Hydrogeological investigation for assessment of the sustainability of low-arsenic aquifers as a safe drinking water source in regions with high-arsenic groundwater in Matlab, southeastern Bangladesh

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ABSTRACT

Exploitation of groundwater from shallow, high prolific Holocene sedimentary aquifers has been a main element for achieving safe drinking water and food security in Bangladesh. However, the presence of elevated levels of geogenic arsenic (As) in these aquifers has undermined this success. Except for targeting safe aquifers through installations of tubewells to greater depth, no mitigation option has been successfully implemented on a larger scale. The objective of this study has been to characterise the hydrostratigraphy, groundwater flow patterns, the hydraulic properties to assess the sustainability of the low-arsenic aquifers at Matlab, in south-eastern Bangladesh, one of the worst arsenic-affected areas of Bangladesh. Combining groundwater modelling with monitoring hydraulic heads in multi-level piezometer tests, ¹⁴C-dating of groundwater, conventional hydraulic testing and assessment of groundwater abstraction rate proved to be a useful strategy. A model comprising of three aquifers covering the top 250 m of the model domain showed to best fit the evaluation criteria for calibration. Matlab is a recharge area, even though it is adjacent to the great Meghna River. Irrigation wells are placed in clusters and account for most of the groundwater abstraction. Even though the hydraulic heads are affected locally by seasonal pumping, the aquifer system is fully recharged during and after the monsoon period. Groundwater simulations demonstrated the presence of deep regional and horizontal flow systems with recharge areas in the eastern, hilly part of Bangladesh and shallow small local flow systems driven by local topography. Based on modelling and ¹⁴C groundwater data, it can be concluded that the natural local flow systems reach a depth of 30 m b.g.l. in the study area. A downward vertical gradient of roughly 0.01 down to 200 m b.g.l. was observed and reproduced by calibrated models. The vertical gradient is mainly the result of the aquifer system and -properties rather than abstraction rate, which is too limited at depth to make an imprint. Although irrigation wells substantially change local flow pattern, targeting low-As aquifers seems to be a suitable mitigation option for providing people with safe drinking water. However, installing new irrigation- or high capacity production wells at the same depth is strongly discouraged as these substantially change the groundwater flow pattern. The results from the present study and other similar studies can further contribute to develop a rational management and mitigation policy for the future use of the groundwater resources for drinking water supplies.

Keywords: Bangladesh, arsenic, groundwater, flow-modelling, drinking water source, hydrogeology

1. INTRODUCTION

During the last four decades, the rural populations of Bangladesh have shifted their primary source of drinking and irrigation water from surface water to groundwater. Consequently, groundwater has been the main factor leading to two recent achievements in the fields of access to safe water and food security. Today, approximately 10 million drinking water hand tube wells (HTW) have been installed to avoid waterborne diseases, such as cholera and dysentery and although irrigation initially used surface water, about 70% of the irrigation water is abstracted from the aquifers, which account for 85% of the total abstracted groundwater. The exponential increase in groundwater exploitation has been prompted by highly productive aquifers and low cost technologies (Ahmed *et al.* 2004, Jakariya *et al.* 2005, Ravenscroft *et al.* 2005, Jakariya and Bhattacharya, 2007). The occurrence of elevated levels of naturally occurring arsenic (As) in groundwater has undermined the success of supplying safe drinking water. As a consequence, the safe water coverage has dropped drastically and it is estimated that about 35-77 million people are at risk of being exposed to too high concentrations of arsenic in their drinking water (Smith *et al.* 2000, Smedley and Kinniburgh 2002). Groundwater with elevated arsenic concentrations is associated with the shallow Holocene sediments of the Bengal basin and anaerobic conditions. Arsenic is mobilized through reductive dissolution of Fe(III)-oxyhydroxides present in the sediments. Local variations in geological conditions play an important role for mobilization and immobilization of arsenic at the sediment-water interface (Bhattacharya *et al.* 1997, Nickson *et al.* 1998, 2000, BGS and DPHE 2001, Smedley and Kinniburgh 2002, van Geen *et al.* 2003, Ahmed *et al.* 2004, Bundschuh *et al.* 2004, McArthur *et al.* 2004, Bhattacharya *et al.* 2006). The most important remedial action is to provide arsenic safe drinking water (Kapaj *et al.* 2006). The magnitude of the human tragedy will depend on the rate at which mitigation programmes can be implemented as the arsenic health effect is a product of the arsenic concentration in the drinking water and the period of exposure (Ravenscroft *et al.* 2005). In order to find sustainable solutions to the crisis, alternative safe drinking water options have been tested. However, many of the proposed solutions have not been well accepted by the stakeholders, since the concept of drinking tube-well water is deeply rooted in the mind of the people (Jakariya *et al.* 2005, 2007, Jakariya and Bhattacharya, 2007, Bundschuh *et al.* 2010, Johnston *et al.* 2010). Today governmental and non-governmental organisations install deep hand tube wells (>150 m) to avoid high As groundwater found in the Holocene sequences (BGS and DPHE 2001) and certain local drillers target low-arsenic groundwater within a depth of 100-150 m on the basis of the colour of the sediments, which has been verified as a possible criterion (Stollenwerk, 2005, von Brömsen *et al.*, 2005, 2007). Concurrently, groundwater is further exploited for irrigation purposes. Thus, there is a strong need for improving the knowledge of the hydrogeological system, in order to delineate aquifers (Hoque *et al.* 2011), to target low-arsenic groundwater

(von Brömssen *et al.* 2005, 2007), and to guarantee a sustainable use of the groundwater resources (Michael and Voss 2009a,b).

The objective of this study has been to understand the hydrogeological system, the aquifer properties and the groundwater flow pattern to assess the risk for cross-contamination between the aquifers containing high levels of dissolved As and safe aquifers being targeted by local drillers, and to delineate the major processes that affect the sustainability of the low arsenic aquifers. Hydrogeological field investigations have been carried out in combination with groundwater modelling for testing and describing the behaviour of the hydrogeological system at Matlab, in south-eastern Bangladesh, one of the worst affected areas of Bangladesh. Furthermore, results of this study may contribute to the development of a pragmatic management and mitigation policy for the future use of the groundwater resources for drinking water supplies.

2. GEOLOGY AND HYDROGEOLOGY

2.1 Geological setting

The Bengal Basin accommodates one of the largest delta systems of the world. The Ganges, Brahmaputra and Meghna (GBM) river system carry an enormous volume of sediments into the basin and generate, with active subsidence, a colossal thickness of Tertiary and Quaternary sequence (Umitsu 1987 and 1993, Goodbred *et al.* 2003, Hasan *et al.* 2007). Since the Miocene, deltaic sediments have prograded from the north, accumulating up to >10 km thick layers of sediments towards the Bay of Bengal in southern Bangladesh. From oil-prospecting drillings the top Tertiary sequence in the study area has been characterised. According to Alam *et al.* (1990) the uppermost part of the Tertiary sequence includes the Girujan clay, the Tipam sandstone, the Bokabil- and the Bhuban formations.

Bangladesh covers the major part of the Bengal Basin which is classified into three distinctive units. The Tertiary hill ranges occur in the east, southeast and north-northeast and consist of claystones, sandstones, shales and limestones (BGS and DPHE 2001). The hills have been formed due to the collision of the Indian shield at the Indo-Burma boundary forming the Indo-Burman fold belt. The Pleistocene Barind and Madhupur Terraces in the central north and Holocene plains act as a thin sediment veneer in large part of the Basin. The terraces are uplifted fluvial and alluvial deposits and include clay, silt, sand and pebbles of Pleistocene age that have been exposed to oxidation during the latest ice-ages. Groundwater within the terraces has been found to be low in As and the aquifer sediments are red-, brown- and yellowish in colour. The Quaternary sedimentation is believed to have been controlled mainly by the global climate change coupled with the rise of the Himalayan Range. A thick sequence of Quaternary sediments have been accumulated in the basin, especially in two distinctive environments and associated sub-environments in the north and south of the Ganges and lower Meghna Rivers. The Meghna flood plain is a low-lying landscape. Coarser sandy sediments have been deposited as channel facies under the fluvial re-

gime in the north whereas finerclastic facies have formed under the deltaic regime in the south (Hasan *et al.* 2007, Burgess *et al.* 2010, Hoque *et al.* 2011). The Holocene sequence includes piedmont deposits that occur mostly in the northern Bangladesh, floodplain and other interfluvial/overbank deposits of the Ganges-Brahmaputra-Tista-Meghna river system, in the delta plains of the Ganges-Brahmaputra-Meghna system, and in the coastal plains and active sub-basins including large inland lakes or “haors and bil” (Ahmed 2005). During the late Holocene time, as marine transgressions were waning, marshy or swampy lowlands developed in several parts of the Basin giving rise to peat deposits and sediment rich in organic matter.

The flood plain is characterized by meandering rivers, natural levees and back swamps. The upper part of the Holocene sequence includes the flood plains, fine-grained and/or muddy deposits, down to approximately 10 to 20 m (Umitsu 1987, 1993, Goodbred *et al.* 2003). Below the floodplains are channel deposits including coarser sediments such as sand and gravel. The Holocene sequence extends down to the depth of approximately 100 m. The deepest Holocene deposits are found at the Meghna River. Goodbred *et al.* (2003) identified oxidised surfaces that may coincide with oxidised low-arsenic aquifers described by von Brömssen *et al.* (2007) at the depth of 80 m halfway between Comilla and Meghna and at shallow depths (<20 m) at Comilla and outside Dhaka. The floodplain is covered by non-calcareous grey to dark grey flood plain soil (Brammer 1996). A thick sequence of the Quaternary sediment constitutes the substratum of the study area. The topmost Holocene sequence is composed of alluvial sand, silt and clay with marsh clay.

The location of the Meghna river channel has been relatively constant over the last 18 000 yr (Umitsu 1993). It can be assumed that the present location of the Meghna coincide with the location of Palaeo-Meghna river channel dating back to 120 000 yr BP (BGS and DPHE 2001). Thus it can be assumed that the sediments near and below the present river channel are relatively coarse with high permeability. This has also been observed in borelogs collected by DPHE/DFID/JICA (2006).

2.2 Climate and Rainfall

Bangladesh has a typical South-Asian tropical monsoon climate with considerable variation in rainfall over the year. Most parts of Bangladesh, including Matlab, receive more than 1 500 mm/yr, but in the hilly areas of north eastern Sylhet as much as 5 000 mm/yr may fall. Approximately 90 % of the rainfall occurs during the monsoon, between May and October. The monsoon period is followed by a moderately warm winter and spring between November and February and a hot and humid period between March and May. Temperature varies from approximately 10 to 36°C (Rahaman and Ravenscroft 2003, Hasan *et al.* 2009). Evapotranspiration in the region (data for Dhaka) is 1 602 mm/yr and varies from 89 to 188 mm/month peaking in April and May (BGS and DPHE 2001; Figure 1). Large parts of Bangladesh is flooded each year as a result of the heavy monsoon, the low-lying landscape and the increased discharge from the great rivers of Ganges, Brahmaputra and Meghna, which drain

large areas of the Himalayas. The river water table fluctuation in the study area is approximately 4 m.

Figure 1. Long term monthly rainfall and potential evapotranspiration (average) for Dhaka City, 1953 -1977 (modified from BGS and DPHE 2001).

2.3 Hydrogeological setting

The alluvial Holocene aquifers of the delta plain are prolific and found within shallow depth. Groundwater table levels in the Holocene aquifers are located close to the ground surface and fluctuate with the annual rainfall pattern. Locally, they are affected by heavy pumping and groundwater abstraction even though in most such places the system is fully recharged during the monsoon. The natural groundwater level amplitudes are in the order of 2-5 m over the year. As Bangladesh experiences a tropical monsoon climate with heavy rainfall during June to October the groundwater levels start to increase during May/June and decreases in September. The groundwater levels are lowest from January to March (BGS and DPHE 2000, Hasan *et al.* 2007).

Several attempts have been made to describe the aquifers in the Bengal basin (UNDP 1982, EPC/MMP 1991, BGS and DPHE 2001, DPHE/DFID/JICA 2006, Mukherjee *et al.* 2008, 2007). Most aquifer models are based only on lithological description. EPC/MMP (1991) developed a four-layer model taking vertical head differences into account and assessing water balance. That model consisted of an upper aquitard, an upper shallow aquifer, a lower aquitard and a lower shallow aquifer. The alluvial aquifers of Bangladesh are commonly semi-confined to confined; their transmissivity, hydraulic conductivity and storage coefficients have been determined from a large number of pumping tests (BGS and DPHE 2000). Most aquifer tests have been analysed by classical methods and were based on partial penetration wells. Ravenscroft (2001) described three groundwater flow systems in Bangladesh, namely: i) a local system down to 10 m, this system is a product of local topography such as levees, local hills, terraces, haors and bils and rivers, ii) an intermediate flow system with flow-path down to a couple of 100 m driven by the

larger terraces, major rivers etc. and iii) a basin-scale flow system, down to a depth of several 1000 m. This system would include the whole Bengal Basin with its borders in the Tertiary Hills in the east, the Indian Shield in west, the Shillong Plateau in north and the Bay of Bengal in south.

Groundwater flow patterns are affected because of heavy abstraction of groundwater for irrigation and drinking water purposes (Michael and Voss 2009a, b). Domestic drinking water wells in rural areas of Bangladesh are generally small diameter hand-pump wells. These wells can easily be installed to a depth down to 100 m depending on local geological conditions. Based on population and per capita use, groundwater abstraction for domestic usage can be estimated. Approximately 50 l/day×person is used for industrial and domestic purposes in Bangladesh, in some areas of rural Bangladesh as much as 30 mm/yr can be abstracted for domestic purposes (Michael and Voss 2008). However groundwater abstraction for irrigation is about an order of magnitude higher in rural areas. In some areas of Bangladesh more than 600 mm groundwater/yr is used for irrigation purposes.

3. STUDY AREA

The study area located in Matlab Upazila is situated 60 km south-east of Dhaka east of the confluence of the rivers of Ganges (Padma), Brahmaputra (Jamuna) and Meghna (Figure 2). The area is naturally flooded each year during the monsoon and the surface sediments consist of Holocene alluvial silt deposits. Matlab is one of the most arsenic contaminated Upazilas in Bangladesh (BGS and DPHE 2001, Jakariya *et al.* 2005, Jakariya and Bhattacharya 2007, Jakariya *et al.* 2007). The fraction of the Matlab population that obtain their drinking water from tube wells increased from 55% in 1982 to 95% in 1996. The total population of Matlab is about 450 000. In Matlab, most of the area is covered by topsoil, consisting of alluvial silt and clay.

The shallow Holocene aquifers of Matlab are severely affected by geogenic arsenic. High-arsenic groundwaters are distributed very heterogeneously in the Holocene aquifers (BGS and DPHE 2001). In southern part of Matlab a thick layer of black to grey sediments, which extend down to approximately 40 m, overlies an oxidised unit of yellowish-grey to reddish-brown sediments (von Brömssen *et al.* 2007). Quartz and feldspars with a substantial content of micas dominates these sediments. The upper unit has a general upward fining cycle that represents fluvial sediments of presumed Holocene age. The boundary between the units is represented by the presence of a clayey layer, which may act as an aquitard in the area. The lower yellowish-grey to reddish-brown sandy unit is more heterogeneous in terms of texture and colour characteristics. Visual inspection of washed sediments from the clayey layer and the lower unit indicates that these sediments have been exposed to erosion, weathering and oxidation during the last glacial maximum when the sea level in the BDP declined significantly. Groundwater in the study area occurs at

Figure 2. Map and digital elevation model of the study area. Black line shows the outer boarder of regional flow modelling domain and red line Matlab Upazila.

shallow depths within the Holocene sediments forming extensive multi-layered unconfined to leaky confined aquifers. The groundwater is generally reducing with low concentrations of SO_4^{2-} and NO_3^- and relatively high concentrations of dissolved As, Fe and Mn. The groundwater has high HCO_3^- concentrations, is of Ca-Mg- HCO_3 or Na-Cl- HCO_3 type (or their mix) and neutral or slightly acidic (pH 6-7) (von Brömssen *et al.* 2007, 2008). In Matlab, approximately 150-200 mm groundwater/yr is used for irrigation purposes according to Michael and Voss (2009a, b) estimate.

4. HYDROGEOLOGICAL FIELD INVESTIGATIONS

4.1 Hydrological monitoring and hydrostratigraphy

Ten piezometer nests (Figure 3) were installed and hydraulic heads were monitored on weekly basis and recorded from May/June 2009 until October 2010 to generate hydrographs at varying depth of the aquifers. At 7

of the 10 sites, 5 piezometers were installed at depths from 14 to 238 m. At 3 sites only 3 piezometers were installed. All results have been used to calculate the weekly groundwater hydraulic heads. Hand percussion (piezometers installed between 0-100 m) and donkey rotary drilling (piezometers installed below 100 m depth) methods were used for installation of piezometers. The diameter of the piezometers is 5.08 cm (2 ft) and the screen length 4.6 m (15 ft).

Figure 3. Location of piezometer nests. Red line shows the boarder of Matlab Upazila.

The geometry of the aquifers in Matlab (South and North) has been established through analyses of drilling logs from the piezometer installations, exploratory drillings and secondary sources. Drilling provided sediment samples at each of the 10 piezometer nests. Samples were collected at 1.5 m intervals during the drillings. Visual inspection was made to prepare the bore logs with description of sediment colour and their grain size.

4.2 ^{14}C analysis

Isotopes ^{14}C and ^{13}C were used to estimate the groundwater ages in the study area. During 2006 and 2007 groundwater samples from the study area were analysed for these isotopes. Groundwater samples were collected from the tubewells, NaOH was added, and the bottles were transported to Dhaka University where inorganic carbon was precipitated as BaCO_3 . The precipitate was later analysed at Lund University Radiocarbon Dating Laboratory (<http://www.geol.lu.se/c14/en/>) for ^{14}C and ^{13}C . Values of $\delta^{13}\text{C}$ were used to correct ^{14}C ages by method described by Clark & Fritz (1997).

4.3 Estimation of groundwater abstraction in Matlab

An irrigation wells survey was performed to estimate the total abstraction rate and spatial differences in abstraction in Matlab. A total number of 601 irrigation tubewells was identified and abstraction rate, operation time/season, depth and coordinates were obtained.

4.4 Hydraulic testing

The pumping test was carried out in January 2008 in the middle of the dry season using an irrigation well for abstraction of groundwater. The field work included installation of 9 piezometers at varying depths (23-88 m) and distances from the pumping well (2-36 m) and a 23½ hours pumping test, at the rate of 65 m³/hr. Groundwater levels were monitored in the pumping well and piezometers prior, during and after the pumping period. The piezometers were installed in two perpendicular lines with the origin at the irrigation well (Figure 4).

Figure 4. Location and set-up of pumping test, numbers indicate piezometer placing and depth in ft, i.e. 2:70 indicate placement 2 and that the depth of screen is at 70 ft.

The water levels were also monitored in two nearby private wells located at a distance of 128 and 94 m from the irrigation well at similar depths. The irrigation well had not been in prior use during the season. The water levels were monitored automatically with loggers in two piezometers as well as manually, twice a minute initially. During the installation of the piezometers, with the hand percussion method, washed sediment samples were collected in 1.5 m (5 ft) intervals.

5. GROUNDWATER FLOW MODELLING

5.1 Regional groundwater model

A generic three-dimensional finite-difference groundwater model MODFLOW (Visual Modflow v. 4.1) was used to study the aquifer system. Both regional steady state models and transient flow models covering the eastern part of Bangladesh, from the Tripura Hills to the river Meghna, were developed. Models were realised for natural/undisturbed conditions, i.e. no groundwater abstraction from wells, as well as for the present conditions with high groundwater abstraction for irrigation purposes. The regional transient models were calibrated to match monitored groundwater level fluctuations, while the steady state models were calibrated to match the estimated groundwater ages.

5.1.1 Model area and boundary conditions

The modelled area extends from the Bay of Bengal in the south to the low-lying bils and haors of the Sylhet region in the north, and from the Meghna River in the west to the Tripura Tertiary Hills in the east. The model setting consists of 138 rows, 93 columns and 20 layers to a depth of 1000 m. The lower boundary was assumed to be flat, due to lack of available data. However, groundwater flow interactions at depth were assumed to be negligible. All 601 irrigation wells that were identified at Matlab were introduced into the models as specific well points. One irrigation well per km², matching the average distribution and abstraction rate found in Matlab, was introduced for the area outside Matlab into the model. The boundary conditions have been set based on the criteria given in Table 1. Surface water levels from stations of Meghna around the study area, were collected from Bangladesh Water Development Board (BWDB) and used in the model according to figure 5.

Figure 5. Idealised surface water levels (m) introduced as constant head in the model and actual surface water levels at Matlab (Meghna) for 2005.

Table 1. Boundary conditions of the regional model outer limits.

Boundary	Boundary condition	Selection criteria
South	Constant head at sea-level.	It is assumed that Bay of Bengal is a hydraulic boundary with a constant head at 0 m.a.s.l.
East	No-flow boundary	Tripura Hills is a watershed towards east.
West	Constant head at Meghna surface to appr. 140 m b.s.l. at Matlab with greater depth towards south and lesser towards north. R. Gumti, surrounding parts of Matlab is included as constant head down to 16 m b.s.l. Constant heads has been varied according to surface level measurements.	It is assumed that the great river Meghna and the lesser river Gumti is a hydraulic boundary.
North	No-flow boundary	The groundwater flow is assumed to follow the northern boundary in east-west direction and thus little flow would cross the northern boundary.
Lower	No-flow	At 1000 m depth groundwater flow would be small.
Upper	Drain at 0.1 m below surface.	As excess water reaches the surface it is removed from the model simulating surface overflow.
	Recharge	For the transient model recharge was calculated as $P-ET \geq 0$ and applied on a monthly basis following data presented in Figure 1.
Irrigation wells	Pumping wells	It was assumed that irrigation stand for most of the groundwater abstraction and thus only the surveyed irrigation wells were included in the model.

5.1.2 Conceptual hydrogeological model

The model area includes the Tertiary Hill ranges in the East, the floodplains demarcated by the Tertiary Hills and the delta plains in the south. The Tertiary Hills stretches out under the unconsolidated Holocene and Pleistocene sequences of alluvial sediments deposited by the Meghna River. At near surface (down to 25 to 100 m b.g.l.) there are the Holocene aquifers where high arsenic groundwater is frequently encountered. Holocene alluvial sediments, with potentially high arsenic mobility, cover most of the modelled area, from the Tertiary Hills in East to Meghna river in West.

The regional aquifer system can be divided spatially into four major units, the Holocene floodplains, Pleistocene fluvial deposits, Dupi Tila and Tertiary sedimentary bedrock. Another unit may exist, but has not been taken into account in the model, and that is the Meghna river channel deposits that are likely to have generally higher hydraulic conductivities (BGS and DPHE 2001). As described above, three flow systems can be assumed to exist. Flooding of the lowlands during the monsoon season may reverse the groundwater flow direction.

Statistical analysis of tube well data, showing that there is almost no tube well installed at the depth of approximately 30 m (unpublished data from Sida AsMat project covering 13 000 tubewells and southeastern part of Matlab), indicates that at least one thick shallow aquitard is present. This coincides with previous drillings (von Brömssen *et al.* 2007) as wells as exploratory drillings and piezometer installation logs. DPHE/DFID/JICA (2006) describe a multilayered system of aquifers and aquitards. When idealising the system (DPHE/DFID/JICA 2006) four sequences of aquitards and aquifers (unconsolidated sands) were identified down to the depth of approximately 250 m.

5.1.3 Parameterisation

In order to idealise and simplify the complexity of the aquifer system, it was assumed that the system was anisotropic with higher horizontal hydraulic conductivity than vertical hydraulic conductivity. This assumption is reasonable considering the sedimentological characteristics of the Bengal basin comprising fining upward cycles of sediments in these settings (Michael and Voss 2008). Two major approaches with subsequent modifications were used; i) an anisotropic model assuming homogeneous conditions from surface level down to the bottom of the modelling domain (1,000 m b.s.l.) where vertical hydraulic conductivity (K_v) $\ll$ horizontal hydraulic conductivity (K_h) and ii) an anisotropic model including generic aquitards identified through exploratory drillings and aquifer delineation as well as a third aquitard identified and described by DPHE/DFID/JICA (2006).

The hydraulic properties varied for both modelling approaches (i.e. anisotropic homogeneous and generic aquifer/aquitard model). The variation of the properties of the model were based on results from i) our pumping tests, ii) the Michael and Voss (2009a, b) steady-state regional modelling of the Bengal Basin and iii) the aquifer parameter data (BGS and DPHE 2001) for the Holocene and Pleistocene aquifers of Bangladesh. The horizontal hydraulic conductivity was varied between 10^{-3} and 10^{-6} m/s. The vertical hydraulic conductivity was varied between 10^{-6} and 10^{-9} m/s. The hydraulic conductivity in the aquitards, included in the models, was varied between 10^{-9} and 10^{-7} m/s. The storage properties were varied for the calibration of the transient models only. The specific yield (S_y) was varied between 0.1 and 0.20. The total porosity (n) was set to 0.3 and the effective porosity (n_e) was varied between 0.15 and 0.3. A reasonable storativity (S) of approximately 10^{-4} to 10^{-3} (BGS and DPHE 2001) results in specific storage (S_s) for the aquifers varying from 10^{-4} to 10^{-6} 1/m, as $S = b \times S_s$, depending on the thickness of aquifer (b).

For the transient model, the recharge was calculated as the difference between the rainfall and evapotranspiration (ET). During the dry period from November to April, no rain was applied in the model and the applied recharge varied from 0 mm/month to a maximum 300 mm/month (in July). For the steady state model the recharge was set to 700 mm/yr.

5.1.4 Calibration

The steady state model was calibrated to match the interpreted groundwater ages using the MODPATH backtracking flow module. The proce-

dure, as described by Michael and Voss (2008) was applied. The transient models were calibrated to match the measured hydraulic head fluctuations in the installed piezometer nests. The transient model was then realized for five years to generate a stable model. In cases, when the model was not stabilised within five years, it was executed again, using input from the previous run. The amplitude and timing of groundwater levels fluctuations could be calibrated fairly well with a generic approach, i.e. the model could simulate the behaviour of the system, and the amplitudes of the hydraulic heads in simulations correlated with measured hydraulic heads. However, as local hydrogeological properties could not be reproduced exactly in the model, a correlation between specific piezometer nests was difficult to achieve.

5.2 Simulation of pumping test with a groundwater model

Visual Modflow Pro (version 4.1) was used as a modelling tool for simulating the pumping test. Only saturated flow was simulated. The model was set up for transient conditions describing the pumping test. An area of 1000×1000 m surrounding the pumping well was modelled to simulate the pumping test and the base of the modelling domain was set to 110 m below the ground surface. The flow domain was discretized into 35 rows, 42 columns and 17 layers.

It was assumed that the system is homogeneous and anisotropic with a higher horizontal hydraulic conductivity than that of the vertical hydraulic conductivity except, for the upper most layer, which was assumed to be silty clay with a low hydraulic conductivity ($K=10^{-8}$ m/s). The initial heads were set to -2 m b.g.l., using only relative levels and drawdowns obtained in the modelling. No recharge was applied to the groundwater model, since the model only describes the situation during the pumping test. Constant heads were used as boundary conditions for the exterior boundary of the modelled domain and no-flow boundary conditions were applied to the bottom boundary.

General aquifer properties for the shallow aquifers in the flood plains of the Bengal Basin given by BGS and DPHE (2001) were used as initial values for the calibration. The model was calibrated to match the measured drawdown in the piezometers during the pumping test. The parameter estimation module (PEST) was used to calibrate the model. The data used for the optimisation and the calibrated values for the properties are presented in table 2.

Table 2. Data for parameter estimation module (PEST).

Parameter	Initial value	Min	Max
Horizontal hydraulic conductivity (K_x)	10^{-4} m/s	10^{-5} m/s	10^{-3} m/s
Horizontal hydraulic conductivity (K_y)	10^{-4} m/s	10^{-5} m/s	10^{-3} m/s
Vertical hydraulic conductivity (K_z)	10^{-7} m/s	10^{-8} m/s	10^{-5} m/s
Specific storage (S_s)	10^{-5} 1/m	10^{-6} 1/m	10^{-3} 1/m
Specific yield (S_y)	0.2	0.05	0.2

6. RESULTS AND DISCUSSIONS

6.1 Aquifer delineation based on drilling logs

A 3-D subsurface aquifer model was developed using the program Rockworks (v. 2004). Based on the generalized description of the sediments, three aquifers were delineated, a shallow, an intermediate and a deep aquifer. The three aquifers are separated by two dominantly silty clay aquitards identified and described by Mozumder (2011) and Mozumder *et al.* (2011). The subsurface sequence of the study area has been divided into six hydrostratigraphic units. In most cases, the lower two units are missing within the explored depth. The so-called “oxidized aquifer” (von Brömssen *et al.* 2007) occurs as a shallow aquifer and/or in the upper reaches of an intermediate aquifer. The shallow aquifer is composed predominately of fine sand and its thickness ranges between 25 and 60 m. The existence of the aquitard between the shallow and intermediate aquifers is significant from a hydraulic viewpoint. This unit is dominated by silty clay and sandy clay with a wide variation of thickness varying between 3 and 59 m. The aquitard has been encountered at depth varying between 39 and 70 m.

6.2 Estimation of groundwater abstraction in Matlab

Through the survey of the irrigation wells the total groundwater abstraction rate for Matlab (both North and South) was estimated to 176 mm/yr. Of the total amount, 143 mm/yr (81 %) was abstracted from shallow (<50 m) depths, 25 mm/yr (14 %) from depths between 50-75 m and only 8 mm/yr (5 %) from depths below 75 m. The entire irrigation season is between November to June with the heaviest irrigation from January to April. The vertical flow and the risk of cross-contamination can be correlated with the abstraction rate. Assuming vertical flow only, there is a linear relation between induced vertical groundwater flow and the abstraction rate. If porosity is 0.30 and average groundwater abstraction rate is 176 mm/yr, vertical groundwater flow would be 587 mm/year, due to abstraction for irrigation. In Matlab the present groundwater abstraction is slightly less than in other parts of the country, 200 mm/yr has been assumed for Bangladesh on average (Michael and Voss 2008). If all irrigation water were to be tapped from the deep low-arsenic aquifers, the risk of cross-contamination from shallow high-arsenic aquifers would increase significantly. However, the adsorption of As must be considered as well, which would slow the process (Stollenwerk *et al.* 2007, von Brömssen *et al.* 2008, Robinson *et al.* 2011). Irrigation wells are not evenly distributed in the area, they are rather installed in clusters. Thus, the effect from pumping will differ locally within Matlab Upazila.

6.3 Monitoring of hydraulic heads

The hydrographs produced from monitoring the piezometer nests are shown in Figure 6. Based on the hydrographs some general conclusions can be made:

Measured vertical hydraulic gradient: A vertical downward gradient was apparent in all piezometer nests. The annual average for all nests, as measured between the top- and the lowest piezometer, is 0.006, while the

maximum is 0.029 (Nest 7). In four of the nine piezometric nests (nests 6, 7, 9, 11), an upward gradient is observed during the winter period (November to January). The observed downward gradient is consistent with the modelling results (see later). The region acts as a recharge area rather than a discharge area, although Matlab lies adjacent to the Meghna River.

Amplitude of hydrographs: The amplitude of the hydraulic heads as observed in the piezometers varies between 1.0 and 5.1 m. The highest amplitudes are observed in the deeper piezometers of nest 4 and 5 where the number of irrigation wells was high. Although groundwater abstraction increases the stress imposed on the aquifers, the system is recharged during the monsoon rains, and fully recharged after the monsoon period.

Seasonal variation: The hydraulic heads in the shallow piezometers peak during August to September following the beginning of the monsoon period and the lowest hydraulic heads are observed during the dry-irrigation season between January and May. The shallow part of the groundwater reservoir seems to be recharged rather quickly compared to the deeper part of the reservoir, since the deeper piezometers in many cases (especially nest 4, 6, 7, 9, 10) have their lowest hydraulic heads 2-4 months later. The relatively higher amplitude of the groundwater level fluctuations in the deeper piezometers may be the result of the combination of the water level fluctuations in Meghna and hydraulic properties of the deep aquifers.

Aquifer delineation: The hydrographs show different behaviour of shallow and of deeper piezometers, indicating the presence of two or three separate aquifer units depending on location, i.e. a shallow, an intermediate and a deep aquifer. Using hydraulic pressure heads to delineate of aquifers indicates the presence of the following:

- a shallow aquifer extends down to a depth of approximately 50 m b.g.l.
- an intermediate aquifer located between 50 - 100 m b.g.l.
- a deep aquifer located from approximately 100 to at least 250 m b.g.l.

The deep and intermediate aquifers seem to behave similarly and the distinction is not clear. Thus, an aquitard between the intermediate and deep aquifer may be discontinuous or thin.

Hydraulic heads below mean sea level: In nest 4, 5 and 9, the hydraulic heads measured in the deep and intermediately deep piezometers are below the mean sea level during the end of the heavy irrigation period from March to May. This can be a consequence of pumping only. However, most irrigation water is abstracted from relatively shallow depth. Thus, the lower hydraulic head in the deeper piezometers are caused by an unknown abstraction point or a combination of the identified local irrigation and differences in aquifer properties at depth.

Figure 6. Hydrographs of the 12 piezometer nests.

6.4 Hydraulic testing

Drawdown was obvious in all piezometers although the drawdown in piezometer 1:285 (88 m) was small (only a couple of centimetres). The drawdown in the piezometer closest to the pumping well was only 0.52 m which indicates that this piezometer was installed in silty to clayey sediments with little hydraulic response. The maximum drawdown during the pumping test for each of the piezometers, and the distance to the pumping wells are listed in Table 3 and plotted in Figure 8.

The observed drawdowns in the piezometers 2:70, 3:70, 4:70 and 5:70, and the private well, reveal similar responses as the pumping well and, as expected, indicate relatively homogenous hydrostratigraphic unit. The transmissivity (T) and the leakage coefficient (P'/m') are estimated as $3.8 \times 10^{-3} \text{ m}^2/\text{s}$ and $1.3 \times 10^{-7} \text{ 1/s}$, respectively. It can be assumed, based on drillings at the site, that the thickness of the reservoir is approximately 20 m, and that it is separated from the reservoir at 42 m (140 ft) depth

by a 10 m thick layer with a lower vertical hydraulic conductivity. Based on this assumption, the average horizontal permeability (K_h) of the reservoir is 2×10^{-4} m/s and the vertical permeability (K_v) of the layer separating the two reservoirs is 1.3×10^{-6} m/s.

Table 3. Maximum drawdown during the pumping test for each of the piezometers.

Piezometer	Distance from pump- ing well m	Maximum drawdown M	Depth of piezometer m
1:285	2.0	0.02	88.4
1:140	3.5	0.19	42.7
1:70	4.3	0.52	21.3
2:70	12.0	2.06	21.3
4:70	12.0	2.07	21.3
2:140	13.1	0.19	42.7
4:140	13.2	0.09	42.7
5:70	35.9	1.33	21.3
3:70	36.0	1.48	21.3
School	93.6	0.27	17.4
Private	127.5	0.35	29.0

Figure 7. Log-log plot and interpretation of the maximum drawdown during the pumping test versus the distance from the pumping well. The match point has been chosen so that $K_o(r/B) = 1$, and r/B is 1.

The following evaluation of the results focuses primarily on the drawdowns measured in the piezometers 2:70, 3:70, 4:70 and 5:70. In Figure 8, semi log plots and interpretations of drawdown versus time for the piezometers 2:70, 3:70, 4:70 and 5:70 are shown. Corresponding log-log plots are shown in Figure 9. Calculated hydraulic parameters are listed in Tables 4 and 5.

Table 4. Estimated transmissivity, T , and storage coefficient, S , based on semilog plot.

Piezometer	T $10^{-3} \text{ m}^2/\text{s}$	S 10^{-4}
2:70	2.5	30
3:70	3.0	18
4:70	2.5	30
5:70	3.0	18

Table 5. Estimated transmissivity, T , and storage coefficient, S , based on log-log plot.

Piezometer	T $10^{-3} \text{ m}^2/\text{s}$	S 10^{-4}	P'/m' 10^{-7} s^{-1}
2:70	1.5	26	17
3:70	2.3	15	2.2
4:70	3.2	14	2.7
5:70	3.3	13	1.6

Figure 8. Semi-log plot and interpretation of drawdown versus time for the piezometers 4:70, 2:70, 5:70 and 3:70 screened at the depth 21 m (70 ft) below ground level. Piezometer 4:70 and 2:70 are located at the same distance, 12 m, from the pumping well and piezometer 3:70 and 5:70 both located 36 m from the pumping well.

Figure 9. Log-log plot and interpretation of drawdown versus time for the piezometers 2:70 and 3:70 screened at the depth of 20 m (70 ft) below ground level and located on a an east-west line. The drawdown for the piezometers 4:70 and 5:70 is also shown.

6.5 Simulation of pumping test with a groundwater model

The calibrated values of hydraulic conductivities of the aquifer match the previous studies results, i.e. the hydraulic conductivities are within the same order of magnitude. The PEST module was used to calibrate the model with acceptable results (Table 6), except for piezometer 1:70 that appears to be installed in silty to clayey sediments and/or was not working properly as it does not response accordingly. Measured and simulated drawdowns for selected piezometers are shown in Figure 10.

Table 6. Calibrated parameter values.

Parameter	Calibrated value
Horizontal hydraulic conductivity (K_x)	2.25×10^{-4} m/s
Horizontal hydraulic conductivity (K_y)	10^{-4} m/s
Vertical hydraulic conductivity (K_z)	1.30×10^{-6} m/s
Specific storage (S_s)	7.75×10^{-6} 1/m
Specific yield (S_y)	0.2

Figure 10. Simulated and observed drawdown for piezometer 1:140, 1:285, 2:70, 2:140.

6.6 Regional groundwater model

6.6.1 Steady state flow model

Hydraulic conductivity (K_h and K_v) was varied in order to simulate the regional groundwater flow pattern. Backward particle tracking was used for the calibration of the groundwater travel times versus estimated groundwater ages. Particles were released from the study area at depth corresponding to the corrected ^{14}C groundwater dating (Michael and Voss 2008).

The anisotropic homogeneous modelling approach resulted in calculated groundwater ages that are younger than estimated, using ^{14}C dating, for shallow and intermediate depths (0-75 m) for all models. When $K_h/K_v > 1000$ ratio is used at 200 m depth and below simulated groundwater ages become very old (>50 000 yr) in the model, i.e. the simulated groundwater ages are unreasonably old and not in accordance with previous findings by Hoque (2010) and Aggarwal (2000). Furthermore, the groundwater travelling distances needs to be considerably long, all the way to the eastern boundary of the model. Very long regional flow system must be prevailing at very shallow depth, i.e. 30 m and below.

Based on the aquifer delineation, a four layer model was also developed. This modelling approach improved the calibration of estimated groundwater ages. Introducing aquitards with hydraulic conductivities of 10^{-8} to 10^{-9} m/s improved the accuracy of the model. Figure 11 illustrates the differences in regional groundwater flow patterns between the homogeneous anisotropic model and the four layer aquifer/aquitard model.

Figure 11. Left) Cross-section of the homogeneous anisotropic model; Right) Cross-section of the 4 aquifer/aquitard model. Cross-sections are from west to east across the study area. Time marks of the backward particle tracking are set to 1 000 yr. Blue lines are piezometric heads.

The sensitivity of the model to hydraulic properties of shallower domain as well as low hydraulic conductivity of the Tertiary Hill terrain was tested and evaluated. Simulated groundwater ages at Matlab were not sensitive to these changes and the calibration did not change. The groundwater simulations clearly identified two flow-systems, a regional horizontal flow system with recharge areas at the Tripura Hills and local flow systems driven by local topography. The local flow systems reach a depth of approximately 30 m b.g.l. in Matlab, based on the calibrated steady state models.

In Matlab, very few deep (>100 m) irrigation- and production wells are installed and the vertical gradient observed in most piezometer nests out of the irrigation period is likely to reflect natural groundwater flow conditions. The vertical hydraulic gradient of 0.01 based on the observed field measurements is also consistent with the models developed for the study area. The local recharge zones result in elevated hydraulic heads compared to the heads of the regional flow. Even though the vertical gradient is present in Matlab, cross-contamination is likely to be limited (von Brömssen *et al.* 2007, 2008) or restricted to certain areas with many irrigation wells and with limited aquitards. Introducing groundwater abstraction (pumping wells) into the model substantially changes the local flow patterns, especially around the irrigation pumping well clusters.

6.6.2 Transient flow model

The transient flow model was calibrated to match identified behaviour of the hydrographs (Figure 6). The present study did not attempt to calibrate all measured hydraulic heads from all piezometers with simulated heads in one single model because of the lack of specific hydrogeological information. The transient model was updated continuously and new conceptual models were developed based on the two steady state flow models; altogether four major conceptual model approaches were used:

- homogeneous anisotropic model (the same as for steady state flow model)
- 4 aquifers/aquitard model (the same as for steady state flow model)
- 3 aquifers/aquitard model (in which aquifers 3 and 4 from ii were merged together and treated as one unit). The reason for merging aquifers 3 and 4 was to increase the stress on the deeper aquifer, i.e. piezometers at > 200m depth, to attempt to reproduce field observations that otherwise was difficult to simulate.
- 2 layer model (with no aquitards in between the layers, aquifers 1 and 2 were merged to one unit and aquifers 3 and 4 were merged to another unit. The reason for merging aquifer 3 and 4 was again to increase the stress on the deeper aquifer)

Altogether 51 scenarios were run. The evaluation criteria used for the calibration of the model and the refining the conceptual models were based on behaviour of hydrographs, in particular:

- Amplitude and seasonal fluctuation of hydraulic heads: The amplitude and the seasonal patterns of the simulated hydraulic heads were compared with the monitoring data. Since a system with shallow, intermediate and deep aquifers could be identified through the monitoring programme, special emphasis was put on how the hydraulic heads varied with depth. Some models met the criteria for shallow and intermediate aquifers, but not for the deep aquifers, and vice versa.
- Vertical gradient: As a vertical downward gradient was identified through the monitoring programme, one important evaluation criteria was that the model should reproduce this behaviour.
- Pumping effect: Models simulating drawdown due to groundwater abstraction from irrigation wells met the evaluation criteria.

- Aquifer delineation: The fact that hydrographs from the piezometers at varying depths in the 10 nests indicate a multi-aquifer/layered system was used as an evaluation criterion. Models indicating different behaviour versus depth were considered to meet better the evaluation criteria.

The amplitude and timing of the groundwater levels fluctuations could be calibrated fairly well, i.e. models could simulate the behaviour of the system: the simulated hydraulic heads correlated in general with measured hydraulic heads. However, it was not possible to develop a model that could meet all the evaluation criteria for the entire Matlab study area, and at the same time, to match all hydrographs from each piezometer nests. Rather, common features and parameter values were identified via the modelling that could explain the different hydrographs.

General observations

At shallow depth it was possible to simulate the pumping effect in a satisfactory way, but this was more difficult at large depth as the deepest installed piezometers were installed at >200 m b.s.l. where little or no abstraction was introduced into the model. It is possible that abstraction points not included in the model could explain this behaviour.

It was observed that the amplitude and pattern of the hydrographs obtained from piezometers installed at depths between 50 or 100 m b.s.l. down to a depth of 200 m b.s.l. coincide. In order to simulate this, the unit between 100 – 200 m b.s.l. needed to be rather uniform with a very thin or no aquitard included in the model. Thus a 3 aquifer model generally met the evaluation criteria better than a 4 aquifer model. Borelogs also support the suggested 3 aquifer model. Although it was possible to simulate the impact from groundwater abstraction at all depths, we did not succeed to simulate a drawdown at 200 m depth that coincided with the drawdown observed at 100 m. The observations from nest 4 with a pumping effect and lowest hydraulic head at the depth of 200 m b.s.l. could not be satisfactory simulated, while for nest 5 this was achieved. The pumping effect could be simulated, but in these models the effect was greatest at the depth where most irrigation wells was installed. Hydraulic heads below 0 m a.s.l. were also difficult to simulate with reasonable parameterisation. The nests where simulated drawdowns were largest coincided with the areas with high density of irrigation wells (nest 3, 4, 5, 9 and 12), which were also the nests where largest impacts from irrigation abstraction had been observed.

Generally a lower S_s value ($<10^{-5}$ 1/m) was, with the exception of the shallow aquifer, needed in order to simulate the amplitudes observed at deep piezometer hydrographs. Changing S_y did not affect the results. The fluctuations of the water level in Meghna control, to some extent, the results of the simulated hydraulic heads. This was validated by removing the fluctuation of Meghna in some of the models and also through comparison of the amplitudes of hydraulic heads at depth. In models where the hydrographs at depth were flat, the corresponding

field data from deep piezometer in nest 11 showed fluctuating water levels due to its close proximity to Meghna.

Contrary to most nests, an upward gradient during September to February was observed in nest 9. This pattern could also be seen in the simulations. It should be noted that around nest 9, the topsoil is missing.

Homogeneous anisotropic model

The homogeneous anisotropic model did not meet the evaluation criteria well. Generally, this modelling approach could not reproduce the vertical downward gradient identified in the hydrographs. Homogeneous anisotropic models with a low (100) K_h/K_v ratio could meet the evaluation criteria for amplitudes at shallow and deep depths; however, this set-up could not be calibrated for the steady state scenario. Here simulated heads over depth were close at respective locations, as seen in hydrographs, and the vertical gradients were reasonable, however the aquifer delineation could not be observed and pumping effects were absent even though S_s was low (10^{-5} 1/m). When the K_h/K_v ratio increased (1 000 – 10 000) pumping effects could be seen at shallow depths. However, then the amplitudes and vertical gradients could not meet the evaluation criteria. None of the homogeneous anisotropic models could meet the evaluation criteria of pumping effects on the deep aquifer (visible at a depth of approximately 200 m, piezometer 5). For homogeneous anisotropic models with $S_s = 10^{-4}$ 1/m deep aquifers head pressure fluctuations were almost absent.

3 and 4 aquifer/aquitard model

The conceptual models with 3 or 4 aquifers separated by aquitards met the evaluation criteria better and could simulate the hydrographs satisfactorily, which is consistent with the findings based on steady state modelling results. In order to improve the modelling result, the S_s value was decreased at depth in order to simulate the pumping effect in the deep aquifer (aquifer 3 and 4 in the model). Models, where the aquifers 2, 3 and 4, respectively, had an S_s value of 10^{-5} 1/m or even lower simulated the pumping effect better. For the shallow aquifer an S_s value of 10^{-4} 1/m seems reasonable. The three aquifer/aquitard model (merging the aquifers 3 and 4) met the evaluation criteria better.

Suggested model and properties for aquifers:

Combining the models that best meet the evaluation criteria results in a high yield 3 (or 4) aquifer/aquitard model separated by two or three aquitards and decreasing S_s and K with depth (Table 7). The suggested model properties are in good agreement with those of the steady state model.

Table 7. Suggested aquifer properties based on results from the transient flow model.

	Depth m b.g.l.	K_h m/s	K_v m/s	S_s 1/m
Aquifer 1	0-50	$10^{-5} - 10^{-4}$	$10^{-6} - 10^{-4}$	$5 \times 10^{-4} - 5 \times 10^{-3}$
Aquifer 2	75-100	$10^{-6} - 10^{-5}$	$10^{-6} - 10^{-5}$	$10^{-5} - 10^{-4}$
Aquifer 3	100->	$10^{-6} - 10^{-5}$	$10^{-6} - 10^{-5}$	$10^{-6} - 5 \times 10^{-6}$

Figure 12. Simulated hydraulic heads of a three aquifer/aquitard model meeting the evaluation criteria well, this model met the evaluating criteria for nest 3, 5, 8 and 12 well, for nest 4, 6, 7 reasonably well and the results for nest 9, 10 and 11 were poor.

The groundwater flow models clearly support the conceptual model of the smaller and locally abundant flow-systems driven by local topography for the shallow and to some extent the intermediate aquifer. These local flows-systems are more obvious during the monsoon period as the re-

charge raises the groundwater levels and thus amplifies the locally developed flow-cells at shallow and intermediate depths (Figure 13).

Figure 13. Simulation results illustrating the two flow system.

Flooding of the lowlands gives the system a more regional flow-pattern as compared to modelling without flooding. The model used does not take into account the surface water levels and thus results in more distinct local flow-patterns. If flooding were modelled, the resulting vertical hydraulic conductivity would probably be higher than the value used in the models. Deep unidentified aquitards and the lower boundary of the model (set to -1000 m in the model) play an important role, as the specific storage is connected with the thickness of the aquifer. In the model, this is accounted for by varying the S_s value. Typically a thicker model with lower S_s value would behave similarly to a thinner model with proportionally higher S_s value.

6.7 ^{14}C analysis

The ^{14}C -activity in the groundwater samples varied from 23 to 86 pMC (percent modern carbon), $\delta^{13}\text{C}$ values ranged between -19.6 ‰ and -13.1 ‰ (Table 8). The corrected groundwater age was linearly correlated with the depth of tube wells and the groundwater samples were old; ages 1250 – 11 960 yr indicate restricted groundwater flow at depth below 30 m. The estimated groundwater ages at the depth of 40 m (6 100 yr) coincide with the estimated age of sediments at the depth of 36 m in the area (8 000 yr; von Brömssen *et al.* 2008). The groundwater ages also coincide with the findings of Aggarwal *et al.* (2000) and Hoque (2010).

When one assumes that the groundwater recharge is local, the measured vertical gradient of 0.01 and the vertical hydraulic conductivity (K_v) of 1.5×10^{-8} m/s fit the slope of the ^{14}C -ages of groundwater vs. depth very well. If ^{14}C ages are extrapolated young groundwater would be expected

at a depth of approximately 25 m b.g.l., which coincides with the depth of the previously described local flow-systems.

Table 8. ^{14}C -activity and $\delta^{13}\text{C}$ values for tubewells samples.

Depth	^{14}C -activity	$\delta^{13}\text{C}$	Estimated age	Tubewell
m	pMC	‰	yr	No
26	85.89 ± 0.45	-17.6	1 250	54
40	47.23 ± 0.30	-17.3	6 100	37
49	53.26 ± 0.34	-13.1	$5\,095 \pm 65$	32
58	36.80 ± 0.28	-17.6	$8\,065 \pm 65$	58
69	28.98 ± 0.25	-19.6	$10\,865 \pm 80$	63
80	22.67 ± 0.23	-12.9	$11\,960 \pm 80$	35

Figure 14. Groundwater ^{14}C -ages and calculated ages based on downward vertical flow.

7. CONCLUSIONS

Through detailed studies of prevailing aquifer conditions, the scientific community has now been able to delineate the main mechanisms of mobilisation and enrichment of As in the aquifers of Bangladesh (Ahmed *et al.* 2004, BGS and DPHE 2001, Bhattacharya *et al.* 1997, Nickson *et al.* 1998, Smedley and Kinniburgh 2002, van Geen *et al.* 2003). Although many studies on high arsenic groundwater in Bangladesh have been carried out, only a few have focused on groundwater flow in relation to elevated concentrations of arsenic or delineation of low-arsenic aquifers for tapping safe groundwater (Michael and Voss 2009a, b, Hoque 2010 and 2011, Burgess *et al.*, 2010). Accordingly, assessing sustainability of low-arsenic aquifers in regions with elevated concentrations of As and the

risk for cross-contamination remains a main concern. The groundwater models developed, proved to be a useful tool for enhancing the understanding of the groundwater flow system when combined with field observations of seasonal hydraulic head fluctuations and ^{14}C dating of groundwater.

Even though Matlab lies adjacent to the Meghna River, the region acts essentially as a recharge area. Hydraulic heads fluctuate between 1 and 5 m as expected. Irrigation wells accounting for most of the groundwater abstraction are placed in clusters. Thus, hydraulic heads are affected only locally, as observed in the installed multi-level piezometers. Even though almost 180 mm groundwater/yr, as an average of Matlab, is abstracted for irrigation purposes, the system is fully recharged during and after the monsoon period.

The anisotropic homogeneous modelling approach resulted in $K_z \ll K_{x,y}$ by a factor of 10^3 - 10^4 . This is in accordance with previous studies (Michael and Voss 2009a, b). However, the three aquifer/aquitard layer model fit the measured hydraulic head fluctuations better and the delineation of the aquifers that was done based on results of the piezometer nest drillings. This agreement between the model and determined field observations adds to the credibility of the 3 aquifer/aquitard model.

The groundwater simulations identified at least two flow-systems; i) a deeper, regional horizontal flow system with recharge areas at the Tripura Hills in the east and ii) shallow, local flow systems driven by local topography and with local groundwater recharge. The local groundwater flow systems result in elevated hydraulic heads compared to the lower hydraulic heads of the deeper regional flow system as vertical hydraulic conductivity is lower than horizontal hydraulic conductivity and aquifers are separated by continuous or discontinuous aquitards. Calibrated groundwater models indicate that the local flow systems in Matlab reach a depth of approximately 30 m b.g.l. These modelling results are consistent with groundwater ages based on ^{14}C , indicating that young groundwater should be expected down to a depth of approximately 25 m b.g.l.

The downward vertical gradient, down to 200 m b.g.l., observed in the multi-level piezometer nests is consistent with modelling results. As very few deep (>100 m) irrigation- and production wells are installed in the area the vertical hydraulic gradient is assumed to be mainly a result of aquifer properties, geometry, hydrology and topography, rather than driven by groundwater abstraction. Furthermore, a natural vertical hydraulic gradient of 0.01 and a K_v value of 1.5×10^{-8} m/s, which is a reasonable value for homogeneous anisotropic model, fit the ^{14}C -ages of the analyzed groundwater samples well.

Even though a vertical hydraulic gradient is present in Matlab, cross-contamination is likely to be limited or restricted to specific areas with higher number of irrigation well and discontinuous aquitard distribution. Introducing the irrigation pumping wells into the models substantially

changes the local flow patterns, especially around pumping well clusters. If irrigation- and/or production wells were to be lowered to deeper depths an increased vertical flow will be induced as observed in multi-level piezometer nests today. The vertical flow and risk for cross-contamination will correlate with the abstraction rate.

It was observed that hydraulic heads of certain deep piezometers was below the mean sea water level during the end of the heavy irrigation period. While the cause of this behaviour has not been verified, the most reasonable explanation is groundwater abstraction.

Even though this study has highlighted the behaviour of the groundwater flow in Matlab and the risk for cross-contamination, further groundwater flow studies are needed. Even so, targeting low-arsenic aquifers is a viable option for providing people with safe drinking water. When groundwater at depth is found low in arsenic concentrations it should be further developed for drinking water purposes. At the same time installing irrigation- or production wells at depth is strongly discouraged. The results from this and similar studies can further contribute to a development of a rational management and mitigation policy for the future use of the groundwater resources for drinking water supplies.

8. ACKNOWLEDGMENTS

The Ramboll Foundation (pnr 61150619881), Sida-SAREC (dnr 2002-129), MISTRA (2005-035-137) and Sida (the SASMIT project, contribution no. 73000854) are acknowledged for funding different parts of this study. We are thankful to the people of Matlab in Bangladesh for making our stay and work an unforgettable moment. We thank the people involved and engaged directly and indirectly in making the work successful; Arif Mohiuddin Sikder, Bishwajit, Rajib, Samrat, Jahid, Aminul, Robi, Ratnajit and Omar, Malek and all the other local drillers at Matlab. Special thanks to Dr. Sven Jonasson at Geologic in Göteborg AB for late-night but fruitful discussions on groundwater flow modelling, Judith for internal review on the manuscript, and ICCDR,B for letting us stay at their guesthouse.

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