, a single-linkage algorithm was used in the first instance in which the clusters are defined so as to maximise the smallest distance between sites in distinct clusters (Romesburg 2004). However, some of the clusters generated by this procedure were very large due to the effect known as ‘chaining’ (Hartigan 1981); to deal with this, large clusters with >50 observations were further split by running the Ward-linkage method which tends to create clusters of more uniform size. Finally, sites within 25km of another cluster were removed one at a time until all clusters were separated by at least 25km. In this clustering process, 767 sites were removed in total: these were not used for model calibration, but were retained for subsequent validation. The remaining 1643 observations (calibration dataset) were used to fit the model that was derived from a total of 212 clusters (Figure 5.6). Each observation in the calibration dataset has now been assigned to a cluster member in such a way that the clusters can be considered as spatially independent. The theory described by Chandler and Bate (2007) can be used here to adjust standard errors and likelihood ratios for the within-cluster dependence in the calibration data.

5.3.4 Statistical Interactions

Covariates may interact with each other so that the effect of one covariate upon the response variable may depend on the values of others. For example, previous studies (DPHE 1999; Ravenscroft 2001) examined statistical associations between aquifer’s hydraulic properties and groundwater As concentrations and suggested that the relationship varies within different geological units in Bangladesh. Here this point is further illustrated by an example. Consider two geological units, one containing iron-oxyhydroxide minerals whose dissolution would lead to the mobilisation of As in groundwater and the other containing no such minerals. In this case, one might expect groundwater As concentrations to show a significant association with aquifer recharge in the first unit, but not necessarily any association in the second. Thus the association between groundwater recharge and As concentration varies between geological units, resulting in a statistical interaction.

The presence of interactions can have important implications for the interpretation of statistical models (Aiken and West 1991). However, effects of such statistical interactions on groundwater As distributions in Bangladesh have not been tested previously. Statistical interactions are easily handled within any regression framework, including the survival regression models considered here. Mathematically, this is achieved by adding an extra term to the model which is a product of the interacting covariates (Chandler and Wheeler 2002).

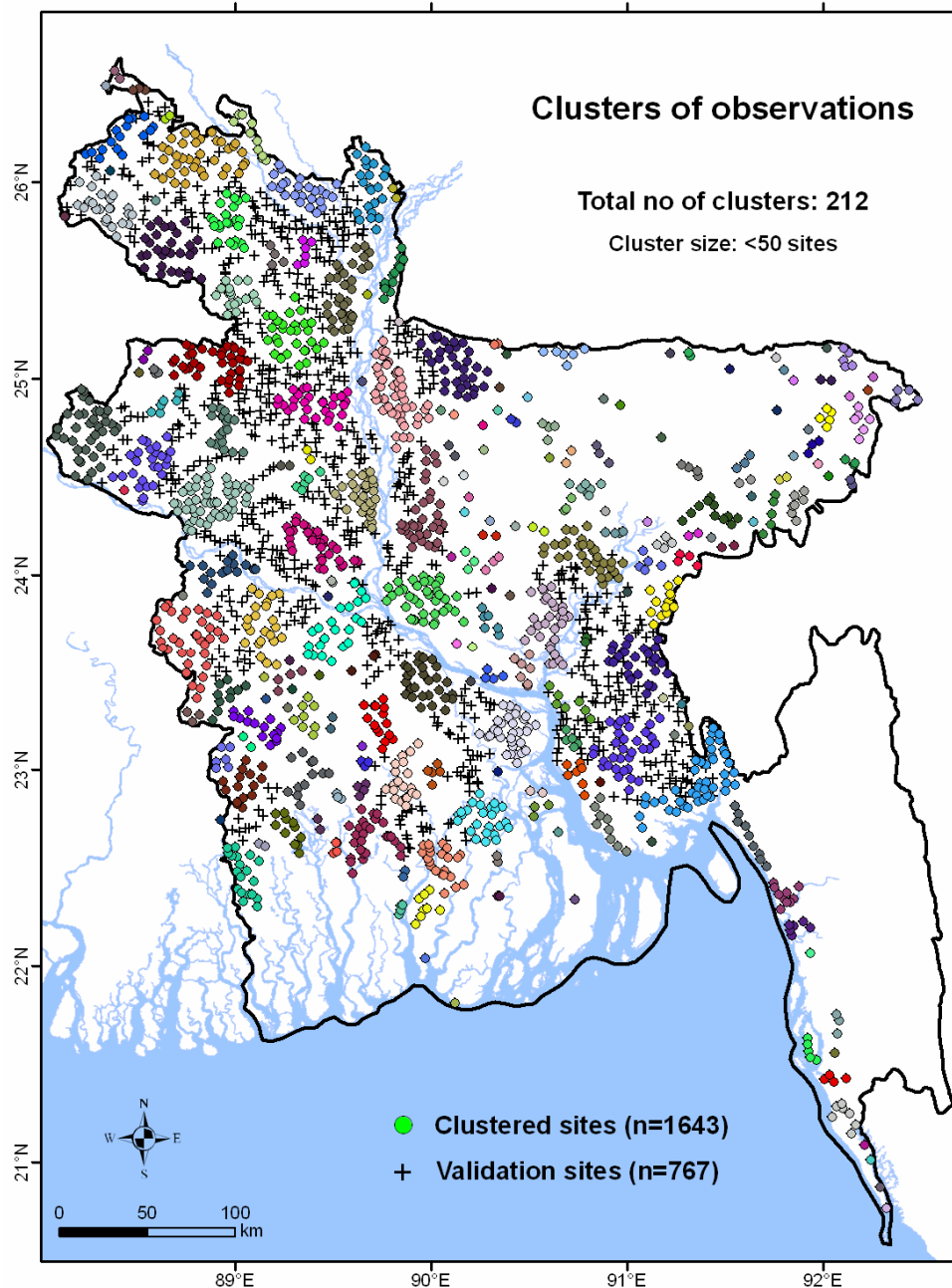


Figure 5.6 Spatial distribution of the colour-coded clusters of As observations (n=1643) as well as unclustered observations (n=767) that were grouped using the hierarchical clustering method in order to resolve the inter-site spatial dependence in the As dataset. Clustered observations were used to fit the calibration model and random observations were used to validate the fitted model.

In the present study, several statistical interactions are included between covariates along with their main effects to explain variability in As observations. Exploratory analyses reveal substantial variations in relationships between groundwater As concentrations and mean annual recharge within different geology in Bangladesh (Figure 5.7). Similar relationships exist between groundwater As and net recharge trends (Figure 5.8), and between groundwater As and sampling depths (Figure 5.9). Therefore, the covariates (groundwater recharge, recharge trends and sampling well depth), and their individual interactions with the surface geology are considered in the model.

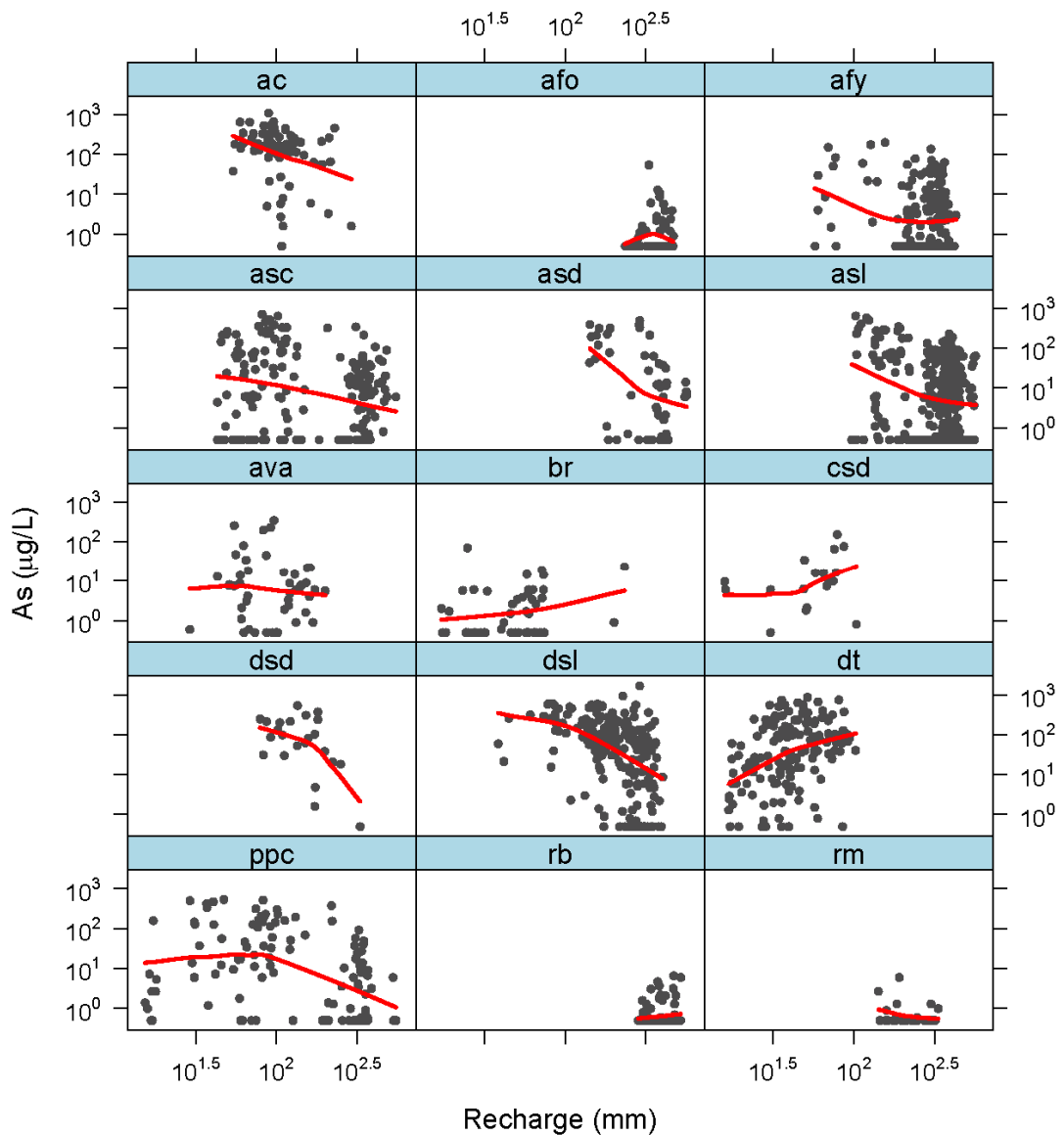


Figure 5.7 Variations in the relationship between As concentrations in groundwater and mean annual (net) recharge to shallow aquifers within various geological units in Bangladesh. The red line in each individual panel is a nonparametric regression estimate (LOWESS) (Cleveland 1981) of the relationship between As concentrations and net recharge.

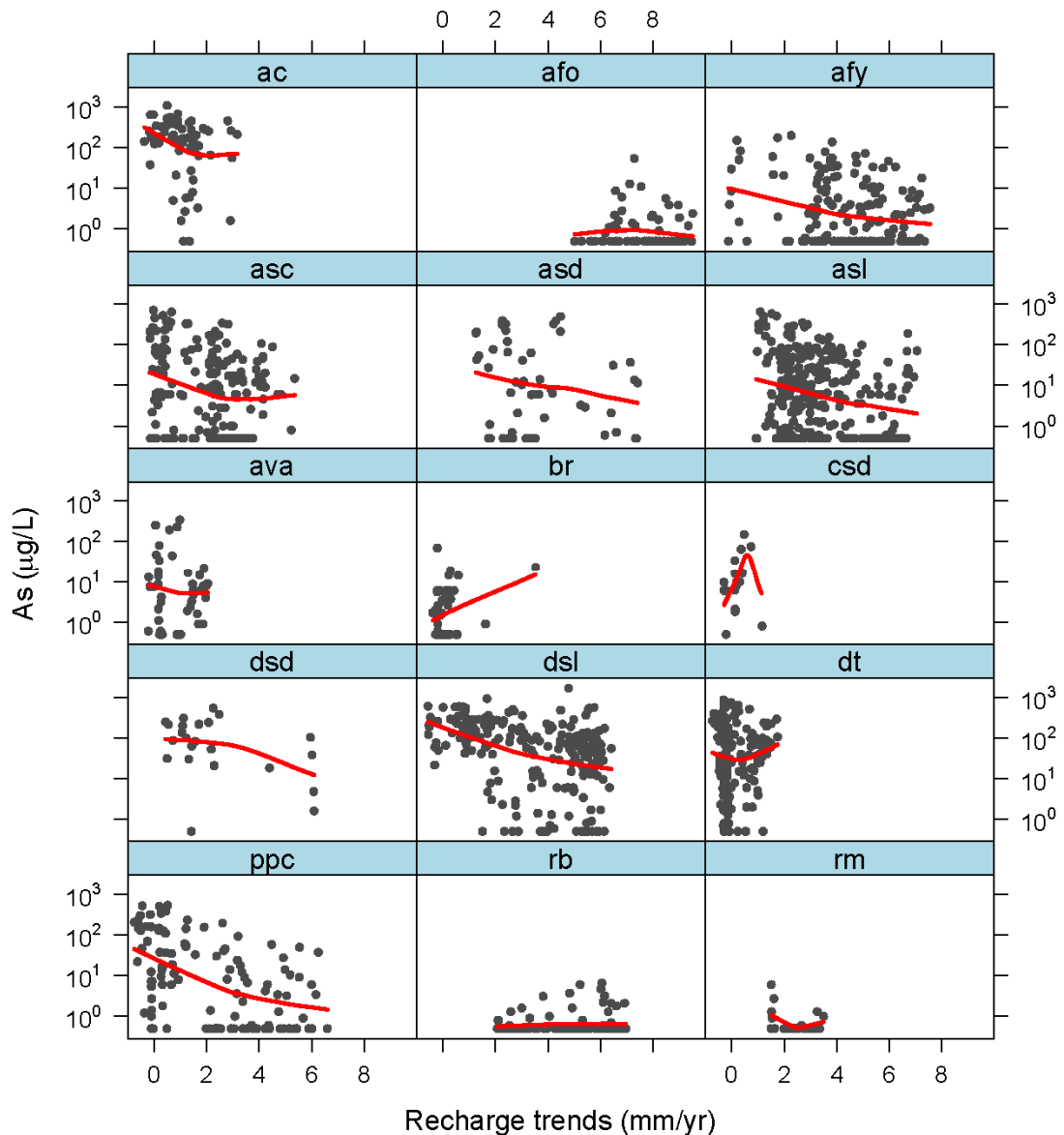


Figure 5.8 Variations in the relationship between As concentrations in groundwater and trends (1985 to 1999) in mean annual (net) recharge to shallow aquifers within various geological units in Bangladesh. The red line in each individual panel represents a locally-weighted polynomial regression (LOWESS) (Cleveland 1981) between As concentrations and net recharge trends.

5.3.5 Model Fitting

Fitting a generalised regression model (GRM) with the Weibull distribution involves choosing the covariates and estimating the corresponding parameters. The model was built up in stages as described below. Table 5.3 summarises the basic statistics of covariates used in the model. Since the number of covariates is large these are categorised broadly into four groups representing the major physical processes influencing As variations in groundwater: (i) geology and hydrogeology, (ii) groundwater dynamics and recharge processes, (iii) geography, altitude and seasonality, and (iv) groundwater abstraction.

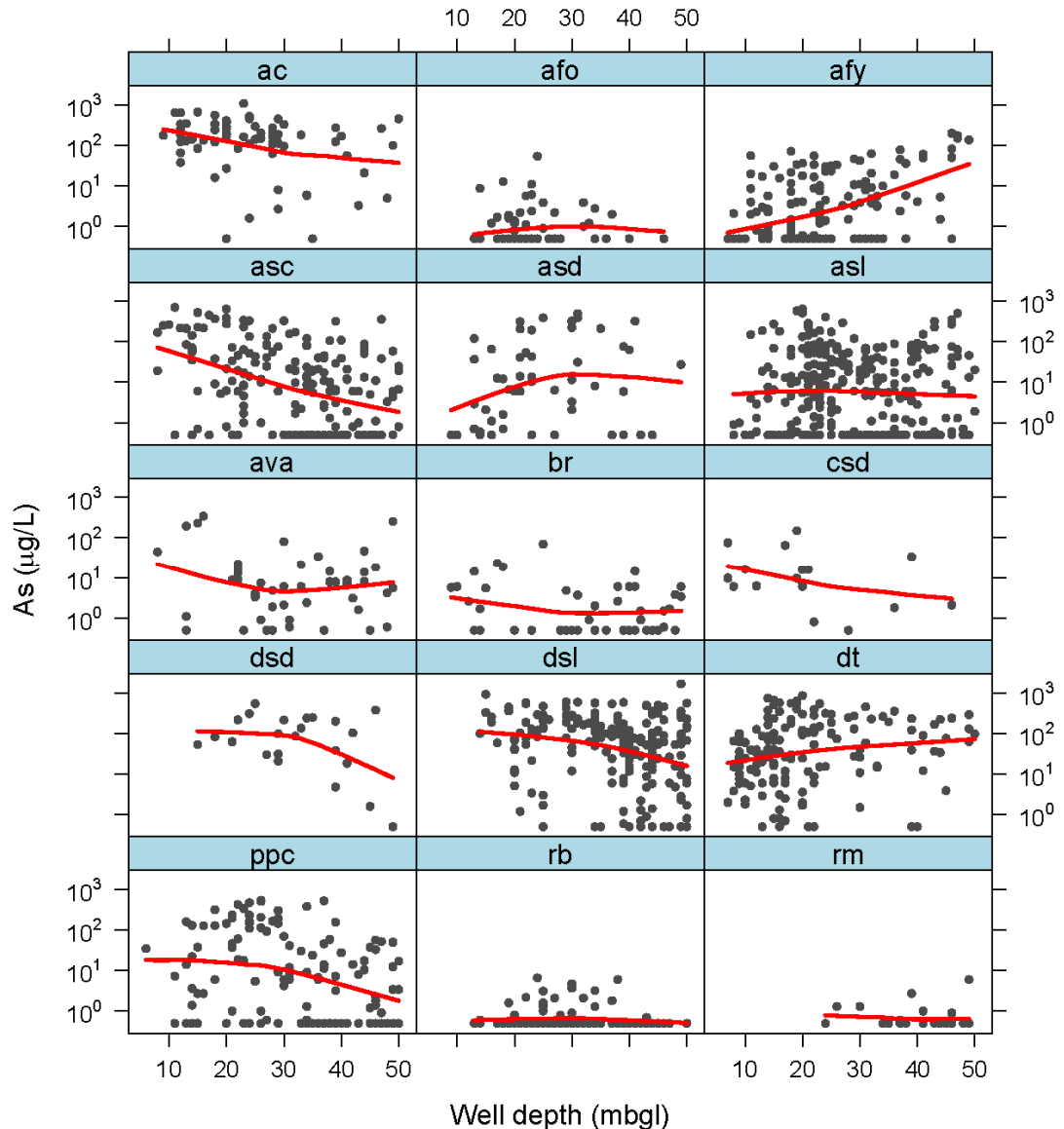


Figure 5.9 Variations in the relationships between As concentrations and sampling depths within different ($n=15$) surface geological units in Bangladesh. Depth to these surveyed wells are very shallow (<50 mbgl). The red line in each individual panel represents a locally-weighted polynomial regression (LOWESS) (Cleveland 1981) between As concentrations and well depth.

The basic factors include geographic coordinates (latitudes and longitudes) of the sampling locations as well as the Legendre polynomial (degree two) transformations of the latitudes and longitudes (Chandler 2005), and surface elevation at each sampling location. Seasonality in sampled As variations was represented by the sine and cosine functions of each sampling date. Additionally, the variation in As concentrations with sampling depth was represented by the intake depth of each surveyed well. Subsequently, the factors representing surface geology, hydrogeology, groundwater dynamics, recharge process, and abstraction were sequentially added to the model together with the associated interaction terms. Terms were added to the model and overall fitting of the

model was assessed by examining the standardised deviance residuals. At this stage, all the covariates listed in Table 5.3 have been added regardless of their apparent statistical significance producing deliberately an overfitted (comprehensive) model. Subsequently, adjusted LR tests were applied to assess the significance of these covariates in explaining the overall As variation in groundwater. The LR test for individual covariates was performed by (1) forming a simpler model upon dropping the corresponding term(s) (including any interactions) from the fitted model, and (2) testing the simpler model against the fitted, comprehensive model applying the adjusted LR test.

5.4 Modelling Results

The statistical model describes the variation in As concentrations in shallow groundwater and its relationship with surface geology, and hydrogeological processes that can possibly affect As mobilisation in the aquifer. The resulting model has a total of 76 terms, 43 of which represent interactions. The model includes six covariates representing geology and hydrogeology, six covariates representing groundwater dynamics and recharge processes, four covariates relating to geography, altitude and seasonal structure, and one covariate for abstraction representing trends in groundwater-fed irrigation. A summary of the modelling results is given in Table 5.4. The exponential transformation of each regression coefficient (e^{β_j}) is the average multiplicative effect of a 1-unit increase in the value of the corresponding covariate upon the mean As concentration.

5.4.1 Model Diagnostics and Validation

It is necessary to check the fit of any statistical model before interpreting the result. Checks of statistical models primarily involve (i) diagnostics of the model structure, (ii) examination of the assumed probability distribution, and (iii) assessment of the predictive ability (Chandler and Wheater 2002). In addition to these standard checks, it is often informative for a multi-site model to construct a variogram of the model residuals to check for any unexplained spatial structure in the dataset.

Standardised deviance residuals for the fitted model were computed as described in section 5.3.2. Figure 5.10 shows the spatial distribution of the model residuals whereas the variogram in Figure 5.11 shows their spatial dependence. Results show approximately, 96% of the deviance residuals fall between -2 and 2 . Higher residuals (>2) are observed in 1.3% observations for which the mean As concentration is $193 \mu\text{g/L}$;

lower (<-2) residuals are observed in 3.1% observations of which all are censored below a threshold of $0.5 \mu\text{g/L}$. The residual variogram shows that there is no spatial structure over the greater lag distance; short-scale, up to a distance of 0.25° ($\sim 25 \text{ km}$), dependence in residuals suggests the inter-site dependence which has been discussed in section 5.3.3.

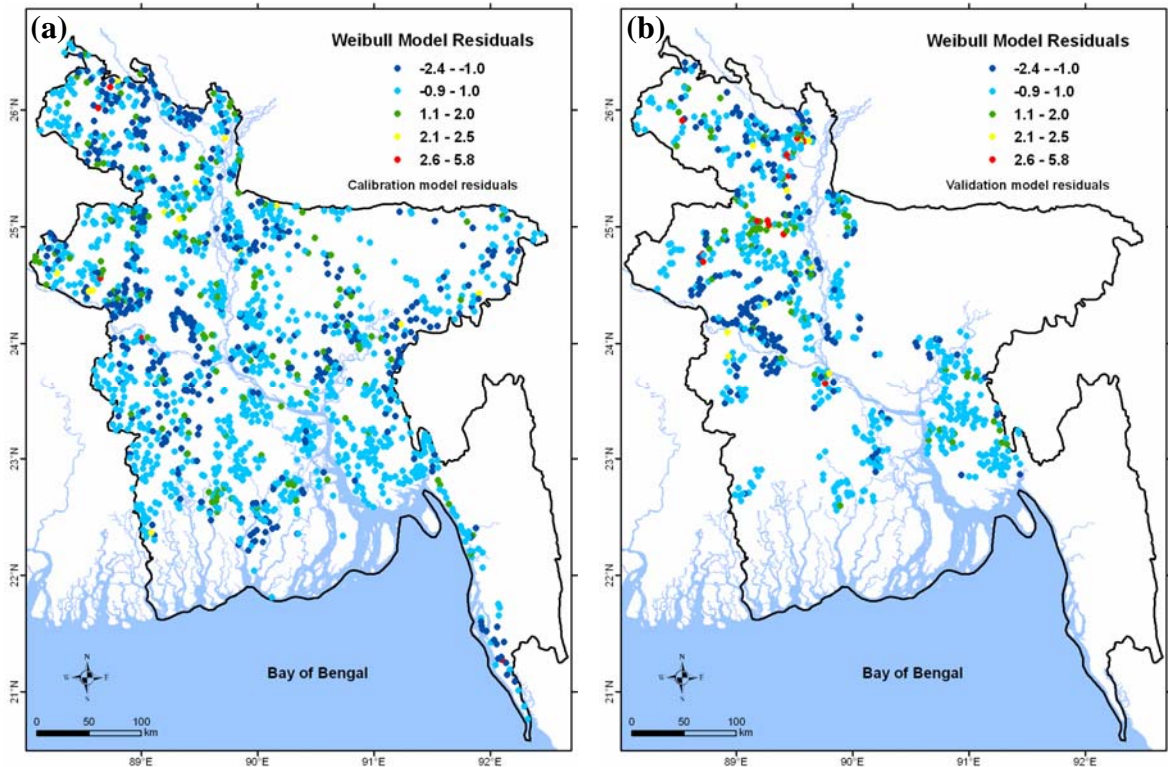


Figure 5.10 Spatial distribution of standardized deviance residuals from (a) the calibration model, (b) validation of the fitted model using a subset of covariate datasets.

It is necessary to ensure that the probability structure of the fitted model is correct since this is used to compute the likelihoods upon which inferences are based (Chandler and Wheeler 2002). In the absence of censoring, the simplest way to check the probability structure is via a quantile-quantile plot. However, quantiles of observed quantities are difficult to define in the presence of censoring and, therefore, alternative techniques are used here. In survival regression, the assumption for the Weibull distribution in the fitted model is generally checked visually by plotting $\log[-\log(1 - F(\tau))]$ against $\log(\tau)$ (also known as “cloglog” plot in R) (Kleinbaum and Klein 2005; Therneau 2009); a straight line plot (Figure 5.12a) indicates that the choice of Weibull model is reasonable for the As dataset. Although a few points in the lower tail of the distribution are slightly deviated from the normal curve, however, these fall within the uncertainty envelopes of pointwise 95% confidence intervals (shown as dashed lines).

Table 5-3 Basic statistics of covariate datasets used to fit the generalised regression model for explaining the variation of As concentrations in groundwater in Bangladesh.

Covariates / Factors	Data type and Unit	Mean	Median	Standard deviation	Data range
Arsenic (As) concentration (n=1643)	Numerical ($\mu\text{g/L}$); point measurements	62.29 ^a 62.31 ^b	5.60 ^a 5.60 ^b	129.84 ^a 129.81 ^b	<0.5 to 1660
Surface geological cover	Non-numeric or categorical; polygonal GIS layers	n.a.	n.a.	n.a.	15 units
Upper silt and clay cover (USC)	Numerical (m); gridded dataset	14.00	13.60	6.63	0.5 to 33.40
Hydraulic conductivity	Numerical (m/day); gridded dataset	30.85	29.30	15.53	5.7 to 75.80
Specific yield	Numerical; gridded dataset (%)	5.82	6.00	2.51	0.1 to 10.70
Darcy flux	Numerical (cm/day); gridded dataset	3.63	2.33	3.75	0.05 to 31.51
Well depth	Measured/estimated depth (m bgl) to well screen	27.88	26.00	10.78	6.0 to 50.0
Dry-season groundwater table	Numerical (m bgl); gridded dataset	5.38	5.18	2.03	1.55 to 14.14
Wet-season groundwater table	Numerical (m bgl); gridded dataset	1.40	1.19	1.02	0.01 to 11.50
Groundwater levels trends	Numerical (cm/year); gridded dataset	-3.60	-2.56	5.72	-62.56 to 5.8
Mean groundwater fluctuation	Numerical (m); gridded dataset	3.97	3.89	1.50	0.9 to 8.04
Mean annual recharge	Numerical (mm); gridded dataset	248.17	283.81	137.43	15.4 to 569.7
Recharge trends	Numerical (mm/year); gridded dataset	3.02	2.74	2.28	-0.74 to 9.5
Longitude	Measured (GPS) coordinates (in degree)	89.85	89.71	0.99	88.08 to 92.48
Latitude	Measured (GPS) coordinates (in degree)	24.17	24.21	1.11	20.77 to 26.57
Surface elevation	GIS Raster, 300m spatial resolution (m msl)	14.85	10.93	13.85	0.63 to 93.75
Seasonality (water sampling dates)	Sampling dates (decimal year)	1998.80	1998.42	0.56	1998.01 to 1999.93
Trends in groundwater-fed irrigation	Numerical (mm/year); gridded dataset	7.17	6.90	4.46	-1.1 to 20.2

Note: mean, median and standard deviation for As dataset were estimated using Regression on Order Statistics (ROS)^a, and Kaplan-Meier nonparametric (K-M)^b estimators (see Helsel, 2005) using the NADA package within the “R” environment. n.a. not appropriate for descriptive statistics.

Table 5-4 Summary of the fitted, comprehensive model for the As dataset in Bangladesh providing estimated coefficients of model parameters and naive standard errors, adjusted standard errors with the corresponding Wald test statistic (z-value), and statistical significance (p-value). DF means degree of freedom.

Covariates/Factors	Coefficient	DF	Std. error (naive)	Std. error (adjusted)	z-value	p-value
Geology and hydrogeological factors:						
Surface geology	-4.7576 to 2.5463	14	0.593 to 3.135	0.640 to 3.096	-3.299 to 3.980	0.0001 to 0.9870
USC unit	-0.043	1	0.016	0.012	-3.663	0.0002
Hydraulic conductivity	-0.002	1	0.010	0.008	-0.172	0.8630
Specific yield	0.178	1	0.133	0.100	1.780	0.0751
Darcy flux	-0.037	1	0.035	0.023	-1.646	0.0998
Well depth and its interaction	-0.008	15	0.008	0.009	-0.894	0.3710
Groundwater dynamics and recharge factors:						
Dry-season GWT	0.288	1	0.257	0.235	1.223	0.2210
Wet-season GWT	-0.193	1	0.150	0.155	-1.248	0.2120
Groundwater level trends	0.040	1	0.024	0.019	2.135	0.0328
Mean groundwater fluctuation	-0.446	1	0.323	0.240	-1.861	0.0628
Mean recharge and its interaction	-0.003	15	0.005	0.006	-0.468	0.6400
Recharge trends and its interaction	0.201	15	0.382	0.395	0.508	0.6120
Geographical, altitudinal, and seasonal factors:						
Longitude (degree 1 Legendre)	-0.407	2	0.490	0.430	-0.946	0.3440
Latitude (degree 1 Legendre)	-1.344	2	0.645	0.579	-2.320	0.0203
Longitude (degree 2 Legendre)	-0.839	1	0.395	0.312	-2.688	0.0072
Latitude (degree 2 Legendre)	-1.789		0.698	0.622	-2.878	0.0040
Longitude1: Latitude1	0.709	1	0.799	0.754	0.940	0.3470
Surface elevation	-0.006	1	0.018	0.017	-0.350	0.7260
Cosine (sampling date)	-0.543	1	7.215	6.773	-0.080	0.9360
Sine (sampling date)	0.845	1	2.152	2.019	0.419	0.6760
Groundwater abstraction factor:						
Irrigation trends	-0.098	1	0.034	0.026	-3.798	0.0001
Geo-interactions terms:						
Geology : Well depth	-0.056 to 0.096	14	0.013 to 0.066	0.015 to 0.050	-3.503 to 5.170	0 to 0.9960
Geology : Mean recharge	-0.037 to 0.029	14	0.005 to 0.050	0.006 to 0.064	-1.651 to 2.478	0.0132 to 0.9620
Geology : Recharge trends	-1.510 to 2.800	14	0.384 to 4.559	0.404 to 4.710	-1.201 to 1.903	0.0571 to 0.9350

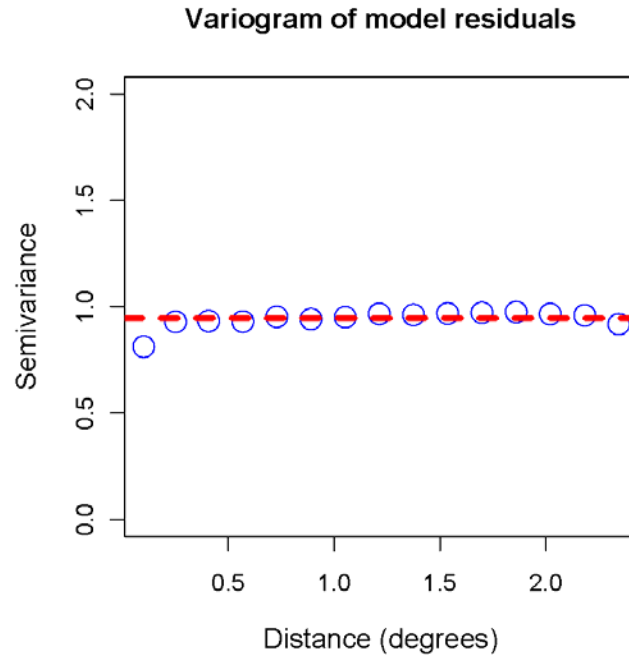


Figure 5.11 Variogram of the standardised deviance residuals for the fitted model; sample variance of the residuals is shown as dashed red line.

The predictive ability of the resulting model has also been checked using a validation dataset. A subset ($n=767$) of As concentrations data (described in section 5.3.3) was used to validate the calibration model. The validation of the fitted model yields comparable residuals with the mean of -0.16 and standard deviation of 1.15 although the standardised deviance residuals (2.6%; 20 locations) are larger than 2 of which the average observed As concentration is high (mean of 20 observations is $267 \mu\text{g/L}$). Additionally, spatial distribution of the deviance residuals for the validation dataset compares (Figure 5.10b) well with that of the calibration data. Similar to the calibration model, a cloglog plot (Figure 5.12b) shows that the assumption for the Weibull distribution is valid. Overall, these comparative analyses indicate that the modelling results are reproducible.

5.4.2 Model Interpretation

Diagnostics in the previous section suggest that the fitted generalised regression model (GRM) provides a good representation of the overall structure in the As dataset. The distribution assumption (for the Weibull model) looks reasonable. Additionally, the validation test of the model suggests that the modelling results are satisfactory. The fitted GRM with 76 degrees of freedom explains approximately 49% ($R^2=0.49$) of the national-scale variance in groundwater As concentrations and rejects (p -value 0) the null

hypothesis that covariates do not explain As variations. Given the extreme variability in groundwater As dataset the performance of GRM can be considered satisfactory. The remaining variance which is not explained by the covariates is essentially due to extreme variations in As concentrations and hydrogeological factors themselves.

In this section, the modelling results are interpreted in order to explain the associations between groundwater As concentrations and various covariates representing groundwater dynamics, recharge and hydrogeological processes. Examples of correlation coefficients are provided between As and covariates to show how these relationships vary with the results of this modelling which examines simultaneous effects of covariates on As variations.

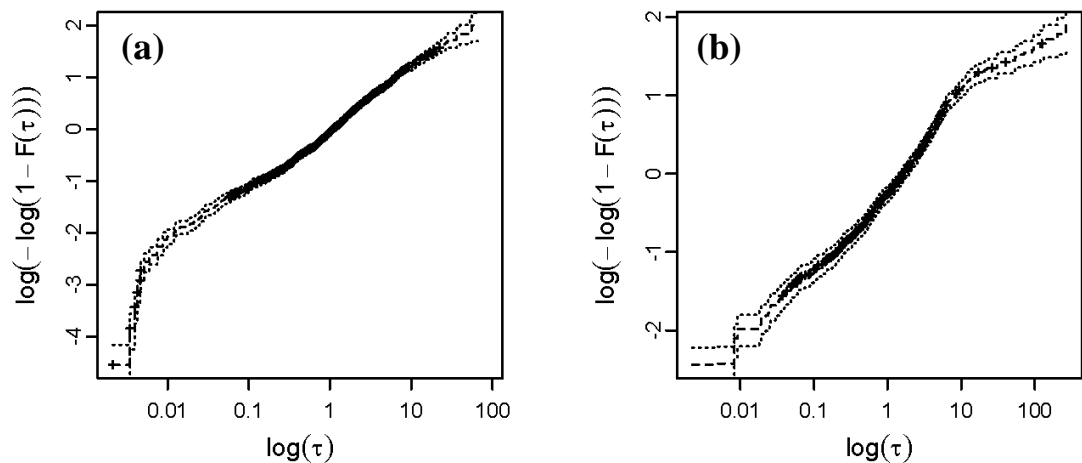


Figure 5.12 Weibull model assumption is checked with a cloglog plot of $\log(-\log(1-F(\tau)))$ and $\log(\tau)$. A straight line in the plot indicates that the assumption for the Weibull distribution is valid. Both plots (a) for the fitted, calibration model, and (b) validation of the fitted model suggest that the Weibull distribution is suitable for modelling groundwater As dataset.

5.4.2.1 Effects of Geology and Hydrogeology

Modelling results show that surface geological units and their two-way interactions with other factors (e.g., sampling depth, mean recharge, recharge trends) contribute 56 terms to the full model. If all of these terms are dropped from the model, the adjusted LR test statistics in Table 5.5 show an adjusted p -value of zero indicating that the effect of surface geology and the geo-interactions are strongly significant in explaining the variation in groundwater As concentrations in Bangladesh. Surface geology and its interactions alone explain 43% variance of the total national-scale variations in groundwater As concentrations.

Table 5-5 Effect of dropping predictor covariates and their associated terms from the full As model according to naïve and adjusted likelihood ratio (LR) test procedures. Any p -values less than 10^{-10} are reported as zero. DF means degree of freedom.

Covariates/Factors	DF	p -value	
		Naïve	Adjusted
Geology and hydrogeological factors:			
Surface geology and geo-interactions	56	0	0
USC unit	1	0.0003	0.0089
Hydraulic conductivity	1	0.8631	0.9406
Specific yield	1	0.0747	0.1889
Darcy flux	1	0.1040	0.3003
Well depth and interaction	15	1.7×10^{-8}	1.3×10^{-6}
Groundwater dynamics and recharge factors:			
Dry-season GWT	1	0.2171	0.2728
Wet-season GWT	1	0.2112	0.2099
Trends in mean GWL	1	0.0336	0.0944
Mean groundwater fluctuation	1	0.0598	0.1693
Net annual recharge and interaction	15	0.0003	0.0216
Trends in net recharge and interaction	15	0.1194	0.0508
Geographical, altitudinal, and seasonal factors:			
Geographic coordinates and interaction	5	5.7×10^{-5}	3.7×10^{-5}
Surface elevation	1	0.7265	0.7477
Seasonality (sine + cosine of sampling date)	2	0.0583	0.1705
Groundwater abstraction factor:			
Trends in irrigation	1	0.0001	0.0044
Geo-interaction terms:			
Only geo-interaction terms	42	9.7×10^{-9}	0

Variations in hydrogeological conditions in the shallow aquifer are also attributed to heterogeneous distribution of the upper silt/clay (USC) unit. A non-parametric rank correlation (Spearman) between As concentrations and thickness of USC unit is -0.020 (p -value 0.47). Modelling results show an average multiplicative effect for USC thickness of -0.043 (LR test p -value 0.008) on the mean As concentration. Although no substantial difference is observed in the overall relationships between USC thickness and mean As concentrations the problem with the correlation is that it fails to account simultaneously for the multiplicity of drivers of As concentrations in groundwater. The other aspect of GRMs is that they enable us to predict the change in the response variable based on its

associations with the covariates. Model coefficient for the covariate USC indicates that when all other covariates remain unchanged a 1 m increase in the thickness of USC deposits may decrease the mean As concentration (national mean of 62.29 µg/L calculated from 1643 observations) by a factor of $\exp(-0.0427 \pm (2 \times 0.016))$ (see Table 5.4 for coefficients and standard errors) so that the mean As concentration is reduced by $4.2 \pm 3\%$.

Modelling results show that the effects of hydraulic properties of shallow aquifers alone on As concentrations are not significant in explaining As variations in groundwater. In spite of significant correlations (Spearman) of -0.21 , -0.26 , and -0.37 (p -values < 0.001 for all coefficients) respectively between As and hydraulic conductivity, specific yield, and Darcy flux, the modelling results show that their effects (considering simultaneously with other covariates) on As variations are not significant at the 5% level (see Tables 5.4 and 5.5 for the modelling results and LR test statistics).

The relationship between well depth and As concentrations is also not straightforward as it varies within geological units. Although the overall effect of depth is slightly negative (the coefficient for the main effect is -0.008 in Table 5.4), this covariate interacts with the geological units and hence the main effect coefficient cannot be considered in isolation. The effect of this covariate should be combined with the coefficient of its interactions with surface geology. The effect of these statistical interactions on As variability is described in detail in section 5.4.3.5.

5.4.2.2 Effects of Groundwater Dynamics and Recharge

Groundwater dynamics and recharge processes are represented by a total of six covariates in the model that have variable effects on the mean As concentration. Modelling results show that effects of groundwater table (i.e., dry and wet season groundwater tables) and annual fluctuations in groundwater levels on national-scale As variations are small. These covariates carry trivial weight or explanatory power (p -values > 0.2 ; not significant at the 5% level) to explain the national-scale variations of As in groundwater and their removal from the fitted model does not significantly affect the model performance (Table 5.5). Modelling results question previously reported statistically significant associations between groundwater levels and As concentrations based on correlation analysis and linear regression (Ravenscroft et al. 2005; Shamsudduha et al. 2009). This observation

further implies that, in the presence of other influential covariates, the effects of seasonal groundwater tables on the variation of As concentrations are insignificant.

Long-term (1985 to 1999) trends in mean groundwater levels have moderately significant (LR test p -value 0.091) negative effects on the variation of As concentrations in groundwater. This association suggests that, after adjusting for all of the other covariates considered, areas with declining trends in groundwater levels may experience overall decrease in groundwater As variations over time. Modelling results indicate that at two locations that are identical in all respects except that long-term annual mean groundwater levels at the second location are declining at the rate of 1 cm/year faster than at the first, one would expect the mean As concentration to be ~4% lower at the second site than at the first. However, there are areas in Bangladesh where dry-season groundwater levels are declining due to increased recent abstraction which is also increasing annual water-level fluctuations (see Chapter 2). Modelling result shows that mean groundwater fluctuations have a negative multiplicative effect (-0.446; LR test p -value 0.16) on the mean As concentration in groundwater. This indicates that 1 m increase in mean groundwater fluctuation can decrease the mean As concentration (62.29 $\mu\text{g/L}$) by a factor of $\exp(-0.446)$ or 0.64 (decrease by ~36%) when other covariates remain unchanged.

A moderately strong effect (LR test p -value 0.019) is observed between mean annual groundwater recharge and As concentrations with an interaction between mean recharge and surface geology. Importance of including the interaction with surface geology will be discussed in section 5.4.3.5. For the covariate recharge, the presence of interaction means that the effect of mean annual recharge on the mean As concentration must be interpreted as geology-specific. For example, a 1 mm increase in mean annual groundwater recharge within a particular geological unit (e.g., Chandina alluvium, see Figure 5.2) can decrease the mean As concentration by the following relationship when all other covariates are considered to remain unchanged:

$$\exp[-0.003 (\text{recharge}) + (-0.037 (\text{geology} : \text{recharge}))] = \exp(-0.04)$$

Exponentiated the value of -0.04 reports that the mean As concentration (mean 221.6 $\mu\text{g/L}$ within Chandina alluvium) can decrease by ~4%. In contrast, mean As concentration (65.5 $\mu\text{g/L}$) can however increase by ~3% in Marsh clay and peat geological unit with a 1 mm increase in mean groundwater recharge.

The effect of recharge trends on mean As concentration also varies between surface geological units. Contrasting to the effect of mean recharge, modelling results indicate that the mean As concentration may experience an increase with a corresponding increase in recharge trends within the Chandina alluvium where recharge conditions are moderate (mean recharge is 111 mm and recharge trend is 1.1 mm/year over a period of 1985 to 1999) compared to the national mean of net groundwater recharge of 238 ± 142 mm and mean of recharge trends of 2.9 ± 2.3 mm/year.

5.4.2.3 Geographical, Altitudinal and Seasonal Variations

Geographical coordinates (longitude and latitude), surface elevation (altitude) and sampling dates (seasonal variations in sampling) have significant effects on mean As variations at the national scale in Bangladesh. These space-time covariates capture any unexplained variability in As concentrations in addition to groundwater dynamics, recharge, geological, and hydrogeological variables. If these geographical coordinates (latitudes and longitudes), their polynomials, and the interaction term are dropped from the fitted model the p -value (3.7×10^{-5}) (see Table 5.5 for LR test statistics) suggests that the model cannot effectively capture the regional variability in As concentration. High As concentrations in groundwater are observed in lower latitudes but in higher longitudes in the country. According to adjusted LR tests (p -value 0.747), surface elevation is not an important covariate to explain the national-scale As variations in groundwater. However, previous studies (Shamsudduha et al. 2009) show that elevated is related to As concentrations in groundwater; areas in northern parts are less affected with As than low-lying floodplains and delta plains in southern parts of Bangladesh. Modelling results (LR test p -value 0.17) suggest that there are no considerable effects of the seasonality (sampling dates are used as a proxy variable) on the mean As concentration. A time-series record of groundwater As concentrations would, however, be necessary to validate this finding.

5.4.2.4 Effects of Groundwater Abstraction and Irrigation

Groundwater abstraction at the national scale is represented by long-term (1985-1999) groundwater-fed irrigation trends in water supplies in the fitted model. Irrigation trends are found as a strong covariate to explain groundwater As variations in Bangladesh. The main effect of irrigation trends on the mean As concentration in shallow groundwater is negative (coefficient of -0.098). The LR test statistics show that the inclusion of irrigation trends as a covariate in the model has a significant effect (LR test p -value of

0.004) (Table 5.5). The modelling result indicates that in an area where a persisting irrigation trend increases by 1 mm/year this can decrease the mean groundwater As concentration by a factor of $\exp(-0.098)$ or 0.91, which is equivalent to ~10% decrease in mean As concentration. For example, if groundwater-fed irrigation increases 15 mm over the next 15 years (i.e., trend 1 mm/year) over the Chandina alluvium, then the mean As concentration (221.6 $\mu\text{g/L}$) over that geological unit may decrease by 10%. Currently, low-As concentrations are observed (Figure 5.1) in north-central, northwestern, and western parts of Bangladesh where intensive groundwater-fed irrigation has been taking place since early 1970s to sustain the dry-season Boro rice cultivation (see Chapter 4).

5.4.2.5 Importance of Geological Interactions

In the modelling process, the significant interactions between surface geology and several covariates such as groundwater sampling depth, mean groundwater recharge and recharge trends, are of particular interest. The most significant statistical interaction is observed between surface geology and sampling depth of wells (LR test p -value <0.0001). The statistical interaction between surface geology and mean recharge is considerably significant (LR test p -value 0.019); and between surface geology and trends in recharge is merely significant (LR test p -value 0.048).

Adding an interaction term between geology and sampling depth as an extra predictor ensures that the fitted model captures the variable relationship between As and depth within different geological units. The interactions of mean groundwater recharge and recharge trends with surface geology reflect the geologically-dependent effects of recharge processes that mobilise groundwater As in shallow aquifers throughout Bangladesh. The combined effect of mean groundwater recharge on the log-mean As concentration varies from positive (0.026 in Marsh clay and peat unit) to negative (-0.039 in Chandina alluvium) based on its interaction with surface geology. These interesting interactions shed light on the actually physical processes that has been taking place within various geological deposits in the Bengal Basin. A possible explanation is that some geological units (sandy surficial deposits) favour greater groundwater recharge than others (clay-covered geology). Net recharge can be enhanced in geologically favourable locations by increasing groundwater-fed irrigation (discussed in Chapter 4) which, in turn, can flush out previously mobilised As from the shallow aquifer. In contrast, active flushing of groundwater As is expected to be much lower in areas where direct recharge can be inhibited by surface geology (e.g., deltaic silt, tidal deltaic deposits) and where

groundwater-fed irrigation is low. This forms the basis for testing some of the hypotheses previously proposed (Harvey et al., 2002; Harvey et al., 2006; Klump et al., 2006; Stute et al., 2007) from localised studies to explain As mobilisation in shallow groundwater in Bangladesh. The next chapter applies the GRM to validate the principal assumptions of these As-hypotheses on the national scale.

5.5 Summary and Conclusions

In this chapter, generalised regression models (GRMs) are developed for explaining the national-scale variability in groundwater As concentrations in shallow aquifers in Bangladesh using information from several covariates that represent important geological and hydrogeological processes. This study demonstrates that such robust statistical models can address several critical features of the highly variable As dataset and can be applied for modelling other environmental variables where datasets feature (i) highly skewed distribution, (ii) non-detect (e.g., censored) observations, and (iii) inter-site dependence between the neighbouring spatial sites. The GRMs have the ability to examine the simultaneous effects of multiple covariates on the response variable (As in this study) and can detect a number of physically convincing associations. The ability of GRMs to model the combined effects by including interaction terms is an interesting feature that allows the complex structure of the dataset to be examined.

The fitted (calibrated) GRM shows the effect of predictor covariates and their interactions on the variation of As concentrations in groundwater. Although the calibrated GRM is deliberately overparameterised and includes factors that are not statistically significant, its good predictive performance with the validation dataset shows the reproducibility of the modelling results. In addition to the validation test, a number of other effective but relatively simple model checks have been applied to test (1) the distributional assumption of the GRM, and (2) the explained structure in the As dataset using model residuals. Individual simpler models (nested within the fitted model) were developed to check the statistical significance of predictor variables using the likelihood ratio tests that are adjusted for the inter-site spatial dependence.

Modelling shows that surface geology and surficial silt/clay (USC unit) covers explain ~33% of the total variability in groundwater As concentrations. In contrast, hydrological properties of aquifers (e.g., hydraulic conductivity, specific yield, Darcy flux) do not seem to have much effect on the variation in As concentrations. Groundwater

level dynamics represented by mean annual fluctuations and temporal groundwater-level trends can explain ~12% variability in As concentrations. Surface geology, groundwater dynamics, recharge processes and their statistical interactions with geology, in concert, can explain ~44% of the regional-scale variability in As concentrations.

The GRM also has the ability to predict changes in the response variable with corresponding changes in the covariates. Considering the interaction effect with surface geology the modelling results show that an increase in mean annual recharge by 1 mm can decrease the mean As concentration over most of the geological units by 0.1% to 4%. The effect of irrigation trends on the mean As concentration is very strong: an increase of a persisting irrigation trends by 1 mm/year can decrease the mean As concentration by approximately 10%. These findings clearly support the notion that groundwater-fed irrigation that effectively induces actual groundwater recharge to shallow aquifers can flush out the previously mobilised As from the system.

GRMs clearly demonstrate the ability to examine complex structure in groundwater As dataset and partition the total variance of As concentrations into a number of physically convincing hydrogeological processes. However, there is one issue that has not been addressed in this modelling exercise which is collinearity in covariate datasets. Collinearity is a statistical phenomenon in which two or more covariate datasets are highly correlated (Chandler and Scott 2011). Although collinearity does not reduce the global predictive capacity of the model the estimated coefficient may change erratically for the highly correlated covariates. Collinearity can be a critical issue in environmental fields where variables are generally highly correlated. This issue will be addressed in the future work.

Chapter 6

Testing Arsenic Mobilisation Hypotheses

Applying generalised regression models at the national-scale, this chapter tests the principal assumptions of some of the credible yet contradictory local-scale hypotheses on the mobilisation of groundwater As in shallow aquifers in the Bengal Basin.

6.1 Introduction

Generalised regression models (GRMs) developed in the previous chapter to explain the national-scale variations in groundwater As concentrations in shallow aquifers in the Bengal Basin are applied here to test the validity of current hypotheses for the mobilisation of As in groundwater. Each hypothesis (see Figure 1.3 in Chapter 1) derives from localised studies where background As concentrations are high (Harvey et al. 2002; McArthur et al. 2004; Harvey et al. 2006; Meharg et al. 2006; Stute et al. 2007), and is based on observations of spatial and vertical variations in groundwater As concentrations and their associations with several hydrogeological factors. The local nature of these studies makes it difficult to generalise the proposed mechanisms with confidence, and no national-scale evaluation of the underlying assumptions has yet been carried out.

This chapter first provides a detailed review of As-mobilisation hypotheses and their inherent operating assumptions regarding the hydrogeological factors controlling the variability in As concentrations in shallow groundwater. Secondly, for each hypothesis a set of testable hydrodynamic mechanisms is derived that are directly or indirectly linked to the mobilisation process of groundwater As. The comprehensive GRM of the previous chapter can be used to test the consistency of these mechanisms with the observed pattern of As concentrations, by carrying out formal comparisons of the comprehensive model with simpler versions in which hydrodynamic components are removed if they are irrelevant under the hypothesis being tested.

6.2 Groundwater As Mobilisation in Bangladesh

6.2.1 Distribution of As and Proposed Mobilisation Hypotheses

Since the detection of elevated As in groundwater from the 1990s, a large number of studies in Bangladesh and the neighbouring Indian state of West Bengal, have focused on the bio-geochemical aspects of As occurrence and mobilisation (Bhattacharya et al. 1997; Nickson et al. 1998; BGS and DPHE 2001; Ahmed et al. 2004; Swartz et al. 2004; Saunders et al. 2005; Zheng et al. 2005; Harvey et al. 2006; Metral et al. 2008). Although, chemical weathering and dissolution of some detrital minerals (e.g., biotite) also contribute to As in groundwater (Shamsudduha 2007a; Seddique et al. 2008), most investigators agree that As is mobilized in shallow groundwater by the biogenic reduction of Fe-oxyhydroxides (Nickson et al. 2000; Islam et al. 2004; Saunders et al. 2005; Zheng et al. 2005). Reducing conditions at shallow depths (<100 m) are, however, widespread in the alluvial aquifers throughout Bangladesh (BGS and DPHE 2001) and unable to explain observed variability in As concentrations in groundwater (Burgess et al. 2002; van Geen et al. 2003b).

The spatial distribution of As concentrations in Bangladesh shows (see Figure 1.3 in Chapter 1) regional-scale variability that is generally attributed to surface geological features (BGS and DPHE 2001; Ahmed et al. 2004). At the national scale, the variability in As concentrations within these broad geological units are, however, relatively small. Surface geology also controls the distribution of the alluvial aquifers in the Bengal Basin that are also known as the “Holocene aquifers”; these refer to young and shallow aquifers that are commonly found in delta plains, major river floodplains, and alluvial fan areas in the Bengal Basin (Ravenscroft et al. 2005). The vertical profile of As with increasing depth in the aquifer is sometimes characterised as being bell-shaped with highest As concentrations are generally observed between 20 and 40 m below ground surface (BGS and DPHE 2001; Harvey et al. 2006). However, this is not always the case in practice, particularly when depth profiles of As concentrations are examined at single locations (multi-level monitoring wells) (Dhar et al. 2008; McArthur et al. 2008; Metral et al. 2008; Hoque 2010) as well as within most of the surface geological units (Figure 6.1). The depth profile of As in the most affected geological unit in Bangladesh (Chandina alluvium, “ac”), however, resembles a bell-shaped profile where As concentration peaks out at a depth of 20 mbgl but decreases downward. As concentrations in the deltaic

deposits (“dt”) show a similar but wider profile where peak As concentrations occur at a depth around 35 mbgl. Interestingly, the As-depth profiles in the alluvial silt and clay (“asc”) unit show the highest As concentrations to occur at very shallow depths (~10 mbgl) and then decrease with increasing depth. Within the Marsh clay and peat (“ppc”) deposits, the As-depth profile reveals multiple modes in peak As concentrations (e.g., ~25 and ~90 mbgl). As concentrations within the alluvial fan deposits (“afo” and “afy”) are consistently lower than 50 µg/L. Finally, the relatively older and deeper aquifers (i.e., “rb” and “rm” deposits of the Pliocene-Pleistocene age), which are the main aquifers located beneath the north-central Madhupur clay and north-western Barind clay deposits, are primarily As-free (Ahmed et al. 2004; Shamsudduha and Uddin 2007). A range of hypotheses including geological heterogeneity, aquifer hydraulics, groundwater dynamics, and recharge processes have been proposed to explain the bell-shaped depth profile of As concentrations in both national and local scale studies (BGS and DPHE 2001; McArthur et al. 2004; Ravenscroft et al. 2005; Harvey et al. 2006; Klump et al. 2006; Neumann et al. 2010).

Based on observations at one location in Sreenagar Thana of Munshiganj District in south-central Bangladesh (area ~12 km²) in south-central part of Bangladesh (H1 in Figure 1.3), Harvey et al. (2002; 2006) proposed that the bell-shape depth profile results from the downward transport of organic carbon (OC) from ponds, rivers or irrigated rice fields as a result of irrigation return flows and localized recharge. This “young carbon hypothesis” (Figure 6.2a) asserts that the flushing of OC from surface sources into shallow aquifers provides reducing agents that mobilise As bound to Fe-oxyhydroxides (Harvey et al. 2006). Arsenic is also mobilised from Fe-oxides under anoxic conditions which coincide with periods of recharge when irrigation return-flows transport As into aquifers (Polizzotto et al. 2005; Harvey et al. 2006). This mechanism has, however, been challenged by several authors (Aggarwal et al. 2003; van Geen et al. 2003a). With respect to irrigation, recent studies in south-central and central Bangladesh (H1, H2, and H3 in Figure 1.3 in Chapter 1) show that the residence time of As-contaminated groundwaters at shallow depths (10-30 m bgl) is 30-55 years and hence that these groundwaters predate the main period of shallow (<100 m) groundwater-fed irrigation in most parts of Bangladesh (Klump et al. 2006; Stute et al. 2007) which started during the 1980s (World Bank 2005). Moreover, the role of pond water in mobilising As is challenged by others (Sengupta et al. 2008) who provide evidence from a study site (area ~1.2 km²) in West Bengal (H4 in Figure 1.3) that pond water and groundwater are geochemically distinct.

Ponds are not therefore considered to contribute sufficient OC to shallow aquifers to drive the microbially mediated reduction of Fe-oxyhydroxide minerals and mobilisation of As in groundwater.

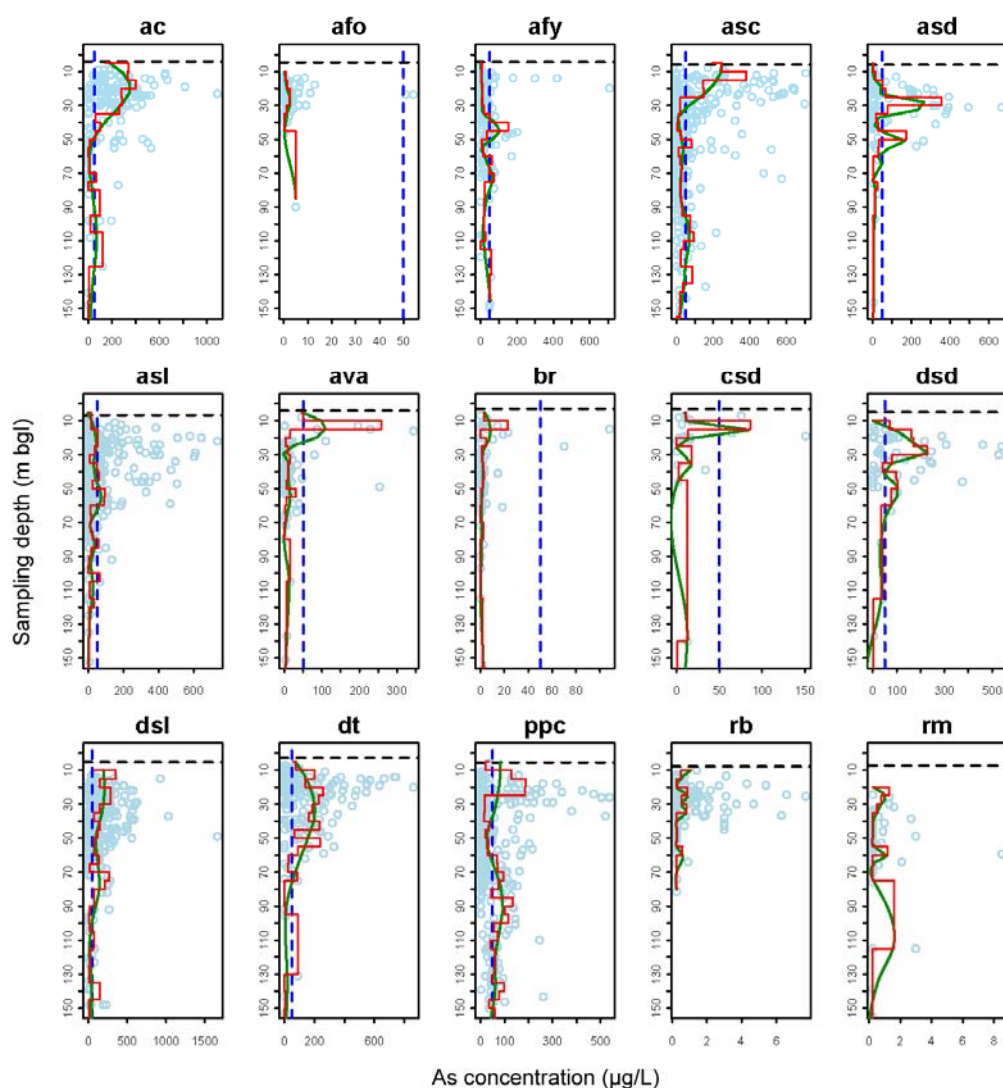


Figure 6.1 Dependence of groundwater As concentration upon depth below ground level, grouped by surface geological units in Bangladesh. In each panel, blue circles are individual As data points (NHS As data); step-wise red lines are the 75th percentile values in each 5-m bin of sampling depth; green lines are the Lowess smooth line; vertical, dashed blue lines represent Bangladesh As standard; and horizontal, dashed black lines are the mean dry-season groundwater table in each geological units (see Figure 5.2 for detailed names and locations).

Several alternative sources of OC to drive the reduction of Fe-oxyhydroxides and mobilisation of As in groundwater have been proposed. The “As-peat hypothesis” (Ravenscroft et al. 2001; McArthur et al. 2004; Ravenscroft et al. 2005) contends that OC is leached from peat deposits which are widespread and abundant in Holocene sediments of the Bengal Basin (Umitsu 1993; Goodbred and Kuehl 2000). Higher As concentrations in groundwater coincide with the presence of peat layers indicated by borehole lithologies (BGS and DPHE 2001). Rather than having been leached from peat, a study (Meharg et

al. 2006) proposed that OC was codeposited with As and provide evidence from core samples from four regions in Bangladesh (H5 in Figure 1.3). Meharg et al. (2006) also challenge the “young carbon hypothesis” showing that elevated As and OC occur in surficial sediments in the Sundarbans mangrove of south-western Bangladesh (Figure 1.3) where there is no groundwater abstraction for irrigation. In support of their “As-OC codeposition hypothesis”, Meharg et al. (2006) show that As concentrations in the Holocene aquifers are low ($< 50 \mu\text{g/L}$) where sediments are relatively depleted in OC.

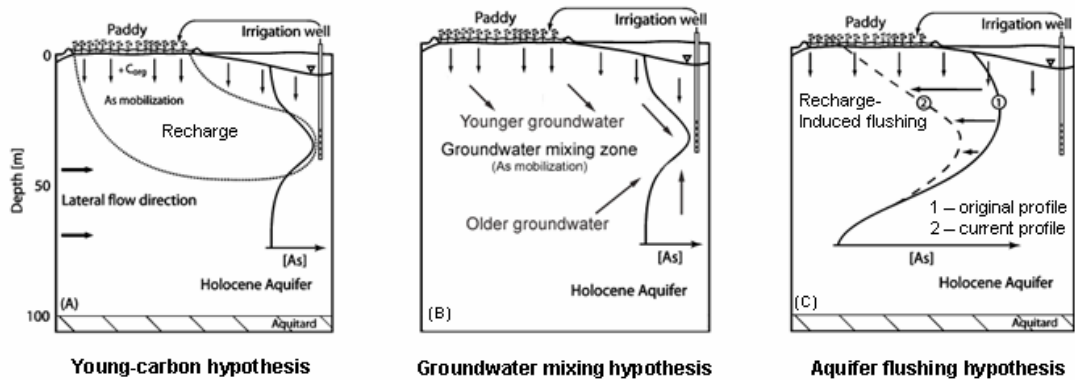


Figure 6.2 Schematic diagrams of different hypotheses on the mobilisation of As in groundwater: (a) young carbon hypothesis (H-1), (b) groundwater mixing hypothesis (H-2), and (c) aquifer flushing hypothesis (H-3). Diagrams were modified from Klump et al. (2006).

Yet another study (Klump et al. 2006) proposed a hydrodynamic model (“groundwater mixing hypothesis”) (Figure 6.2b) to explain As mobilisation in shallow groundwater. Using environmental tracers and numerical models at a site (H2 – the same study site of H1 in Figure 1.3), they observe that highest As concentrations occur at depths of around 30 mbgl where young groundwater (5-40 years) is believed to mix with older (>55 years) groundwater as a result of convergent flow induced by intensive abstraction of shallow irrigation wells at depths of 40 to 50 mbgl. In their study area, the average As concentration is $277 \mu\text{g/L}$ (based on NHS As data) and about 45% of the total area was irrigated during 2002 (BADC 2003; Harvey et al. 2006). According to this “groundwater mixing hypothesis”, As is mobilised by increased hydraulic gradients driving groundwater flow in shallow aquifers caused by intensive abstraction (over last 20-30 years) for irrigation during the dry season. However, Klump et al. (2006) provide no explanation for the release of As (i.e., how does mixing of young and old groundwaters or flow paths relate to the geochemical release of As in the aquifer). They speculate that peak As concentrations result kinetically from the mixing of shallow, young groundwater and deeper, older groundwater where they observe the greatest range in the mean residence times of groundwater. This hypothesis is inconsistent with evidence

of lower As concentrations in north-western and north-central areas of Bangladesh where more intensive groundwater abstraction for irrigation (50-90% of the total area) has lowered dry-season groundwater levels in shallow aquifers over the last 20-30 years (Ravenscroft et al. 2005; Meharg et al. 2006)

Over an area (~25 km²) in Araihasar Thana of Narayanganj District in central Bangladesh (H3 in Figure 1.3), Stute et al. (2007) propose another hydrodynamic model based on their observations that: (i) groundwater most affected by dry-season irrigation has the lowest As concentrations, and (ii) As concentrations correlate positively with groundwater residence time (19 µg/L/year, $R^2=0.83$) in very shallow groundwater (<20 mbgl). Intense irrigation is believed to decrease aqueous As concentrations due to active recharge and vigorous flushing of aquifers (BGS and DPHE 2001; McArthur et al. 2004; Ravenscroft et al. 2005; Stute et al. 2007; van Geen et al. 2008). The positive correlation between As concentrations and groundwater residence times suggests that either the kinetics of As mobilisation or its removal through abstraction (i.e., recharge, induced by abstraction, reduces groundwater residence times) controls observed variations in As concentrations in very shallow aquifers (Stute et al. 2007). This “aquifer flushing hypothesis” (Figure 6.2c) is consistent with the evidence showing that older tubewells commonly contain higher concentrations of As and discharge from groundwater-fed irrigation wells has lower As concentrations (van Geen et al. 2003b; Burgess et al. 2007).

6.2.2 Hydrodynamic Components of the As-hypotheses

A common limitation to each of the hypotheses presented above and summarised in Table 6.1 is that they were developed from localised observations (see Figure 1.3 in Chapter 1) and have not been rigorously tested beyond this scale. Each study suffers from the problem of sampling bias as conceptual models were generated and tested in the study sites where background As concentrations are generally high (>50 µg/L) (see Figure 1.3 and Table 6.1). GRMs are developed (Chapter 5) to test the viability of each hypothesis to explain the variability of As concentrations in the Bengal Basin of Bangladesh. First, an assertion from each hypothesis is derived that is testable using this GRM. Since the testable As-hypotheses (H-1, H-2, and H-3) all assume specific hydrodynamic conditions (see Table 1.1 in Chapter 1), this can be done by synthesising each one in the light of the implied groundwater dynamics, hydrogeology, and recharge processes.

H-1 (Young carbon hypothesis) argues that re-infiltrated irrigation water (indirect recharge) and direct recharge via ponds mobilise As in groundwater by delivering OC to the shallow aquifers. If this hypothesis applies at the regional scale, positive associations should necessarily be observed between elevated As concentrations ($>50 \mu\text{g/L}$), increased groundwater-fed irrigation and increased net recharge regardless of the variation in surface geology.

H-2 (Groundwater mixing hypothesis) proposes that intense abstraction for irrigation induces mixing between younger and older groundwaters at depths of around 30 mbgl that causes As mobilisation in shallow aquifers. According to this hypothesis, elevated As concentrations ($>50 \mu\text{g/L}$) should be positively associated either with a declining trend in the long-term groundwater levels or increased annual fluctuations in groundwater levels where the shallow aquifers are fully replenished each year during the monsoon season. Since increased groundwater-fed irrigation is likely to accelerate groundwater mixing at depth, H-2 also suggests a positive association between irrigation and groundwater As in areas of elevated As concentrations.

In complete contrast to H-1, hypothesis H-3 (Aquifer flushing hypothesis) holds that increased net recharge to shallow aquifers induced by the intensive irrigation, reduces groundwater residence times and decreases As concentrations. This would imply that greater groundwater recharge to shallow aquifers over the period of 20-30 years (period of intensive groundwater-fed irrigation) should be associated with reduced As concentrations throughout Bangladesh.

Hypotheses, H-4 (As-peat hypothesis) and H-5 (As-OC codeposition hypothesis) do not possess any direct hydrodynamic component to test using the GRM formulated previously. These geologically-dependent hypotheses, however, imply that As concentrations in shallow groundwater are generally low ($<50 \mu\text{g/L}$) in the areas of intensive irrigation for dry-season rice cultivation. H-4 and H-5 have previously been verified at regional scales in Bangladesh (Ravenscroft et al. 2005) using correlation or linear regression analysis. For H-4, negative correlations are observed between groundwater As concentrations and recorded maximum depths to water table (bgl) between 1961 and 1993 in 309 Thana (third administrative unit) in Bangladesh by Ravenscroft et al. (2005). Furthermore, they note a negative correlation between groundwater As concentrations and percentage of irrigated areas by groundwater during 1996 in 340 Thana. Although the fitting of linear regression is weak ($R^2 < 0.2$) in both of

these analyses, the relationships are reported statistically significant at the 99.99% ($p < 0.001$) level. There are, however, several limitations to these approaches: (i) maximum recorded depths to water-table at different locations in Bangladesh were measured at different times between 1963 and 1993 which do not necessarily account for the long-term trends of groundwater levels indicative to increased abstractions for groundwater-fed irrigation; and (ii) simple linear regression cannot assess the simultaneous effects of multiple factors.

Table 6-1 Summary of mean As concentration, surface geology, and other hydrogeological parameters estimated over the localised hypothesis sites (H-1, H-2, and H-3) from the national datasets (used in this study) and independent datasets (derived from local studies).

Predictor covariates	Study area (H-1 and H-2)		Study area (H-3)	
	This study*	References [†]	This study*	References [‡]
Mean As concentration ($\mu\text{g/L}$)	277	290	74	96
Geology and hydrogeological factors:				
Surface geology	asc, asl	asc, asl	asl, asd	asl, asd
USC unit (m)	9.2	3.5 – 10	16.5	4.0 – 10.0
Hydraulic conductivity (m/day)	26	29	16.0	17.0
Specific yield	~0.04	0.01 – 0.02	~0.03	n.a.
Darcy flux (cm/day)	1.4	1.2 – 2.3	1.6	n.a.
Well depth (m bgl)	43	48	25	18 – 20
Groundwater dynamics and recharge factors:				
Dry-season GWT (m bgl)	5.4	~4.5	4.5 – 5.0	~3.8
Wet-season GWT (m bgl)	0.7	0 – 0.5	0.5	0 – 0.5
Trends in mean GWL (cm/year)	0.33	n.a.	-2.4	n.a.
Mean groundwater fluctuation (m)	4.5	~4.0	3.8	~4.0
Mean annual recharge (mm)	198	~250	195	230 – 448
Mean recharge trends (mm/year)	2.8	n.a.	2.0	n.a.
Altitudinal factor:				
Surface elevation (m msl)	3.5	3.5 – 4.5	4.5	5 – 6.5
Groundwater abstraction factor:				
Irrigation trends (mm/year)	3.2	increased ⁺	5.5	increased ⁺

* values of factors extracted at each hypotheses site are collated or estimated from the national-scale database used in this study for statistical modelling.

[†] values of factors collated from a number of studies in the H-1 and H-2 hypotheses site: Harvey et al. (2002; 2006), Swartz et al. (2004), Klump et al. (2006), and Neumann et al. (2010).

[‡] values of factors collated from a number of studies in the H-3 hypothesis site: van Geen et al. (2003b), Zheng et al. (2005), Stute et al. (2007), and Aziz et al. (2008).

+ studies indicated an overall increase in groundwater-fed irrigation (for dry-season Boro rice cultivation) in and around the study sites but not quantified.

6.3 Statistical Models for Hypothesis Testing

The As mobilisation hypotheses discussed here were not proposed as statistical models that can be readily tested using the GRMs developed in this study. However, the primary mechanism(s) discussed in these hypotheses can be represented by several hydrogeological factors that are represented directly in the fitted GRM from Chapter 5, known here as the full or comprehensive model. Simpler GRMs consisting of single or multiple factors representing geological and hydrogeological processes are nested within the full model. The importance of the various factors can thus be checked by comparing the full and reduced (simpler) GRMs using likelihood ratio (LR) tests, appropriately adjusted for inter-site dependence as discussed previously (Chapter 5).

A total of 12 simplified GRMs have been tested against the full GRM. A summary of the test statistics and statistical significance of each test is given in Table 6.2. These results show that dropping of some terms can significantly reduce the predictive capacity of the model whereas for other terms there is no significant change. The hydrogeological interpretation of this test is that when a particular covariate or a group of covariates are found to be critical for the model, the corresponding hydrogeological factors carry substantial weight to explain the variability in As concentrations in groundwater. For example, the most important factors in the model (model1 in Table 6.2) are the surface geology and its interactions with depth, groundwater recharge, and trends in net recharge. A *p*-value of close to zero implies that the null hypothesis is rejected and the covariates in the fitted GRM can explain the variations in As concentration in shallow aquifers of Bangladesh. In fact, surface geology and its interactions alone can explain ~43% of the national-scale variance in groundwater As concentrations (see Chapter 5). In contrast, adjusted LR test statistics show that aquifer's hydraulic conductivity, specific yield, and Darcy velocity are the least important factors (see model 6 in Table 6.2).

6.4 Discussion

6.4.1 Validity of the Current As-hypotheses

The As mobilisation hypotheses discussed here were proposed based on observations of groundwater geochemistry and local hydrogeological conditions but disregard the critical influence of large-scale hydrogeological features (e.g., surface geology) on the variability of As in shallow aquifers. Inferences and causal links were made based on simple

bivariate or multivariate associations in most cases that failed to unfold the simultaneous effects of multiple covariates on groundwater As variations. Modelling results enable us to examine which of these hypotheses originated from highly localised studies hold to explain the large-scale variability of As mobilisation in the Bengal Basin.

Table 6-2 Adjusted likelihood ratio (LR) test statistics of simplified models nested within the full model after systematically dropping terms that represent groundwater dynamics, geological, hydrogeological, groundwater recharge processes, and groundwater-fed irrigation. Results show the level of significance of each covariate or a group of covariates after dropping from the fitted model. Any p -values less than 10^{-10} are reported as zero. DF means degree of freedom.

Model number	Terms deleted	Degrees of freedom (current)	p -value
0*	None	-	-
1	Surface geology and all geo-interaction terms	20	0
2	Surface geology, upper silt/clay (USC) unit and all geo-interaction terms	21	0
3	Upper silt & clay (USC) unit	77	0.009
4	Only geo-interaction terms (sampling depth, mean recharge, and recharge trends with geology)	36	0
5	Surface geology, USC unit, and hydrodynamic covariates, and all geo-interaction terms	16	0
6	Hydraulic conductivity, specific yield, and groundwater Darcy flux	75	0.442
7	Dry-season groundwater table, wet-season groundwater table, and surface elevation	75	0.603
8	Mean recharge, recharge trends, groundwater level trends, geo-interactions with mean recharge and recharge trends	19	0
9	Mean recharge and interaction between mean recharge and surface geology	63	0.019
10	All groundwater dynamics factors and related recharge processes	44	0
11	All geographical and seasonal factors and surface elevation	71	3.9×10^{-08}
12	Groundwater-fed irrigation (irrigation trends)	77	0.004

Note: Model0 is the full, fitted model that has been tested against the null model without any covariates.

Modelling results show that the effects of surface geology and its interactions with depth and mean recharge on the variation of groundwater As are the most critical. Results show overall negative effects of groundwater-fed irrigation, mean recharge and groundwater levels trends on the As variation. These observations suggest that the principal assumptions for the young carbon hypothesis, which links increased

groundwater-fed irrigation with greater mobilisation of As in shallow aquifers, do not hold to explain the variability in As concentrations throughout Bangladesh. This hypothesis suggests that there should be positive associations between mean recharge, groundwater-fed irrigation and As concentrations; these associations are not also supported by the modelling results. Indeed, the modelling shows that the mean As concentration in groundwater can decrease by ~10% if a persisting irrigation trend increases by 1 mm/year when other covariates remain unchanged. Greater mean groundwater recharge rates are observed in areas of low As concentrations in shallow aquifers throughout the country. Supporting the idea of pumping-induced greater recharge, the groundwater mixing hypothesis suggests that increased recharge induces convergent groundwater flow to the depth of greater abstraction (~30 mbgl) which mixes the shallow, young groundwater with the deeper, older groundwater and subsequently mobilises As. Greater increases in mean annual recharge are observed as a result of intensive groundwater abstraction for the dry-season irrigation (see Chapter 4) but higher recharge is not observed to be associated with high As concentrations; the relationship between net groundwater recharge and As concentrations however varies between geological units in Bangladesh.

Further evidences of inverse relationship between groundwater-level trends and As concentrations (declining trends are associated with low As concentrations) negate the critical hydrodynamic assumptions of both young carbon and groundwater mixing hypotheses to explain the national-scale As variability in shallow groundwater. In contrast, all these findings are largely in favour of the aquifer flushing hypothesis (McArthur et al. 2004; Ravenscroft et al. 2005; Stute et al. 2007; van Geen et al. 2008) which can explain the national-scale As variations in shallow groundwater.

The mechanism of the aquifer flushing hypothesis involves removal of As from aquifer sediments and water by active groundwater recharge and flushing. Active recharge to aquifers can dilute previously mobilised As over time (McArthur et al. 2004); areas of greater mean annual recharge to shallow aquifers coincides with low-As areas. Further evidence is provided by a recent study in three geologically different regions in Bangladesh (van Geen et al. 2008) where mean As concentrations are 6 µg/L, 96 µg/L, and 500 µg/L, respectively. They propose that the regional-scale spatial distribution of groundwater As reflects the differential flushing of shallow aquifers by active recharge which varies due to surface geology (i.e., grain size of sediments) and hydrogeological

properties. It is observed in the present study that the effect of mean recharge on the variation of As in groundwater largely depends on surface geological conditions and recharge alone does not explain the national-scale variability in As concentration. Another implication is that further increases in net recharge due to continuing abstraction for dry-season irrigation can flush out more As from shallow aquifers but this process may build up As accumulations in soil and food grains in future (Saha and Ali 2007).

6.4.2 Performance of GRMs at Localised Scales

It is necessary to check how the national-scale GRM effectively represents groundwater As concentrations and hydrogeological variables of the localised study areas reported by authors of As-mobilisation hypotheses (Harvey et al. 2006; Klump et al. 2006; Stute et al. 2007). Dominant surface geology, mean As concentration, and hydrogeological variables are summarised in Table 6.1. Average values of the covariate datasets used in this national-scale study compare well with that of reported by the localised studies. Mean As concentration (290 $\mu\text{g/L}$) derived from independent observations within the same study site of both young carbon and groundwater mixing hypotheses compares well with the mean As concentration of 277 $\mu\text{g/L}$ estimated from the NHS As dataset (BGS and DPHE 2001). Similarly, the mean As concentration of 96 $\mu\text{g/L}$ in the site of aquifer flushing hypothesis is comparable with 74 $\mu\text{g/L}$ derived from the national As dataset. Similarly, surface geology, groundwater and hydrogeological parameters, and mean annual recharge derived from the national dataset (used in this study) and independent observations made within the localised study areas are comparable. This implies that datasets used in this study to develop the national-scale GRMs are suitable to represent the average conditions of surface geology, hydrogeology, and groundwater As concentration in the localised study sites.

Multi-site models capture well the overall structure of groundwater As concentrations at the national-scale but may experience uncertainties. The main sources of uncertainties in the spatial models are (1) unexplained variations in groundwater As concentration itself, (2) errors in the geographic coordinates of the As observation dataset, (3) estimation of covariate datasets (spatial point data), (4) interpolation of covariate datasets (smooth gridded data), (5) collation of covariate datasets at the location of As observations through spatial joining or extraction methods, and (6) delineation and accuracy of the surface geological units in Bangladesh. The unexplained variability in As concentrations and predictability of the fitted model can be improved by incorporating

time-series records of As and covariate datasets. Improved models can be tested at regional to local scales if groundwater As observations and covariate datasets can be compiled with reasonable density and accuracy.

6.5 Conclusions

The principal assumptions underlying several hypotheses on the mobilisation of As in shallow groundwater in Bangladesh have been tested using national-scale generalised regression models that simultaneously examine the effects of geology and hydrogeological variables on As concentrations. Modelling reveals that the young carbon and groundwater mixing hypotheses do not appear to hold the national-scale As variability in shallow groundwater with their hydrodynamic assumptions. Observations of negative associations between mean groundwater recharge, and trends in groundwater-fed irrigation, and As concentrations offers possible explanations of the spatial, national-scale variation of As concentration which are aligned with the principal assumptions of the aquifer flushing hypothesis. Statistical modelling also highlights the critical, simultaneous effects of surface geology and its interactions with mean groundwater recharge in explaining the spatial variability of As in groundwater. Hypotheses on the mobilisation of As in groundwater which ignore these critical effects are not able to explain the national or basin-scale variation in groundwater As concentration.

Chapter 7

Conclusions and Future Directions

7.1 Summary and Conclusions

This thesis, for the first time, characterises the national-scale shallow groundwater dynamics in Bangladesh using a newly compiled groundwater level time-series records from a network of 1267 monitoring stations. Using robust statistical techniques this study characterises the trends and seasonality in the shallow groundwater levels and maps areas of declining and rising groundwater levels in Bangladesh. Changes in the shallow groundwater storage from ground-based observations have been tested against new, satellite observations under GRACE (Gravity Recovery and Climate Experiment) satellite data. This thesis also provides new estimates of net groundwater recharge to shallow aquifers in Bangladesh and reveals that intensive groundwater-fed irrigation since the early 1970s has greater impacts on net recharge. New insights into groundwater dynamics, recharge processes, and irrigation help us better understand the spatial variability in groundwater As mobilisation in shallow aquifers. Using advanced statistical modelling techniques this study examines the simultaneous effects of geology and hydrogeological factors on groundwater As variations at the national-scale and evaluates the principal assumptions of a range of hypotheses proposed to explain As mobilisation. Statistical modelling results reveal that the primary assumptions of the “young carbon” and “groundwater mixing” hypotheses are unable to explain the national-scale variability in As concentrations in shallow groundwater. Inverse associations between As concentrations in shallow groundwater and both mean annual recharge and trends in groundwater-fed irrigation suggest that As has been actively flushed from the shallow aquifer as a result of recently increased net recharge induced by intensive dry-season irrigation in Bangladesh. Conclusions are based upon a detailed examination of shallow groundwater dynamics and their influences on As mobilisation in the Bengal Basin.

7.1.1 Conclusion 1: Shallow Groundwater Dynamics

Seasonality dominates the observed variance in shallow groundwater levels; rapidly declining trends in groundwater levels are recently observed in areas of intensive groundwater abstractions whereas steadily rising trends are observed in coastal areas associated with sea-level rise.

Despite reports on rapidly declining groundwater levels in areas of intensive groundwater abstractions for urban and irrigation water supplies in Bangladesh this is the first, systematic national-scale investigation of the spatio-temporal trends in groundwater levels. One of the reasons is the lack of a well-structured, national database of groundwater levels although monitoring of weekly groundwater levels has been conducted by the Bangladesh Water Development Board (BWDB) since the early 1970s. Construction of a national groundwater-level database is one of the major contributions of this thesis. The database consists of approximately 1.8 million weekly records of groundwater-levels compiled from a network of 1267 monitoring stations throughout Bangladesh. Upon construction of the database this study has resolved long-term (1985 to 2005) trends and seasonal components in groundwater levels in Bangladesh applying a nonparametric seasonal-trend decomposition (STL) procedure. Seasonality dominates observed variance in groundwater levels but declining groundwater levels (>1 m/year) are detected in urban and peri-urban areas around Dhaka as well as in north-central, northwestern, and southwestern parts of the country (0.1 to 0.5 m/year) where intensive abstraction of groundwater is conducted for dry-season rice cultivation. Rising groundwater levels (0.5 to 2.5 cm/year) are observed in the estuarine and southern coastal regions. This novel application of the STL procedure reveals, for the first time, the unsustainability of groundwater-fed irrigation supplied by shallow aquifers in some areas in Bangladesh and the hydrological impact of seawater intrusion of coastal aquifers associated with sea-level rise. These findings may provide important insight into the hydrological impacts of groundwater-fed irrigation and sea-level rise in other Asian Mega-Deltas where groundwater monitoring data are limited.

7.1.2 Conclusion 2: Changes in Groundwater Storage

Groundwater storage in shallow aquifers of Bangladesh is declining as a result of intensive abstraction; magnitudes of recent trends (2003 to 2007) are much greater than the long-term (1985 to 2007) trends.

Groundwater storage changes (ΔGWS) in shallow aquifers of Bangladesh have been estimated for two periods: recent (2003 to 2007) and long-term (1985 to 2007) using observed groundwater levels and GRACE satellite-derived records of terrestrial water storage (ΔTWS). This study (1) validates GRACE-derived changes in ΔGWS in the highly seasonal Bengal Basin, and (2) provides estimates of ΔGWS changes. Results show that GRACE satellite measurements correlate well ($r > 0.8$, p -value < 0.0001) with in-situ borehole records from a network of 236 monitoring stations in Bangladesh. It has been feasible to partition the ΔTWS into groundwater, surface water, and soil moisture storages in the Bengal Basin. Surface water storage (river and flood water storage) estimated from a network of 298 river gauging stations explains 25% of the total variation in ΔTWS and is, thus, critical to the resolution of ΔGWS from GRACE data. Soil-moisture data derived from simulated Land Surface Models (LSMs) and observed groundwater-storage fluctuations explain 37% and 38% of the total variation in GRACE TWS respectively. The rate of GWS depletion observed from groundwater levels using a spatially distributed storage coefficient ($-0.75 \text{ km}^3/\text{year}$) is slightly less than the range of estimates (-0.98 to $-1.53 \text{ km}^3/\text{year}$) derived from GRACE data. The recent (2003 to 2007) estimates ($-0.75 \text{ km}^3/\text{year}$) are substantially greater than the observed, long-term (1985 to 2007) trends in GWS depletion ($-0.28 \text{ km}^3/\text{year}$) and are explained primarily by continued increases in groundwater-fed abstraction for the dry-season irrigation and public water supplies over the last two decades.

7.1.3 Conclusion 3: Net Recharge to Shallow Aquifers

Net groundwater recharge to shallow aquifers has increased in areas of intensive groundwater abstraction for dry-season irrigation and urban water supplies.

Estimates of national-scale net (actual) groundwater recharge to shallow aquifers and their long-term trends are not available in Bangladesh. Previous studies estimated potential groundwater recharge which mirrors annual rainfall in the country. This study provides the first, national-scale estimation of net (actual) groundwater recharge over the entire Bangladesh and compares with previously estimated potential recharge. Over a substantial period (1975 to 2007) during which groundwater abstraction increased dramatically over the entire Bengal Basin, changes in net groundwater recharge in Bangladesh are assessed using the water-table fluctuation method. Mean annual groundwater recharge is shown to be higher (300 to 600 mm) in northwestern and southwestern areas of Bangladesh than in southeastern and northeastern regions (< 100

mm) where rainfall and potential recharge are greater. Net recharge in many parts of Bangladesh has increased substantially (5 to 15 mm/year between 1985 and 2007) in response to increased groundwater abstraction for irrigation and urban water supplies. In contrast, net recharge has slightly decreased (-0.5 to -1 mm/year) in areas where groundwater-fed irrigation is low ($<30\%$ of total irrigation) and where abstraction has either decreased or remained unchanged over the period of 1985 to 2007. Irrigation in southern Bangladesh is conducted primarily from surface water as shallow groundwater is mostly saline. Additionally, many agricultural lands in the south have been converted to shrimp farms in recent years. The spatio-temporal dynamics of recharge in Bangladesh illustrate the fundamental flaw in definitions of “safe yield” based on recharge estimated under static (non-pumping) conditions that does not recognise the fact that net groundwater recharge can increase as a result of abstraction. This study also reveals the areas in Bangladesh where (1) further groundwater abstraction may increase actual recharge to the shallow aquifer, and (2) current rates of groundwater abstraction for dry-season irrigation and urban water supplies are unsustainable.

7.1.4 Conclusion 4: Groundwater Dynamics and As Mobilisation

The region-scale variations in groundwater As concentrations in the Bengal Basin are influenced by surface geology, and its interactions with hydrogeological factors; greater recharge and increased groundwater-fed irrigation are associated with low As concentrations in shallow aquifers.

The geological control on the basin-scale variations in groundwater As concentrations in shallow aquifers has been discussed in previous studies. However, the critical influences of surface geology and its interactions with hydrogeological factors have not been investigated at the national or basin scale. Within a statistical modelling framework, this study, for the first time, examines the simultaneous effects of surface geology, hydrogeology, and groundwater dynamics on the national-scale variations of As in shallow aquifers. Generalised regression models (GRMs) are developed in this study to understand As variations in groundwater where the dataset features (1) highly skewed distribution, (2) non-detect (censored) observations, and (3) spatial dependence within the neighbouring locations. Results from GRMs reveal that the effects of geology and its interactions with well depth, mean annual recharge, and trends in annual recharge are significant in explaining As mobilisation in groundwater. Modelling results show that greater annual recharge and increased trends in groundwater-fed irrigation are associated

with low-As concentrations and these factors have the potential to decrease As concentrations in shallow groundwater.

7.1.5 Conclusion 5: As-mobilisation Hypotheses

Hypotheses on the mobilisation of groundwater As that do not recognise the effects of surface geology and its interactions with hydrogeological factors cannot explain the spatial variability in As; increased recharge induced by irrigation actively flushes out As contents from aquifer sediments and groundwater.

The validity of hypotheses for the mobilisation of As in shallow groundwater, developed from localised site investigations in the Bengal Basin has been tested at neither the national nor basin scale. Results from GRMs reveal that the primary assumptions of the “young carbon” and “groundwater mixing” hypotheses are unable to explain the national-scale variability in As concentrations in shallow groundwater. Results from GRMs support that the principal assumptions of the “aquifer flushing hypothesis” are able to explain the national-scale distribution of As in groundwater. Inverse associations between As concentrations in shallow groundwater and actual recharge and trends in groundwater-fed irrigation suggest that As has been actively flushed from the shallow aquifer. The modelling results assert that the effect of groundwater recharge on As mobilisation critically depends on its interaction (i.e., combined effect of recharge and geology on As in groundwater; relationship between net recharge and As concentrations varies within different geological units) with surface geology and current hypotheses that disregard these observations cannot explain As mobilisation at the national or basin scale.

7.2 Recommendations and Future Directions

7.2.1 Monitoring Groundwater Salinity in Coastal Aquifers

This thesis provides evidence of rising groundwater levels in coastal shallow aquifers in Bangladesh commensurate to concurrently observed rises in sea level in the Bay of Bengal. Further research is necessary to verify whether rising groundwater levels can be directly attributed to rises in the sea level. It is necessary to investigate further whether rising groundwater levels stem from differential subsidence in the southern GBM Delta due to sediment loading in the Bengal Basin.

In relation to the former, rising groundwater levels in coastal areas can result from an overall rise in freshwater – saltwater interface within the shallow aquifer. Integrated research on surface-water – groundwater – sea-water interaction may provide better understanding of complex hydrodynamic processes working in coastal aquifers of Bangladesh. There is, however, a dearth of observations in the coastal Bangladesh and no active monitoring of groundwater levels in the Sundarbans.

7.2.2 Testing As-hypothesis Derived from this Thesis

Based on national-scale statistical modelling this study argues that intensive groundwater abstraction (e.g., dry-season irrigation) in As-contaminated areas in Bangladesh can reduce mobile As concentrations by recharge-driven active flushing of the aquifer. Currently, annual groundwater recharge to shallow aquifers in southeastern parts of Bangladesh is low. To test these findings at the local scale further research needs to be conducted in specific areas in Bangladesh where background As concentrations are high ($>50 \mu\text{g/L}$) but actual annual recharge to aquifers is low ($<100 \text{ mm}$). In addition, targeted sampling of groundwater As in different geological settings (i.e., sandy surface areas with greater groundwater recharge and clay covered areas with little groundwater recharge) can be conducted at multiple locations in Bangladesh. Furthermore, time-series monitoring of groundwater As concentrations is necessary to understand the temporal (seasonal and long term) variation in As concentrations and impacts of groundwater-fed irrigation and net recharge on its mobilisation.

7.2.3 Applications of Methods to Other Asian Mega-Deltas

Methodologies applied in this study (such as seasonal-trend decomposition technique) can be to any hydrological system where seasonality is evident in groundwater level time-series records. This study shows that GRACE satellite-derived estimates of groundwater storage compare well with in situ observations in the highly seasonal Bengal Delta. GRACE measurements can be used to derive basin-averaged estimate of groundwater storage in other Asian Mega-Deltas where surface geology, hydrogeology, and climatic conditions are similar to the Bengal Delta but monitoring records of in situ groundwater levels are scanty or unavailable. However, information on soil moisture and surface water storage can be obtained from land surface models or satellite observations.

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Appendices

Appendix 1.1: Maps showing monthly median groundwater levels in Bangladesh.

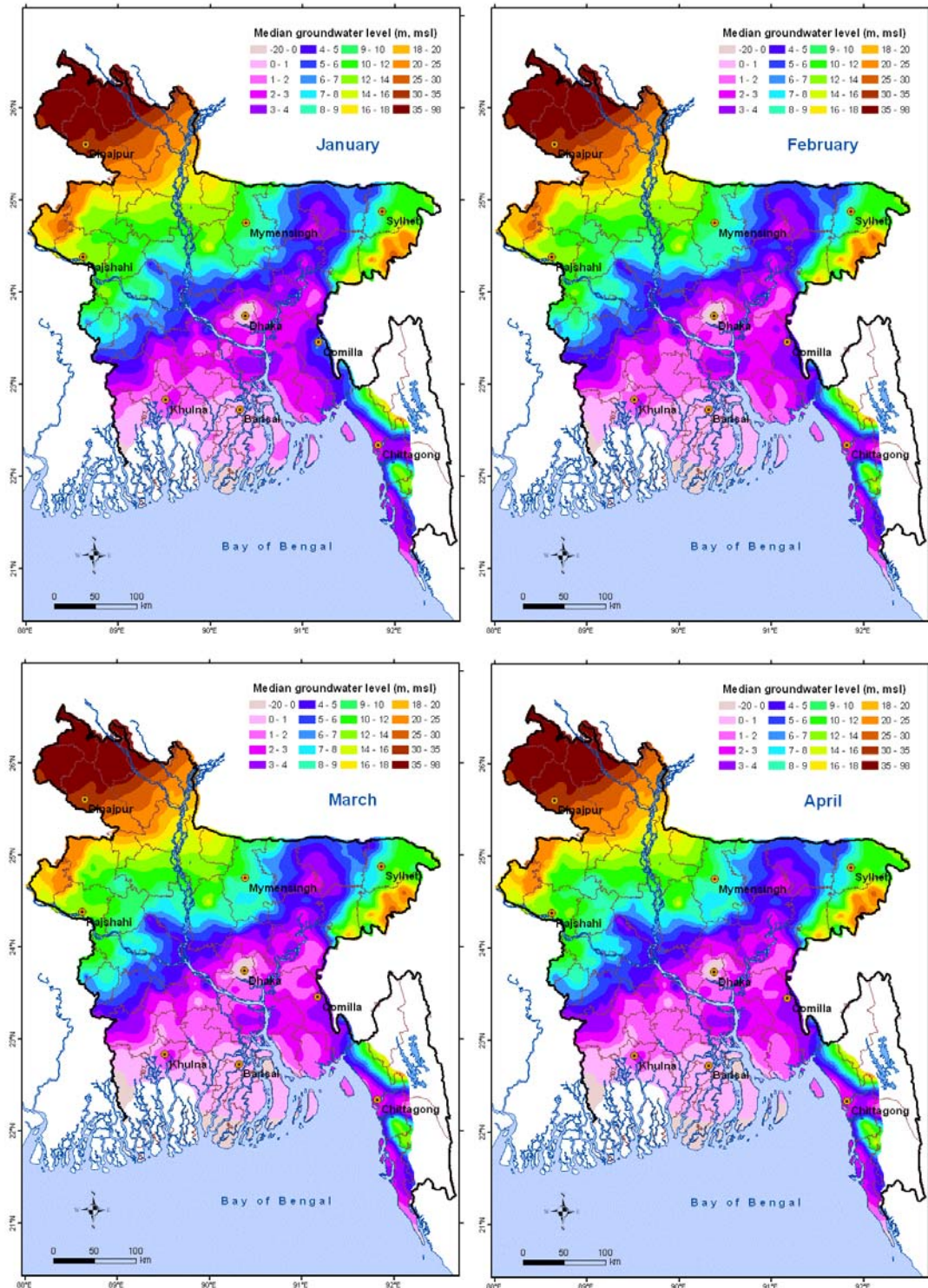
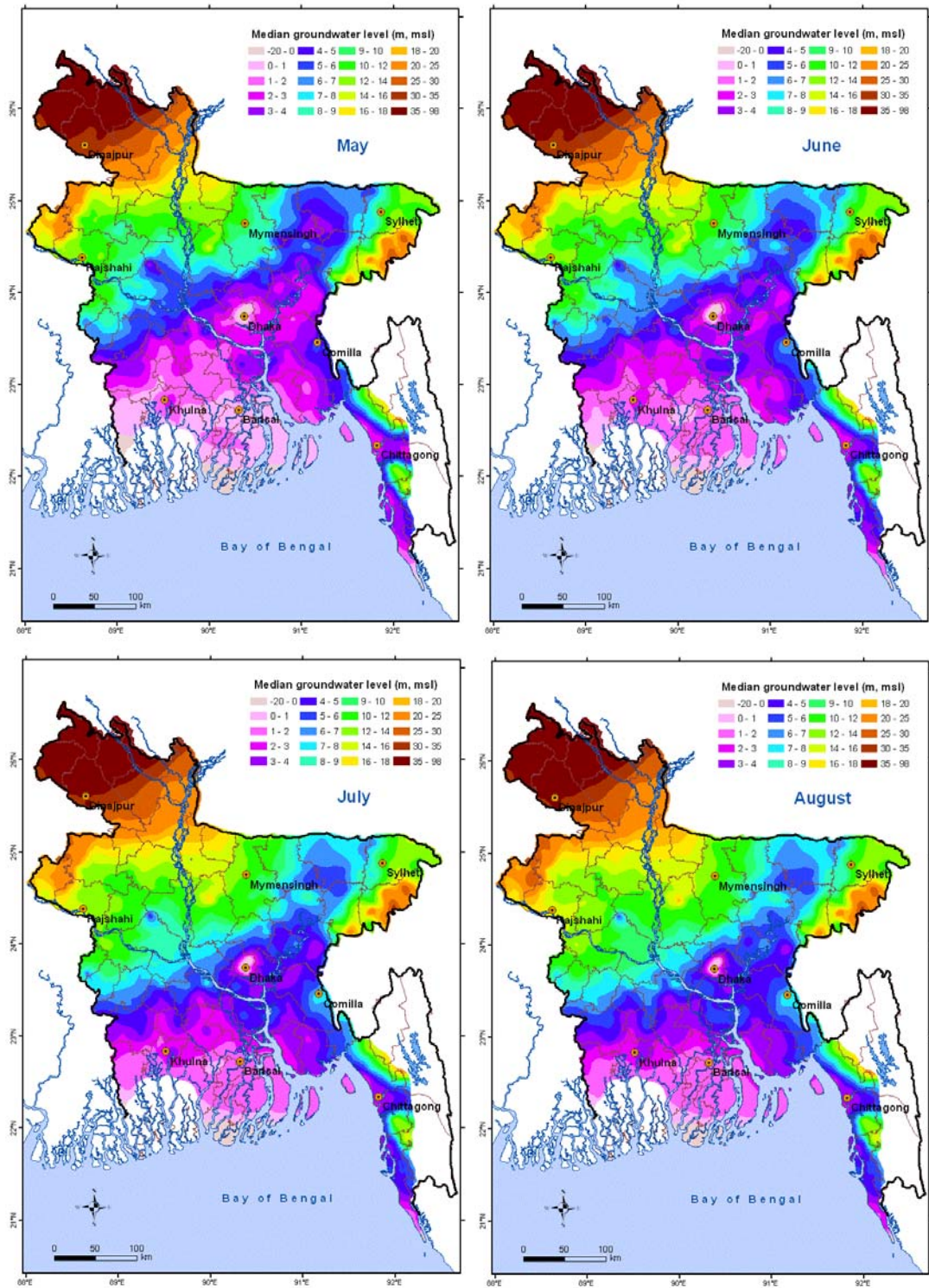
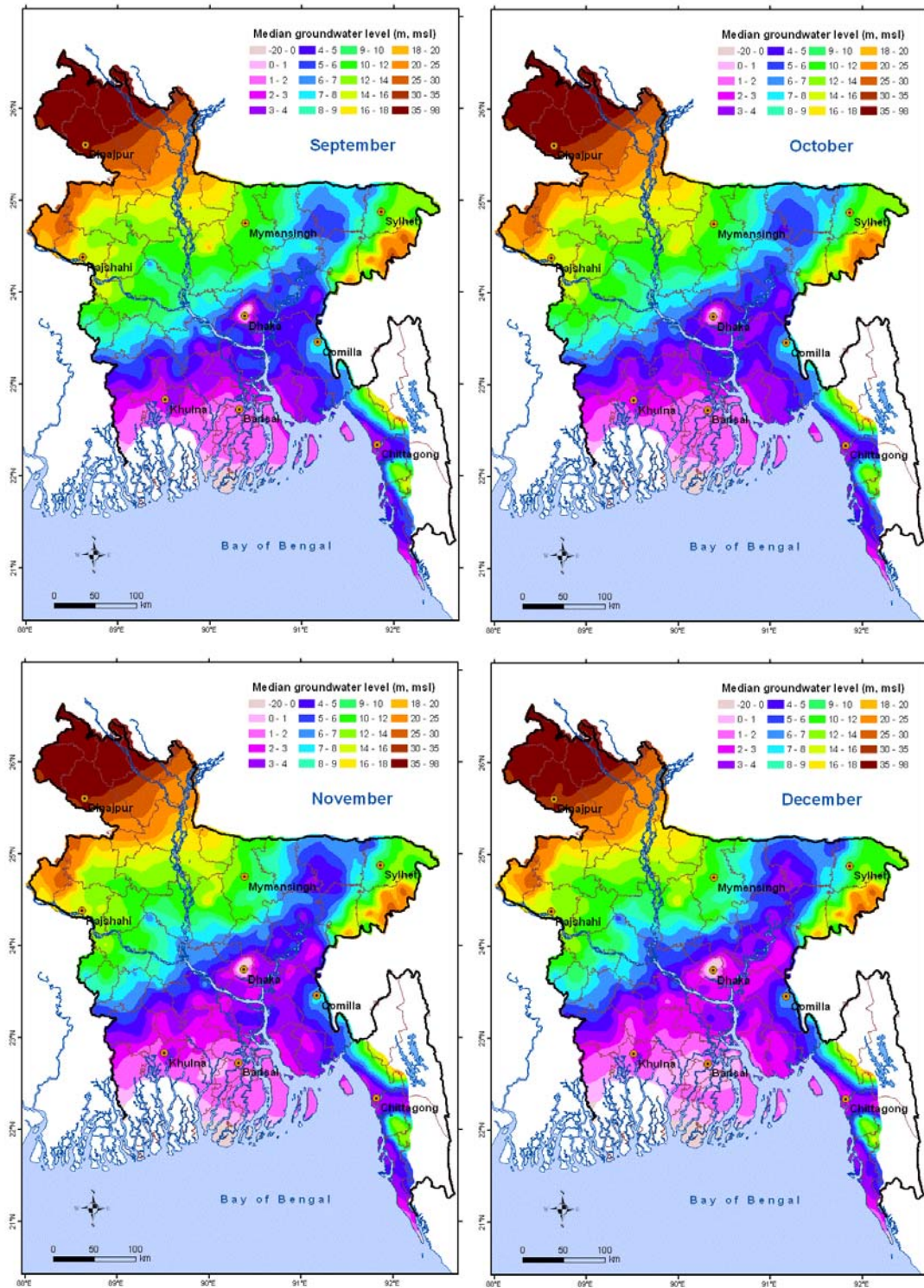


Figure A1.1 Monthly (January to December) median groundwater levels (i.e., hydraulic heads) maps interpolated from 1035 monitoring locations throughout Bangladesh. Monthly median heads highlight the regional as well as local-scale variations in groundwater levels and illustrate seasonal flow paths of shallow groundwater in Bangladesh.





Appendix 1.2: Basic information of 236 monitoring stations in Bangladesh.

Table A1.2. Site details of 236 monitoring wells used for estimating groundwater recharge. These shallow monitoring wells are managed by Bangladesh Water Development Board. Units of PWD (Public Works Datum), and well parapet height, and screen depth are in m.

FileID	District	Thana [†]	Type	Long	Lat	PWD	Parapet height	Screen depth
BA003_A	Barisal	Mehendiganj	Piezo	90.52	22.84	3.06	0.25	21.03
BA010_A	Barisal	Babuganj	Piezo	90.28	22.83	4.11	0.61	25.91
BA011_A	Barisal	Hizla	Piezo	90.52	22.96	3.78	0.71	19.82
BA018_A	Pirojpur	Kawkhali	Piezo	90.07	22.62	2	0.58	39.02
BA030_A	Pirojpur	Bhandaria	Piezo	90.01	22.45	2.62	0.46	62.2
BO001_B	Bogra	Sherpur	Piezo	89.39	24.62	17.22	0.45	26.84
BO002_B	Bogra	Dhunat	Piezo	89.58	24.74	15.21	0.55	20.13
BO006_B	Bogra	Shibganj	Piezo	89.26	24.98	19.91	0.53	32.63
BO007_B	Joypurhat	Joypurhat Sadar	Piezo	89.06	25.13	21.11	0.68	26.23
BO008_B	Joypurhat	Panchbibi	Piezo	89.07	25.23	23.5	0.76	32.44
BO018_B	Bogra	Gabtali	Piezo	89.43	24.96	17.6	0.79	20.13
BO029_B	Joypurhat	Khetlal	Piezo	89.12	24.98	20.85	0.45	42.54
BO030_A	Bogra	Adamdighi	Piezo	89.12	24.77	15.24	0.3	39.65
CM001_A	Brahamanbaria	Kasba	Piezo	91.13	23.79	6.86	0.38	20.35
CM002_A	Comilla	Burichang	Piezo	91.15	23.58	5.62	0.46	21.26
CM003_A	Comilla	Burichang	Piezo	91.05	23.51	6.59	0.46	27.74
CM004_A	Comilla	Burichang	Piezo	91.11	23.55	8.14	0.3	20.35
CM006_A	Comilla	Comilla Sadar	Piezo	91.23	23.46	8.68	0.46	13.87
CM008_A	Comilla	Chandina	Piezo	90.91	23.48	6.46	0.46	21.24
CM009_A	Comilla	Laksam	Piezo	91.16	23.25	7.24	0.38	13.87
CM013_A	Comilla	Chauddagram	Piezo	91.29	23.28	11.35	0.61	34.16
CM015_A	Chandpur	Hajiganj	Piezo	90.85	23.3	5.02	0.46	21.57
CM016_A	Chandpur	Chandpur Sadar	Piezo	90.66	23.28	4.58	0.46	20.96
CM020_A	Chandpur	Kachua	Piezo	90.83	23.44	6.48	0.46	27.44
CM021_A	Comilla	Daudkandi	Piezo	90.74	23.53	6.22	0.3	20.12
CM024_A	Brahamanbaria	Nabinagar	Piezo	91.07	23.85	5.44	0.46	28.06
CM026_A	Comilla	Debidwar	Piezo	91.02	23.6	7.75	0.51	30.79
CM033_A	Comilla	Muradnagar	Piezo	90.91	23.61	4.59	0.46	21.66
CM034_A	Comilla	Muradnagar	Piezo	90.94	23.66	6.15	0.31	16.46
CM038_A	Comilla	Laksam	Piezo	91.1	23.24	9.13	0.61	24.39
CM045_A	Comilla	Burichang	Piezo	91.1	23.51	7.47	0.46	26.83
CM048_A	Comilla	Homna	Piezo	90.73	23.63	6.91	0.46	27.84
CM052_A	Comilla	Daudkandi	Piezo	90.77	23.58	5.29	0.61	32.93
CM055_A	Comilla	Debidwar	Piezo	91.02	23.54	7.42	0.61	26.83
CM058_A	Comilla	Barura	Piezo	91.03	23.3	7.74	0.61	39.04
CM065_A	Comilla	Burichang	Piezo	91.15	23.51	7.07	0.46	36.6
CT024_B	Chittagong	Anowara	Piezo	91.88	22.22	5.97	0.38	12.2
CT026_A	Chittagong	Hathazari	Piezo	91.79	22.44	6.48	0.61	27.13
DH001_B	Munshiganj	Serajdikhan	Dug	90.28	23.63	7.17	0.74	6.79
DH006_B	Manikganj	Manikganj Sadar	Piezo	90.01	23.87	10	0.15	39.58
DH007_B	Manikganj	Manikganj Sadar	Piezo	90.07	23.83	9.73	0.46	32.93
DH011_B	Gazipur	Sreepur	Piezo	90.51	24.17	8.66	0.2	27.44
DH013_B	Dhaka	Sutrapur	Piezo	90.42	23.7	5.98	0.46	25.81
DH024_B	Manikganj	Daulatpur	Dug	89.9	23.96	10.3	0.53	5.33
DH062_A	Munshiganj	Sreenagar	Piezo	90.26	23.53	9.14	0.45	26.21
DH063_A	Munshiganj	Serajdikhan	Piezo	90.36	23.59	7.37	0.46	21.03
DH070_C	Gazipur	Gazipursadar	Piezo	90.39	23.9	8.95	0.41	57.55
DH080_B	Narayanganj	Rupganj	Piezo	90.56	23.86	7.53	0.61	35.36
DH082_A	Narayanganj	Sonargaon	Dug	90.63	23.66	6.59	0.71	6.98
DH086_A	Munshiganj	Tongibari	Piezo	90.47	23.44	6.21	0.45	26.32
DH089_B	Manikganj	Singair	Piezo	90.14	23.77	8.83	0.61	52.13
DH094_B	Gazipur	Kaliakair	Piezo	90.31	24.16	22.32	0.3	23.78
DH095_A	Dhaka	Dohar	Piezo	90.14	23.58	5.97	0.61	57.3
DH099_A	Dhaka	Dohar	Piezo	90.1	23.6	7.27	0.6	51.22

DH107_A	Narsingdi	Roypura	Dug	90.93	24	10.19	0.93	5.13
DH111_B	Dhaka	Mohammadpur	Piezo	90.36	23.76	10	0.22	30.92
DH117_B	Gazipur	Sreepur	Piezo	90.49	24.28	18.81	0.46	47.26
DH125_A	Manikganj	Harirampur	Piezo	89.97	23.74	8.55	0.46	38.1
DH126_A	Munshiganj	Gazaria	Piezo	90.64	23.58	6.56	0.46	38.1
DI034_B	Dinajpur	Dinajpur Sadar	Piezo	88.67	25.57	30.67	0.63	32.94
DI059_C	Dinajpur	Hakimpur	Piezo	89.07	25.29	23.85	0.5	32.94
DI069_B	Thakurgaon	Haripur	Piezo	88.16	25.84	26.64	0.45	26.84
DI074_B	Thakurgaon	Thakurgaon Sadar	Piezo	88.5	26.01	62.99	0.61	32.94
DI083_A	Panchagarh	Tentulia	Piezo	88.5	26.47	90.93	0.3	21.96
DI089_A	Thakurgaon	Ranisankail	Piezo	88.24	25.88	45.17	0.55	35.99
DIS02_A	Thakurgaon	Baliadangi	Piezo	88.32	26.15	51.66	0.46	27.74
DIS04_A	Thakurgaon	Pirganj	Piezo	88.32	25.79	40.51	0.46	39.02
DIS05_A	Dinajpur	Biral	Piezo	88.54	25.59	37.12	0.31	39.04
DIS06_A	Dinajpur	Bochaganj	Piezo	88.5	25.79	41.38	0.38	32.93
DIS07_A	Dinajpur	Bochaganj	Piezo	88.48	25.86	40.04	0.53	34.15
FA001_B	Faridpur	Faridpur Sadar	Piezo	89.85	23.6	8.48	0.46	30.77
FA003_B	Rajbari	Rajbari Sadar	Piezo	89.64	23.76	10.85	0.57	32.32
FA005_B	Rajbari	Baliakandi	Piezo	89.59	23.61	7.7	0.46	35.98
FA011_B	Rajbari	Pangsha	Piezo	89.46	23.7	11.35	0.46	29.88
FA013_B	Gopalganj	Kotalipara	Piezo	89.99	22.94	3.46	0.3	31.09
FA020_A	Faridpur	Bhanga	Piezo	89.96	23.4	6.35	0.53	32.92
FA022_A	Faridpur	Charbhadrasan	Piezo	89.95	23.57	14	0.6	23.53
FA024_A	Shariatpur	Bhedarganj	Piezo	90.45	23.2	6.98	0.56	27.44
FA026_A	Gopalganj	Muksudpur	Piezo	89.87	23.32	5.62	0.51	26.22
FA027_A	Gopalganj	Gopalganj Sadar	Piezo	89.91	23.12	5.22	0.46	31.4
FA030_A	Gopalganj	Kotalipara	Piezo	90.07	23.02	5.39	0.56	32.39
FA036_A	Madaripur	Kalkini	Piezo	90.2	23.07	4.27	0.75	57.22
FA038_A	Faridpur	Sadarpur	Piezo	89.94	23.51	5.66	0.58	29.24
FA039_B	Rajbari	Pangsha	Piezo	89.51	23.72	10.16	0.46	29.88
FA043_B	Faridpur	Boalmari	Piezo	89.73	23.42	9.1	0.73	35.98
FA046_A	Faridpur	Nagarkanda	Piezo	89.79	23.44	5.87	0.56	39.93
FA048_A	Rajbari	Pangsha	Piezo	89.46	23.72	10.23	0.61	37.01
FA049_A	Gopalganj	Kashiani	Piezo	89.78	23.15	6.58	0.71	26.22
FA052_A	Shariatpur	Palong	Piezo	90.36	23.22	6.22	0.53	20.12
FA055_A	Gopalganj	Kotalipara	Piezo	90	23.1	5.49	0.61	35.37
FA056_A	Gopalganj	Gopalganj Sadar	Piezo	89.9	23.04	5.49	0.46	45.19
FA057_A	Faridpur	Boalmari	Piezo	89.72	23.41	7.2	0.46	51.3
FA062_A	Gopalganj	Gopalganj Sadar	Piezo	89.83	23.04	4.71	0.46	33.44
FS07_A	Faridpur	Boalmari	Piezo	89.64	23.39	8.17	0.62	7.29
FS08_A	Faridpur	Boalmari	Piezo	89.71	23.5	8.17	0.62	7.29
FS09_A	Rajbari	Goalandaghat	Piezo	89.78	23.71	5.8	0.46	43.29
JA001_B	Jamalpur	Jamalpur Sadar	Piezo	90.14	24.82	17.46	0.46	29.89
JE001_B	Jessore	Kotwali	Piezo	89.27	23.2	8.29	0.46	40.91
JE003_B	Jhenaidah	Kaliganj	Piezo	89.2	23.39	9.35	0.46	27.13
JE004_B	Jhenaidah	Jhenaidah Sadar	Piezo	89.23	23.48	9.27	0.46	26.83
JE009_B	Jhenaidah	Maheshpur	Piezo	88.8	23.32	8.65	0.46	32.93
JE010_B	Jessore	Manirampur	Piezo	89.24	22.96	7.74	0.46	39.02
JE044_A	Magura	Sreepur	Piezo	89.36	23.48	9.73	0.46	57.61
JE047_A	Narail	Lohagara	Piezo	89.62	23.21	8.1	0.59	59.71
JE048_A	Jhenaidah	Shailkupa	Piezo	89.32	23.6	10.68	0.46	51.83
JE055_B	Jessore	Sharsha	Piezo	88.93	23.08	5.69	0.46	38.2
JE057_A	Jessore	Keshabpur	Piezo	89.3	22.88	4.11	0.53	30.55
KH005_B	Khulna	Daulatpur	Piezo	89.39	22.89	3.78	0.46	51.82
KH016_A	Satkhira	Shyamnagar	Piezo	89.12	22.35	2.86	0.38	51.22
KH021_A	Satkhira	Assasuni	Piezo	89.2	22.56	3.02	0.46	46.49
KT002_B	Kushtia	Bheramara	Piezo	89.01	24.01	14.84	0.4	26.37
KT007_B	Meherpur	Meherpur Sadar	Piezo	88.68	23.82	15.92	0.4	31.31
KT012_B	Meherpur	Meherpur Sadar	Piezo	88.63	23.63	15.22	0.46	20.73
KT017_B	Kushtia	Bheramara	Piezo	88.94	24.12	16.03	0.46	29.95
KT018_B	Kushtia	Daulatpur	Piezo	88.87	24.1	9	0.6	26.92
KT019_A	Kushtia	Daulatpur	Dug	88.78	24.02	18.16	0.66	7.72
KT035_B	Kushtia	Kushtia Sadar	Piezo	89.1	23.83	11.7	0.46	33.56

KT037_A	Meherpur	Meherpur Sadar	Piezo	88.59	23.65	13.87	0.38	57.93
KT038_A	Kushtia	Mirpur	Piezo	88.96	23.87	12.74	0.46	53.66
KT039_A	Kushtia	Bheramara	Piezo	88.95	24.12	16.39	0.41	51.68
KT040_A	Kushtia	Bheramara	Piezo	88.95	24.11	16.52	0.31	56.71
KT043_A	Chuadanga	Alamdanga	Piezo	88.98	23.71	12.52	0.46	48.02
KT044_A	Kushtia	Daulatpur	Piezo	88.83	23.98	17.72	0.45	42.91
MY019_B	Kishoreganj	Katiadi	Piezo	90.82	24.28	9.08	0.45	21.35
MY025_B	Mymensingh	Trishal	Piezo	90.41	24.61	14.23	0.46	33.23
MY030_B	Mymensingh	Muktagachha	Piezo	90.19	24.78	14.38	0.53	29.87
MY044_A	Mymensingh	Nandail	Piezo	90.75	24.59	10.84	0.36	41.45
MY046_B	Mymensingh	Gauripur	Piezo	90.64	24.75	12.54	0.46	30.48
MY053_B	Netrakona	Durgapur	Piezo	90.68	25.15	13.16	0.51	29.26
MY060_A	Mymensingh	Bhaluka	Piezo	90.3	24.36	10.96	0.49	37.8
MY061_B	Mymensingh	Trishal	Piezo	90.46	24.54	11.74	0.46	29.88
MY063_B	Kishoreganj	Austagram	Piezo	91.11	24.34	8.62	0.46	55.28
MY084_A	Mymensingh	Bhaluka	Piezo	90.36	24.36	14.46	0.33	45.12
MY085_A	Mymensingh	Bhaluka	Piezo	90.45	24.43	16.64	0.51	38.41
MY088_A	Kishoreganj	Kishoreganj Sadar	Piezo	90.85	24.4	9.45	0.41	35.06
NA009_A	Lakshmipur	Lakshmipur Sadar	Piezo	90.87	22.96	6.83	0.34	14.63
NA010_B	Noakhali	Noakhali Sadar	Piezo	90.97	22.76	5.85	0.38	14.4
NA012_A	Lakshmipur	Lakshmipur Sadar	Piezo	90.93	22.91	4.19	0.61	14.02
NA013_A	Noakhali	Companiganj	Piezo	91.27	22.77	6.89	0.31	20.73
NA016_B	Noakhali	Noakhali Sadar	Piezo	91.18	22.82	6.58	0.46	21.3
NA019_A	Noakhali	Noakhali Sadar	Piezo	91.19	22.76	5.96	0.61	33.54
NA022_A	Noakhali	Begumganj	Piezo	91.06	23.03	3.63	0.61	33.25
NA026_A	Noakhali	Noakhali Sadar	Piezo	91.2	22.6	5.07	0.4	42.7
NA029_A	Feni	Parshuram	Piezo	91.48	23.13	5.72	0.46	29.28
NA030_A	Lakshmipur	Roypur	Piezo	90.71	22.95	3.07	0.31	29.28
PA006_B	Pabna	Atgharia	Piezo	89.27	24.13	12.9	0.45	32.92
PA008_B	Pabna	Sujanagar	Piezo	89.51	23.88	11.82	0.45	32.92
PA017_A	Sirajganj	Kazipur	Piezo	89.66	24.69	16.23	0.45	30.5
PA030_A	Pabna	Ishwardi	Piezo	89.15	24.14	15.9	0.46	27.43
PA036_A	Pabna	Sujanagar	Piezo	89.52	23.93	11.61	0.41	33.53
PA037_A	Pabna	Sujanagar	Piezo	89.54	23.83	11.92	0.39	31.09
PA038_A	Pabna	Sujanagar	Piezo	89.45	23.87	12.47	0.39	33.4
PA039_A	Pabna	Bera	Piezo	89.64	23.92	10.75	0.38	17.93
PA041_B	Pabna	Bera	Piezo	89.69	23.88	10.35	0.46	21.54
PA042_A	Pabna	Pabna Sadar	Piezo	89.29	24.01	13.3	0.41	35.41
PA043_A	Pabna	Pabna Sadar	Piezo	89.35	24.01	13.38	0.45	35.36
PA049_A	Pabna	Bera	Piezo	89.65	23.96	11.92	0.46	57.91
PA051_A	Pabna	Atgharia	Piezo	89.22	24.16	12.62	0.45	60.28
PA056_A	Sirajganj	Sirajganj Sadar	Piezo	89.68	24.53	15.85	0.45	42.07
PA061_A	Pabna	Bera	Piezo	89.7	23.82	11.28	0.45	45.73
PT004_A	Barguna	Bamna	Piezo	90.06	22.25	2.79	0.57	39.16
PT008_A	Barguna	Patharghata	Piezo	89.94	22.08	2.19	0.43	26.21
RA-03_A	Nilphamari	Dimla	Dug	88.82	26.06	62.7	0.86	5.17
RA-04_B	Nilphamari	Domar	Dug	88.81	26.26	63.58	0.8	4.36
RA-06_B	Nilphamari	Dimla	Piezo	88.95	26.23	57.06	0.53	32.94
RA-09_A	Nilphamari	Dimla	Dug	88.91	26.13	55.31	0.85	4.38
RA-10_B	Nilphamari	Dimla	Dug	89.03	26.13	49.3	0.61	4.04
RA-11_A	Nilphamari	Dimla	Dug	89.04	26.12	50.13	0.61	4.96
RA-12_B	Lalmonirhat	Hatibandha	Piezo	89.13	26.11	47.98	0.53	32.49
RA-14_A	Nilphamari	Domar	Dug	88.82	26.04	53.47	0.76	4.93
RA-16_B	Nilphamari	Jaldhaka	Piezo	89.06	26	48.06	0.46	34.16
RA-19_B	Nilphamari	Jaldhaka	Piezo	88.92	26.1	47.29	0.38	26.82
RA-21_C	Nilphamari	Dimla	Piezo	88.99	26.17	54.08	0.38	34
RA-23_A	Nilphamari	Jaldhaka	Dug	88.99	26.08	51.55	0.84	5.18
RA-24_A	Nilphamari	Domar	Dug	88.87	26.14	45.45	0.61	7.62
RA-25_B	Lalmonirhat	Patgram	Piezo	89.06	26.39	55.73	0.4	20.73
RA-29_A	Nilphamari	Saidpur	Dug	88.91	25.78	41	0.87	6.06
RA-32_B	Lalmonirhat	Lalmonirhat Sadar	Piezo	89.49	25.94	33.84	0.93	7.62
RA-33_A	Lalmonirhat	Lalmonirhat Sadar	Dug	89.44	25.8	31.53	0.38	9.46
RA-36_A	Kurigram	Nageshwari	Dug	89.66	25.97	29.62	0.48	5.22

RA-37_B	Kurigram	Kurigram Sadar	Piezo	89.7	25.8	27.71	0.56	32.49
RA-38_A	Kurigram	Ulipur	Dug	89.63	25.66	26.55	0.77	6.16
RA-41_A	Gaibandha	Gaibandha Sadar	Dug	89.48	25.32	21.13	0.61	6.3
RA-44_B	Nilphamari	Nilphamari Sadar	Dug	88.85	25.97	48.56	0.76	5.18
RA-50_A	Nilphamari	Kishoreganj	Dug	89.1	25.88	43.12	0.75	5.26
RA-53_A	Gaibandha	Palashbari	Dug	89.35	25.27	30.66	0.91	6.28
RA-54_A	Nilphamari	Domar	Dug	88.87	26.09	57.17	0.73	5.7
RA-56_A	Gaibandha	Palashbari	Dug	89.41	25.3	27.76	0.81	5.54
RA-57_A	Gaibandha	Sadullapur	Dug	89.45	25.39	23.19	0.87	9.55
RA-62_A	Kurigram	Nageshwari	Dug	89.71	25.91	28.64	1.59	7.12
RA-64_A	Kurigram	Ulipur	Piezo	89.59	25.68	26.69	0.3	42.85
RA-65_A	Kurigram	Kurigram Sadar	Dug	89.63	25.77	28.13	0.38	6.3
RA-66_A	Nilphamari	Kishoreganj	Dug	89.02	25.85	45.46	0.71	5.1
RA-67_A	Lalmonirhat	Kaliganj	Dug	89.2	25.95	40.43	0.81	8.47
RA-69_A	Rangpur	Kaunia	Dug	89.41	25.78	31.67	0.86	7.84
RA-71_A	Kurigram	Kurigram Sadar	Dug	89.68	25.85	28.25	0.55	6.63
RA-73_A	Gaibandha	Gobindaganj	Dug	89.38	25.21	23.12	0.78	5.21
RA-74_A	Gaibandha	Gobindaganj	Dug	89.37	25.12	22.56	0.35	5.75
RA-78_B	Gaibandha	Saghatta	Piezo	89.57	25.07	18.95	0.45	32.94
RA-79_A	Nilphamari	Domar	Piezo	88.87	26.17	56.8	0.38	44.53
RA-80_A	Gaibandha	Gobindaganj	Piezo	89.35	25.19	24.13	0.3	32.63
RA-81_A	Kurigram	Chilmari	Piezo	89.74	25.6	24.08	0.3	41.25
RA-82_A	Lalmonirhat	Kaliganj	Piezo	89.24	26	44.44	0.3	38.86
RA-84_A	Gaibandha	Sundarganj	Dug	89.51	25.59	25.27	0.3	5.94
RJ023_A	Rajshahi	Mohanpur	Dug	88.68	24.63	16.39	0.81	11.99
RJ030_B	Natore	Singra	Piezo	89.14	24.57	12.35	0.45	29.87
RJ062_B	Naogaon	Naogaon Sadar	Piezo	88.9	24.84	15.96	0.2	32.94
RJ069_B	Rajshahi	Puthia	Piezo	88.88	24.49	15.08	0.36	29.88
RJ080_B	Rajshahi	Godagari	Piezo	88.43	24.4	20.84	0.45	26.82
RJ086_B	Rajshahi	Tanore	Piezo	88.55	24.57	19.56	0.3	35.59
RJ093_B	Rajshahi	Godagari	Piezo	88.46	24.49	20.74	0.45	26.93
RJ094_B	Rajshahi	Paba	Piezo	88.68	24.38	11.8	0.38	24.39
RJ097_B	Rajshahi	Charghat	Piezo	88.69	24.34	17.57	0.38	24.39
RJ099_B	Rajshahi	Charghat	Piezo	88.74	24.28	18.34	0.45	24.39
RJ122_B	Nawabganj	Nachole	Piezo	88.35	24.76	39	0.45	32.01
RJ124_A	Rajshahi	Godagari	Piezo	88.32	24.47	22.07	0.45	45.73
RJ135_A	Nawabganj	Shibganj	Piezo	88.12	24.76	23.67	0.45	41.61
RJ144_A	Natore	Baraigram	Piezo	89.22	24.31	14.25	0.6	44.83
SY011_B	Maulvibazar	Sreemangal	Piezo	91.72	24.29	18.76	0.46	32.31
SY024_B	Maulvibazar	Sreemangal	Piezo	91.65	24.37	13.72	0.46	32.32
SY026_B	Habiganj	Chunarughat	Piezo	91.54	24.22	19.21	0.38	23.94
SY045_B	Maulvibazar	Barlekha	Piezo	92.16	24.7	12.69	0.61	45.12
SY048_B	Maulvibazar	Barlekha	Piezo	92.2	24.75	13.87	0.38	41.31
SY070_A	Sylhet	Beanibazar	Piezo	92.17	24.85	13.7	0.73	42.09
SY071_A	Sylhet	Kotwali	Piezo	91.75	24.94	10.5	0.46	24.4
SY073_A	Sunamganj	Sunamganj Sadar	Piezo	91.46	25.02	9.69	0.46	61.3
SY082_A	Sylhet	Balaganj	Piezo	91.76	24.74	10.47	0.3	47.58
SY092_A	Sunamganj	Derai	Piezo	91.45	24.8	6.14	0.46	74.11
SY102_A	Sunamganj	Tahirpur	Piezo	91.21	25.13	7.82	0.61	59.48
SY105_A	Sunamganj	Jamalganj	Piezo	91.24	24.88	7.79	0.46	62.37
TA005_B	Tangail	Nagarpur	Piezo	89.94	24.05	10.93	0.46	29.89
TA014_A	Tangail	Bhuapur	Piezo	89.8	24.46	14.47	0.3	34.44
TA023_A	Tangail	Nagarpur	Piezo	89.84	24.03	10.57	0.2	65.23
TA024_A	Tangail	Nagarpur	Piezo	89.89	24.04	10.2	0.61	39.02
TA035_A	Tangail	Tangail Sadar	Piezo	89.84	24.28	12.62	0.6	53.04
TA036_A	Tangail	Ghatail	Piezo	90.11	24.51	11.24	0.46	50.6

Note: Piezo means monitoring piezometer; Thana is the third-level administrative unit in Bangladesh.

† Thana is the third level of administrative unit in Bangladesh.

Appendix 1.3: Pair-wise time-series plots of river stage and groundwater levels.

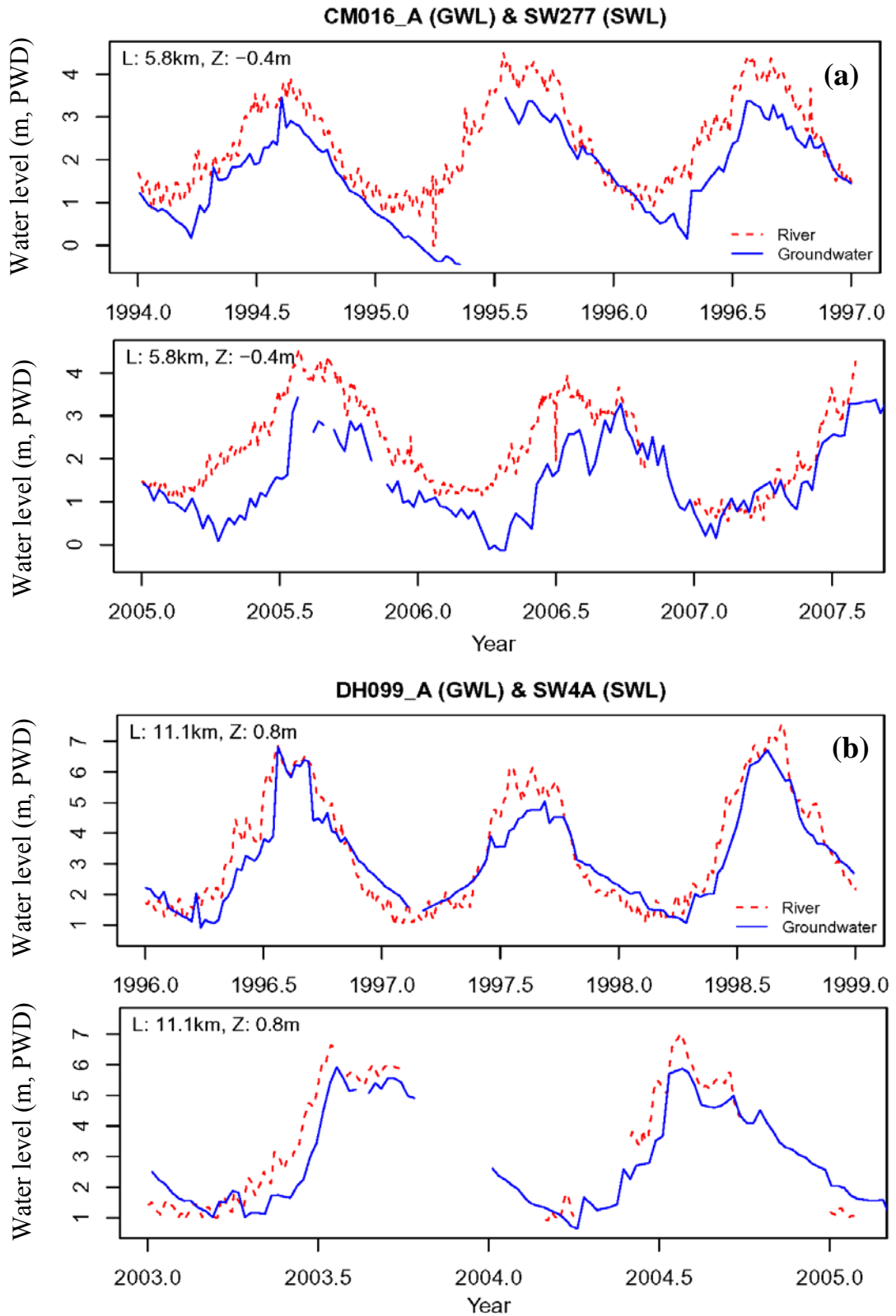


Figure A1.2 Selected groundwater (GW) and surface water (SW) levels of paired monitoring stations are shown in (a-e). Locations of the monitoring stations are shown in Figure 4.4. Distance (L) between paired monitoring stations and elevation difference ($Z=Z_{gw}-Z_{sw}$) are given on each plot. PWD is the Public Works Datum. Sampling time on the X-axis is shown as decimal years where 0.5 means the calendar month “June”.

