
Declining groundwater level and aquifer dewatering in Dhaka metropolitan area, Bangladesh: causes and quantification

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Abstract Large abstraction by water-wells has been causing a linear to exponential drop in groundwater level and substantial aquifer dewatering in Dhaka, Bangladesh. The city is almost entirely dependent on groundwater, which occurs beneath the area in an unconsolidated Plio-Pleistocene sandy aquifer. Analysis shows that the pattern of water-level change largely replicates the patterns of change in the rate of groundwater abstraction. Contribution of the aquifer storage to the abstraction is estimated to be more than 15% in the year 2002. This abstraction has caused a sharp drop in water level throughout the city and turned into two cones of depression in the water level. Upper parts of the aquifer are already dewatered throughout the area, with the exception of part of the northeast and southeast corner of the city. It is calculated that about 41 million cubic metres (MCM) of the aquifer dewatered by the year 1988, which increased to 2,272 MCM in the year 2002. Water-level decline may increase non-linearly due to limiting vertical recharge in areas where the aquifer is dewatered and may severely threaten the sustainability of the aquifer.

Résumé Des prélèvements massifs dans les puits ont causé des chutes de niveau piézométriques linéaires à

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exponentielles et un dénoyage substantiel de l'aquifère à Dhaka, au Bangladesh. La ville est presque intégralement dépendante des eaux souterraines, contenues sous ce secteur dans un aquifère de sables non consolidés plio-pléistocènes. Les analyses démontrent que l'allure des variations de niveau reproduit celle générée par des prélèvements en eau souterraine. La contribution des réserves propres de l'aquifère aux prélèvements est estimée à plus de 15% sur l'année 2002. Le prélèvement considéré a occasionné une chute de niveau à l'échelle de la ville, et est marqué par deux cônes de dépression majeurs. Les franges supérieures de l'aquifère sont déjà dénoyées sur le secteur, à l'exception des extrémités nord-est et sud-est de la ville. Selon les calculs, environ 41 millions de mètres cubes (MCM) de l'aquifère ont été dénoyés en 1988, cette quantité augmentant ensuite jusqu'à 2,272 MCM en 2002. La baisse du niveau piézométrique peut s'amplifier de manière non-linéaire sur les secteurs dénoyés, du fait d'une réalimentation limitée, menaçant sérieusement la pérennité de l'aquifère.

Resumen La extracción fuerte mediante pozos de agua ha causado un descenso lineal a exponencial en el nivel de agua subterránea y un drenaje significativo del acuífero en Dhaka, Bangladesh. La ciudad depende casi completamente de agua subterránea la cual ocurre debajo del área en un acuífero arenoso no consolidado del Plio-Pleistoceno. Los análisis muestran que el patrón de cambio del nivel del agua replica en gran parte los patrones de cambio en la tasa de abstracción de agua subterránea. La contribución del almacenamiento del acuífero a la abstracción se estima en más del 15% en el año 2002. Esta abstracción ha causado un descenso brusco en el nivel del agua en toda la ciudad habiéndose transformado en dos conos de depresión en el nivel del agua. Las partes superiores del acuífero se encuentran drenadas en toda el área, con la excepción de la porción nororiental y la esquina suroriental de la ciudad. Se calcula que aproximadamente 41 millones de metros cúbicos (MMC) del acuífero se habían drenado para el año 1988 lo cual aumentó a 2,272 MMC en el año 2002. El descenso del nivel del agua puede incrementar de modo no lineal debido a recarga vertical limitada en áreas donde el acuífero es drenado y puede amenazar severamente la sostenibilidad del acuífero.

Keywords Over-abstraction · Groundwater level · Aquifer dewatering · Dhaka metropolitan · Bangladesh

Introduction

Like many natural resources, groundwater is being exploited at an increasing rate all over the world. Groundwater is generally preferred as a source of potable water in the developing world because of its ready availability and natural protection from contamination. It is commonly used for irrigation and to supply industrial and domestic needs. A lack of proper understanding of the groundwater system, in terms of resource utilization, is one of the major limitations to the effective management of groundwater resources.

Dhaka is located in the central part of Bangladesh on the River Buriganga. It covers an area greater than 250 km² and is home to more than 10 million people. It is one of the fastest growing megacities in the world and the population of the city is rapidly increasing. The rapid rise in the urban population is a major constraint to development of infrastructure and services, including water supply, sanitation, sewerage and drainage services.

Dhaka is dependent primarily on groundwater for the urban water supply; about 84% of the present municipal water supply comes from groundwater and 16% is from surface water (WASA 2003). The dependence on groundwater for domestic, industrial, and commercial water supply in the city area was more than 95% prior to the commissioning of a large surface water treatment plant (Sayedabad Surface Water Treatment Plant) in 2002. Systematic groundwater development began in the city of Dhaka in 1949 and available records show that groundwater abstraction in the city has increased drastically in recent decades (Ahmed et al. 1999). Water tapped from the Dupi Tila aquifer in the city of Dhaka is free from arsenic, the main constraint on groundwater use for drinking purposes in the southern part of the country (e.g. BGS/DPHE 2001; Ahmed et al. 2004). To meet the ever-increasing demand of the city dwellers, DWASA (Dhaka Water Supply and Sewerage Authority) has undertaken a program for abstraction of more groundwater from the aquifer beneath the city. As of 2003, DWASA produced 1,160 million litres of groundwater per day through 389 DTW (Deep Tube Wells; WASA 2003). The number of private boreholes has also increased substantially to 970 wells (WASA 2000), and abstraction through these wells remains unquantified but is likely to be significant. Though the city is largely dependent on groundwater, currently there is no management plan in place, and large-scale uncontrolled groundwater development is occurring. Lack of proper understanding of the groundwater system is one of the major constraints on sustainable development of groundwater in the megacity. The objectives of this work are to correlate the trend of groundwater level decline and aquifer dewatering with over-abstraction, and to quantify the abstraction in relation to recharge and aquifer storage.

Natural settings

The metropolis of Dhaka resides in the southern tip of the Madhupur Tract—an elevated Pleistocene terrace (e.g. Morgan and McIntire 1959) that stands higher than the surrounding flood plain. The surface elevation of the city area ranges from 1.5 to 15 m above the PWD (Public Works Department) datum (+/- 1 m to mean sea-level). The elevation differences are reflected by the distinct landforms: high lands, flood plains, and abandoned channels and depressions (Fig. 1). The ground surface elevation of the low lands and abandoned channels and depressions (about 50% of the total city area) varies from 1.5 to 3.5 m above PWD datum, which makes the area vulnerable to monsoon flooding. The area is linked with the Ganges-Brahmaputra river system (locally known as Padma-Jamuna-Meghna river system) by the interconnecting streams and retention basins. Four rivers—the Buriganga, Turag, Balu and the Tongi Khal (canal)—form the Dhaka metropolitan area borders. These local rivers feed the flood plains and marshy lands in and around the city. Like other parts of the country the climate of the city is a tropical monsoon climate. The long-term mean annual rainfall is over 2,000 mm, and about 80–90% of this occurs during monsoon (May–October).

The surface geology of the metropolis follows the geomorphic expression of the area. At the land surface, Pleistocene alluvium occupies the dissected uplands, and alluvium of recent river-borne deposits covers the low-lying flood plains (Fig. 1). The area is characterized by a 400–500-m-thick unconsolidated sequence of fluvio-deltaic deposits of Plio-Pleistocene to Holocene age. The Madhupur and/or flood-plain clay materials overlie the unconsolidated fluvio-deltaic sediments composed of gravels, sands, silts and clays. The generalized stratigraphy of the area is given in Table 1. These underlying unconsolidated layers form the main aquifer system for the city of Dhaka and are effectively confined by the Madhupur clay, which is known to be part of the Dupi Tila Formation. This formation is believed to be eroded and/or subsided within the flood plain and depressed areas at the edges are filled up by Holocene sediment known as the Dhamrai Formation and Bashabo Formation according to locality (Davies and Exley 1992). The Dhamrai Formation widely serves as the aquifer for the western region outside of the city while the Bashabo Formation acts as a localized shallow aquifer on the Madhupur Tract, merging with the flood plain in the southeast part of the city. The DWASA abstracts water from the Dupi Tila aquifer within the city between 50 and 200 m below ground level.

Although the aquifer in the metropolitan area is relatively homogeneous, spatial continuity and the connection of the aquifer with the surrounding Holocene flood plain aquifer is not clear. It is understood that the hydraulic conductivity of the Holocene flood plain aquifer should be higher than the Pleistocene Dupi Tila aquifer due to the diagenetic differences. The Dupi Tila aquifer has low transmissivities in the range 500–2,000 m²/day (EPC/MMP 1991), while much higher transmissivities (3,000–

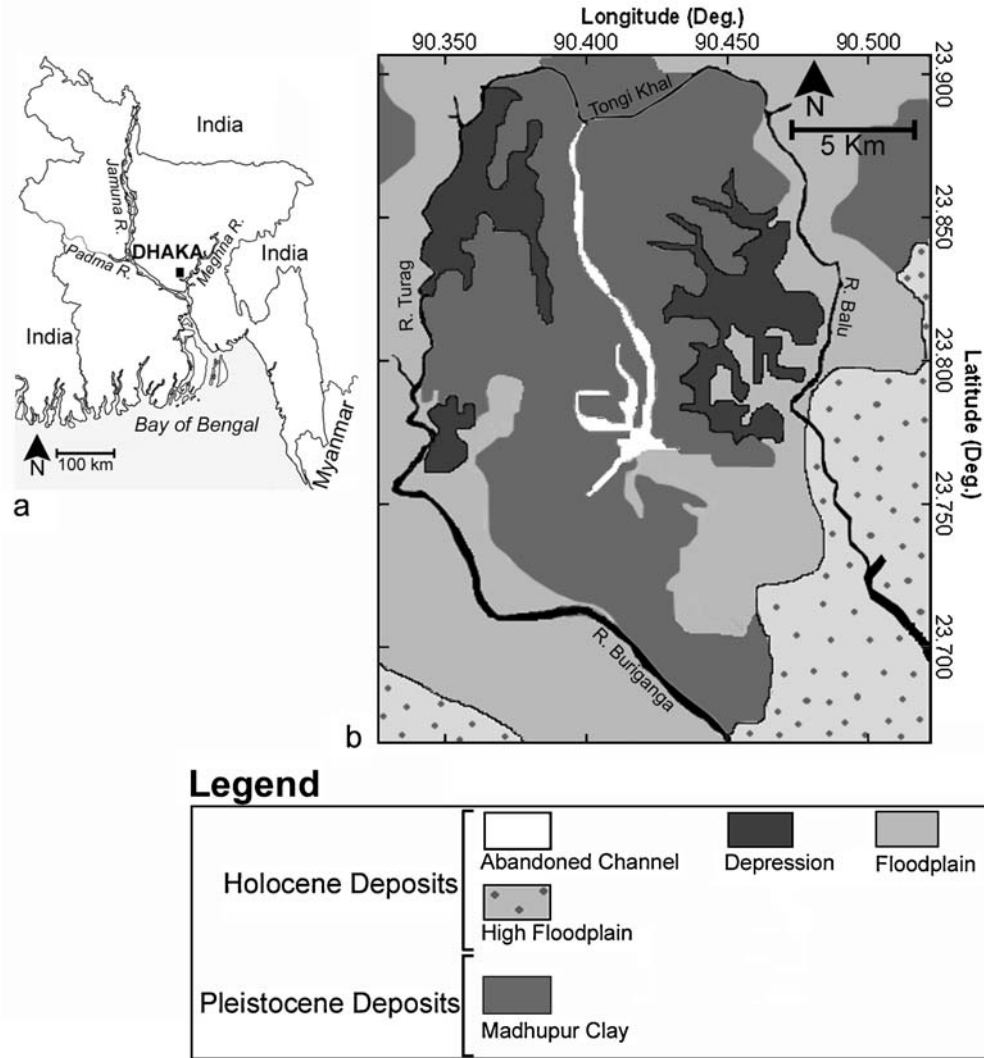


Fig. 1 a Study area in Bangladesh context; b Natural setting of the study area (Dhaka), with surface geology (modified after EPC/MMP 1991)

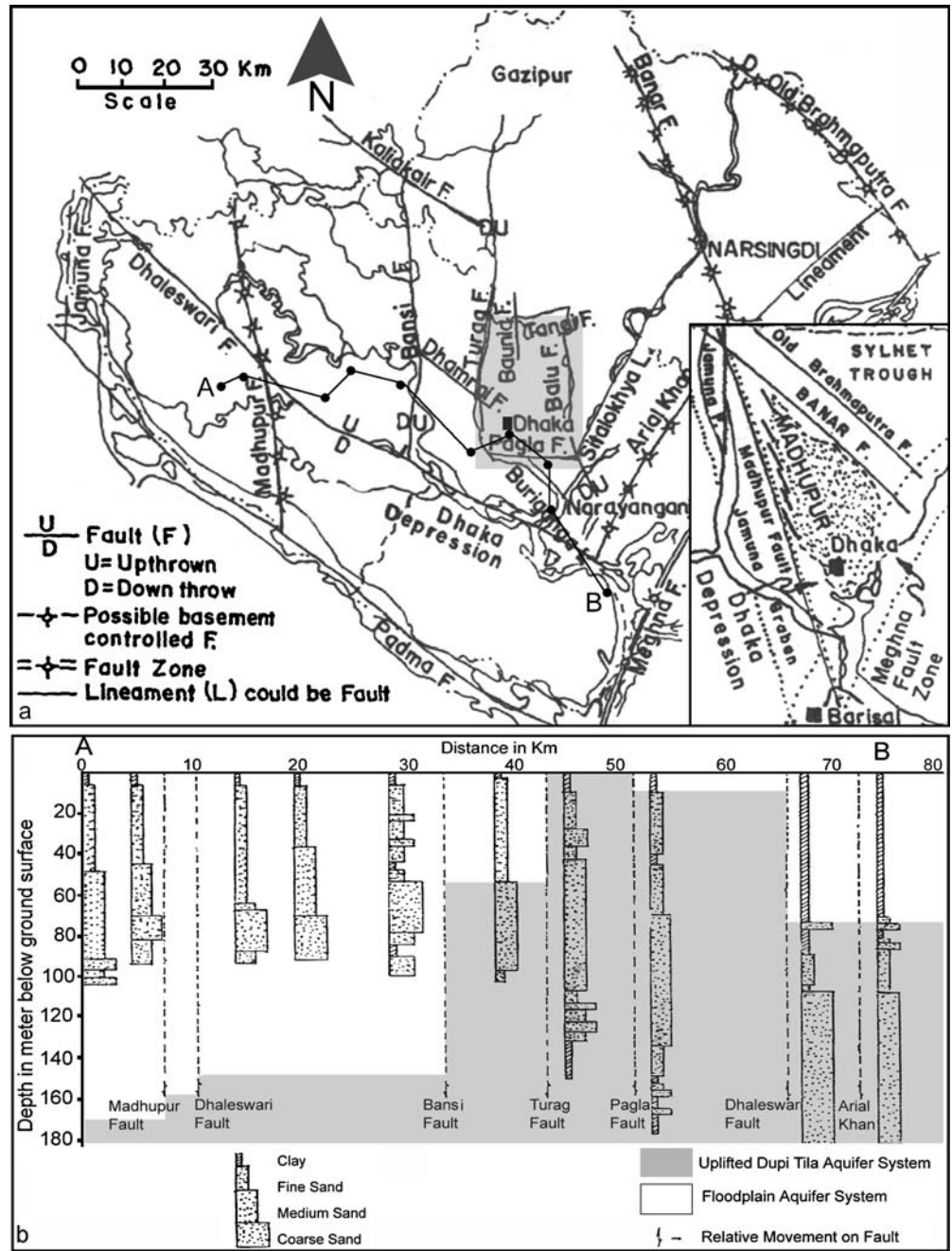
5,000 m²/day; Davies 1994) characterize the flood-plain Holocene aquifer at similar depths. In addition, the flood-plain aquifer has high concentrations of dissolved arsenic, whereas the Dupi Tila aquifer in the city of Dhaka has very low levels to undetectable levels of arsenic. Moreover, hydrostructurally the area is very complex as it is bounded by some very active tectonic elements: the Sylhet trough in the north, the Jamuna Graben in the west, the Dhaka depression in the south and the Meghna Fault zone

in the east (Fig. 2). The Madhupur tract around the city of Dhaka is characterized by numerous faults (Fig. 2a; EPC/MMP 1991; Khandoker 1987), which have a control on the course of local rivers and may affect aquifer-river interaction. These faults control rivers, and landform may act as hydrostructural features on the hydrogeology of the region. According to EPC/MMP (1991), unconsolidated aquifer materials are terminated by the faults and Dhaka seems to be uplifted as a horst block (Fig. 2b). The rivers

Table 1 Stratigraphy of the city of Dhaka region (Modified after Morris et al. 2003)

| Stratigraphic age | Stratigraphic name | Lithology | Thickness (m) | Function in aquifer system |
|--------------------------------|-------------------------|--|---------------|----------------------------|
| The flood plain Area | | | | |
| Holocene | Flood plain | Alluvial silt, sand and clay | 6–15 | Upper aquitard |
| Late Pleistocene to Holocene | Dhamrai Formation | Alluvial sand | 100–200 | Main aquifer |
| Pre-Pleistocene | Not named | Unknown | – | |
| The Madhupur Tract Area | | | | |
| Recent | Lowland alluvium | Swamp, levee, and riverbed sediments | 0–5 | Upper aquitard |
| Holocene | Bashabo Formation | Sand (discontinuous) | 3–25 | Aquifer |
| Pleistocene | Madhupur Clay Formation | Silty clay member, Fluvio-deltaic sand | 6–25 | Upper aquitard |
| Plio-Pleistocene | Dupi Tila Formation | Dupi Tila clay stones Fluvio-deltaic sands | 100–180 | Main aquifer |
| Miocene | Girujan Clay | Bluish clay | 50–100 | Known lower aquitard |

Fig. 2 a Tectonic map of Dhaka region—after EPC/MMP 1991 and Khandoker 1987 (inset). Area under shade indicates the area presented in Fig. 1 and *A–B* is line of section given in **b**. **b** A cross-section along *A–B* shows the uplifted Dupi Tila aquifer in the city of Dhaka with respect to surrounding region (modified after EPC/MMP 1991)



and streams flowing through these fault systems could have cut through the overlying clay aquitard and in some places may be connected with the aquifer by semi-permeable materials. These fault-controlled rivers may play a significant role in the hydrodynamic equilibrium of the area, but the exact mechanism is unclear.

Methods and materials

The present work assembles data on groundwater abstraction and groundwater level/piezometric head from DWASA and BWDB (Bangladesh Water Development Board),

respectively. Some borehole lithologs and geophysical resistivity logs were also collected from the same sources.

Abstraction analysis

DWASA, established in 1963, inherited 33 wells from DPHE (Department of Public Health Engineering), which was responsible for the water supply in the city of Dhaka before 1963. The number rose to 49 in the year 1970 via new installations by DWASA; details of these wells are not available in the current database. However, it is understood that all of these wells, located in the city area of that time (1960s; shown in Fig. 3), were replaced by DWASA in the

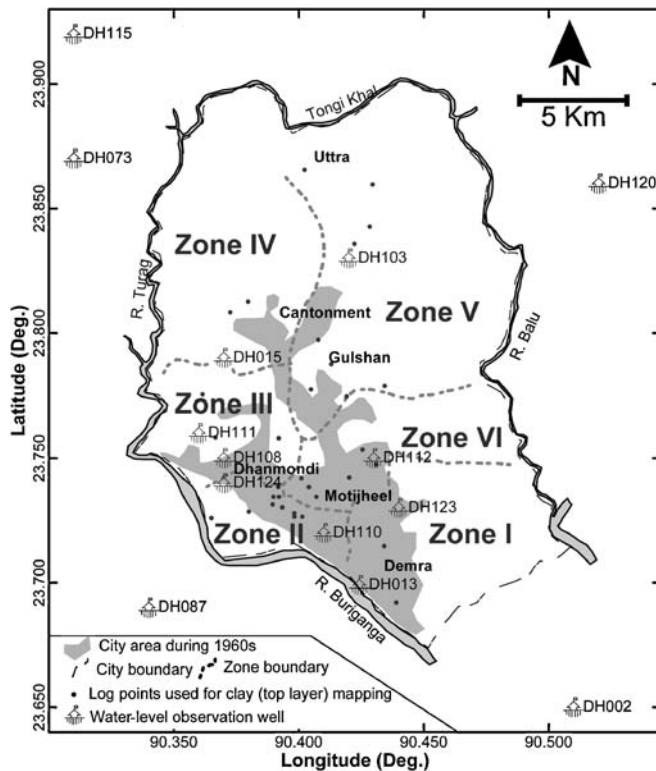


Fig. 3 Locations of BWDB water-level observation wells and logs (litho and geophysical). DWASA public-water-supply distribution zones, approximate extent of urban area during 1960s and prominent locality names are shown on the map

1980s. There is information about replacement of the few DPHE wells in the DWASA database but no record on how long these wells were in inoperative mode. In some cases, it is known that a particular well was replaced but the database contains no information on the replacement. The DWASA database contains information for the period 1970–2003 on the date of well installation, depth to the pump housing, well capacity, static water level, etc.. However, it does not indicate how long these wells remained in operation. In the present analysis, it is assumed that wells are in operation from the year of installation; the few wells that have no data on the year of installation are not taken into consideration. In the case of known replaced wells, their replacement date was used as the starting year of operation. Most of the well locations were obtained by digitizing the paper map from the Bangladesh University of Engineering and Technology (BUET 2000) and some by locating the physical address. It should be mentioned that 59 of 389 (total number of wells in operation by DWASA as of 2003) and private wells are not considered for the spatio-temporal analysis due to lack of information on location and/or starting year of operation. Although the data set is incomplete and accuracy is to some extent compromised, the relationship between the increase in abstraction and fall in water level over the area can be approximated. All available wells in operation in the years 1988, 1993, 1998 and 2002 are plotted on the water-level surface map (see section [Piezometric surface construction](#) below).

DWASA serves the city dwellers through seven distribution zones, six of which are within the city limits (Fig. 3). Zone-wise yearly abstraction data for DWASA and private production wells for the year 1983–2003 have been incorporated in this study to unveil the reason behind the nature and variability of the piezometric surface with time. A small part of the abstraction data for DWASA production wells and some of the data for the private wells are estimated. DWASA abstraction data on individual zones for the years 1990–1992 are missing, but total abstraction data for those years are available. Abstraction for the individual zone was estimated as a percentage of the total abstraction and trend in the data was also considered. Private abstraction data are missing for the years 1983–1990 and 2001–2003, but the total abstraction has been estimated by assuming that private abstraction during the missing years is 0.36 of DWASA abstraction. This ratio is obtained from the average of the available private abstraction data in comparison to the DWASA abstraction.

Water level and piezometric analysis

For the current work, water-level data from 14 observation wells existing in and around the city of Dhaka were collected. The dataset contains the location and depth of observation wells and the height of the measuring point from the PWD datum (Table 2), height of the measuring point from the ground surface and depth to water table from the measuring point for the period 1981–2003. Starting dates for measurements vary for individual observation wells between the years 1981–1990. Water-level elevation is calculated with respect to PWD datum. In some cases, the reference level of water-table measurement is set to zero in the BWDB database, which is unreasonable as the topographic elevation of those areas is about 5 m above the PWD datum. In the present study, a figure for those points is estimated from topographic elevation and height of the measuring point from the ground surface. In some cases, new observation wells were installed in the same location to replace the older wells (Groundwater Circle, BWDB, personal communication, 2007); the height of the measuring level (with reference to PWD datum) at such stations was taken from the subsequent replacement well setup (Table 2) and this measuring level height was applied as reference to the data from the earlier setup. The observation wells are screened 20–60 m below the ground surface. There is no known water-table monitoring bore below these depths specifically outside the city area. Among the observation wells, five are outside the city and the rest are within the metropolitan area.

There are some ambiguities in the BWDB data with regard to the reference measurement point and water-table information for observation wells DH124 and DH112. In both of these stations, the water level is ‘measured’ below the well depth, which is impossible. In the case of DH112, the height of measuring level for the later/replacement setup was used and depth of the screen assumed to be below the water table. It was difficult to sensibly estimate an

Table 2 Information on the Bangladesh Water Development Board (BWDB) water level monitoring bores (extracted from the BWDB electronic database)

| Well ID (old) | Well ID (new) | Latitude | Longitude | Geographic area (thana) | Screen depth (m) | Measurement started | Height of measuring level from PWD (m) |
|---------------|---------------|----------|-----------|-------------------------|--------------------|-------------------------|--|
| DH103 | GT 2608001 | 90.41990 | 23.83009 | Cantonment | 44.20 | 31.03.1992 | 7.16 ^b |
| | | | | | 51.83 ^a | 07.05.2000 ^a | 7.16 ^a |
| DH124 | GT 2616005 | 90.37001 | 23.74009 | Dhanmondi | 41.46 | 08.02.1990 | 7.57 ^b |
| | | | | | – | 10.12.2001 ^b | – |
| DH087 | GT 2638008 | 90.33985 | 23.68973 | Keraniganj | 45.27 | 25.06.1985 | 8.78 |
| DH110 | GT 2642009 | 90.40985 | 23.71973 | Lalbagh | 25.00 | 25.05.1980 | 7.41 |
| | | | | | 52.83 ^a | 25.11.2000 ^a | 8.12 ^a |
| DH015 | GT 2672018 | 90.37001 | 23.78973 | Mirpur | 30.61 | 21.10.1984 | 7.47 |
| | | | | | 42.48 ^a | 21.03.1991 ^a | 7.18 ^a |
| DH108 | GT 2650011 | 90.37001 | 23.75009 | Mohammadpur | 34.75 | 01.11.1981 | 7.59 |
| DH111 | GT 2650012 | 90.36031 | 23.76009 | Mohammadpur | 30.92 | 25.04.1983 | 9.32 |
| DH073 | GT 2672017 | 90.31006 | 23.87010 | Savar | 32.93 | 22.01.1986 | 9.67 |
| DH115 | GT 2672018 | 90.31006 | 23.92010 | Savar | 57.30 | 25.12.1978 | 10.47 |
| DH112 | GT 2668019 | 90.43031 | 23.74973 | Sabujbagh | 30.18 | 22.10.1984 | 7.27 |
| | | | | | – | 01.01.1998 | 5.73 ^b |
| | | | | | 56.3 ^a | 05.01.2001 ^a | 5.73 ^a |
| DH123 | GT 2668020 | 90.44000 | 23.73009 | Sabujbagh | 32.93 | 28.05.1989 | 5.22 ^b |
| | | | | | 51.83 ^a | 11.06.2000 ^a | 5.63 ^a |
| DH013 | GT 2688021 | 90.41990 | 23.69973 | Sutrapur | 25.81 | 10.11.1988 | 5.98 |
| | | | | | 42.07 ^a | 05.07.1998 ^a | 7.14 ^a |
| DH002 | GT 6720005 | 90.51000 | 23.65008 | Narayanganj | 29.27 | 13.01.1987 | 6.20 |
| DH120 | GT 6768008 | 90.52005 | 23.86010 | Rupganj | 20.07 | 19.03.1990 | 8.75 |

^aData is collected from the Groundwater Circle, BWDB, personal communication, 2007

^bEstimated or height of measuring level used from the replacement well set up

– No estimation made

elevation for the measuring point for DH124. Due to this difficulty, data for DH124 station for 2001 onward were not used in the long-term hydrograph. It is assumed that the information in the database is not updated for the replacement setup. Analysis of the data from those stations with a height of measurement level from original well setups shows a large shift which may be due to a change in elevation in the measuring point. The water table at DH124 shows more than 10 m difference (e.g. 41.38 m on 10 December 2001 and 51.80 m on 01 July 2002) within 6 months, and it fell below the well depth mentioned in the database. There is also a data gap for the period of December 2001 to June 2002, indicating some sort of adjustment-time for the new set up as because the water table dropped below the depth of the well; however the information regarding the new set up is not in the database. The authors tried without success via personal communication to collect the missing database information. This big difference in the measurements might have appeared due to a different (localized) hydraulic regime at the new depth or interference by production well(s) nearby. The maximum drop in the water table (53.75 m below the ground surface) was recorded at DH124 station in 2003.

Long-term hydrographs of water-level elevation with reference to the PWD datum (1985 to 2003) were prepared for individual observation stations. Data for the last week of December for the respective years of all 14 stations were used to construct water-level elevation-contour surfaces for the years 1988, 1993, 1998 and 2002. Seasonal fluctuations were absent in the data and did not influence overall water level for any given period within the year. Therefore, December data were arbitrarily chosen as the data for yearly

contouring. Missing data were estimated with respect to earlier and later records. It is assumed that the observation wells are recording the water level of the same aquifer throughout the area. Contouring was based on data from observation wells from the Dhaka metropolitan and neighbouring region using Surfer 8.4 (surface mapping and computing software) (Golden Software, Golden, Colorado, USA). Kriging geo-statistical method (e.g. Cressie 1990) with a linear variogram model was used in each case of grid data generation.

Dewatered volume calculation

A surface map for the base of the top clay layer was prepared using the information derived from 18 borehole lithologs and 14 geophysical resistivity logs through statistical manipulation using Surfer 8.4 software. The dewatered volume calculation was done using the volume calculation facility of the same software, which determines the volume of material between two surfaces, given as grid files. Mathematically, the volume under a function $f(x, y)$ is defined by a double integral

$$\text{Volume} = \int_{x_{\min}}^{x_{\max}} \int_{y_{\min}}^{y_{\max}} f(x, y) dx dy \quad (1)$$

Surfer computes this by first integrating over X (the columns) to get the areas under the individual rows, and

Table 3 Quantification of groundwater abstraction in terms of contribution from recharge and storage

| Year range | Total abstraction (MCM) | Yearly average abstraction (MCM) | Dewatered volume of aquifer (MCM) | Yearly average dewatered volume of aquifer (MCM) | Dewatered pore-volume (MCM) (for porosity 15%) | Yearly average dewatered pore-volume (MCM) | Yearly average abstraction from recharge (MCM) | Yearly average abstraction from recharge (%) | Yearly average abstraction from storage (%) |
|------------|-------------------------|----------------------------------|-----------------------------------|--|--|--|--|--|---|
| 1984–1988 | 1012.88 | 202.58 | 40.98 | 8.20 | 6.15 | 1.23 | 201.35 | 99.39 | 0.61 |
| 1989–1993 | 1320.60 | 264.12 | 164.09 | 32.82 | 24.61 | 4.92 | 259.20 | 98.14 | 1.86 |
| 1994–1998 | 1929.98 | 386.00 | 547.75 | 109.55 | 82.16 | 16.43 | 369.56 | 95.74 | 4.26 |
| 1999–2002 | 2173.00 | 543.25 | 2272.01 | 568.00 | 340.80 | 85.20 | 458.05 | 84.32 | 15.68 |

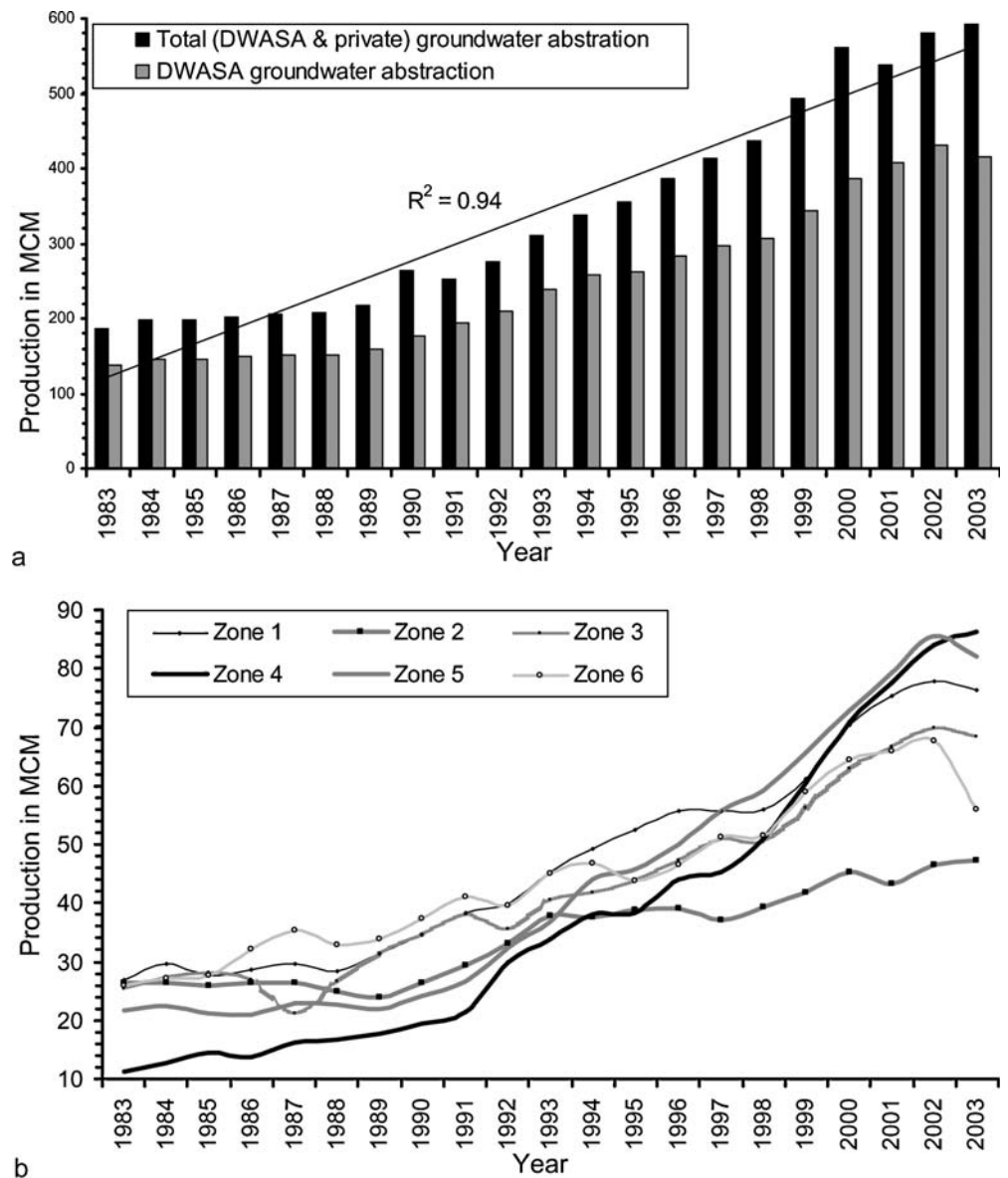
MCM million cubic metres

then integrates over Y (the rows) to get the final volume as explained in Press et al. (1988).

The base of the top clay is taken as the upper piezometric surface and the piezometric surface of 1988, 1993, 1998 and 2002 is taken as the lower surface for dewatered volume

calculation for the respective years. The elevation of the piezometric surface was within the clay before groundwater development (e.g. Morris et al. 2003), indicating the initial confined nature of the aquifer. It is anticipated that the bottom of the clay, as the top piezometric surface, is a

Fig. 4 a Total groundwater abstraction in million cubic metres (MCM) by DWASA and private abstractors in Dhaka metropolis over the years; **b** Zone-wise groundwater abstraction in MCM by DWASA in different distribution zones is displayed



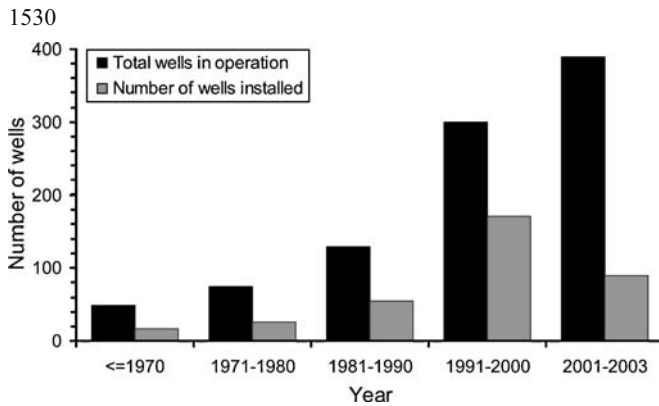
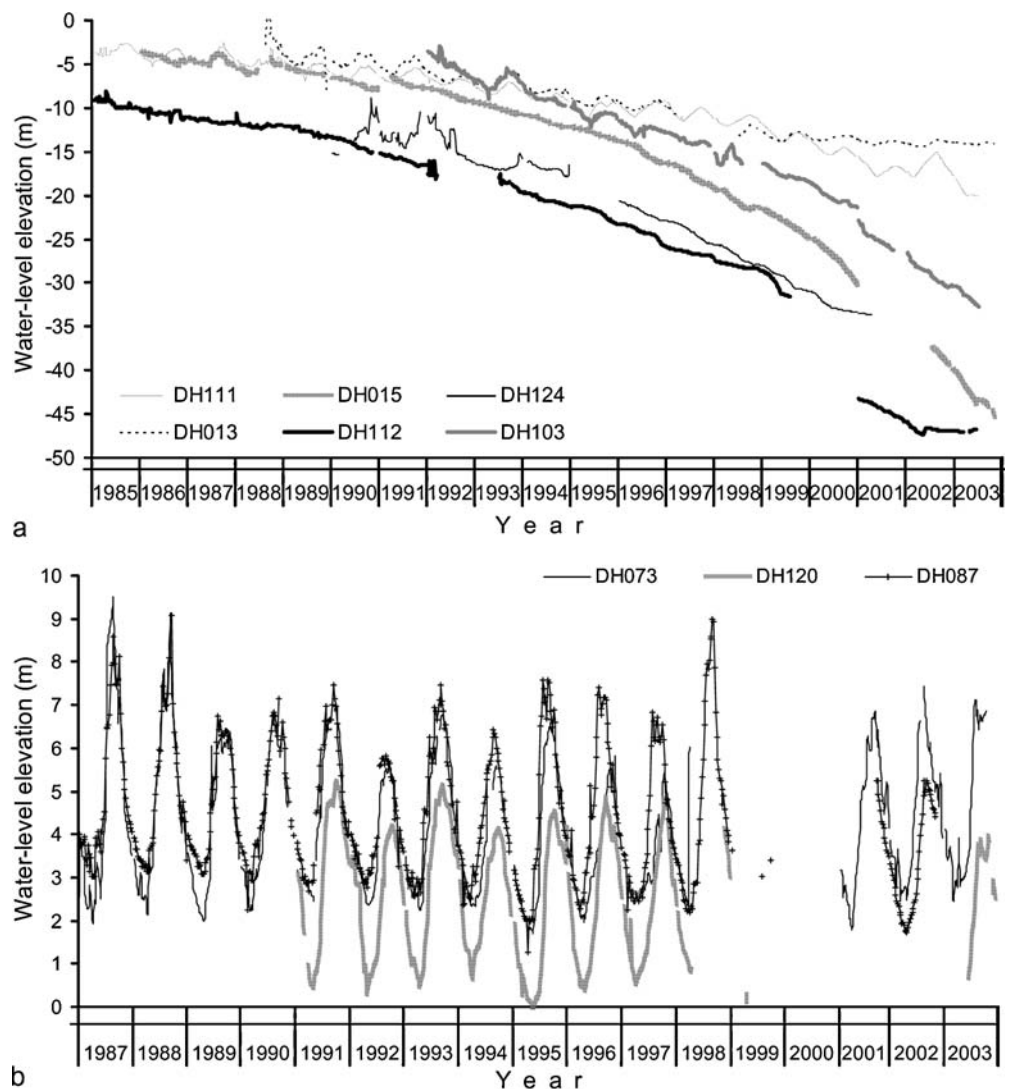


Fig. 5 Graph showing total wells in operation of DWASA, and number of new wells installed during individual time periods

conservative estimate for the dewatered volume derivation because the water table was actually within the clay. In each surface grid construction, a planar earth projection UTM (universal transverse mercator) in metres is used to obtain the volume in cubic metres.

Assuming 15% porosity for aquifer materials, the source of water (recharge versus storage) for abstraction is

Fig. 6 a Long-term hydrographs for individual monitoring bores within the city limit; b Long-term hydrographs for individual monitoring bores outside the city area; station locations are shown in Fig. 3



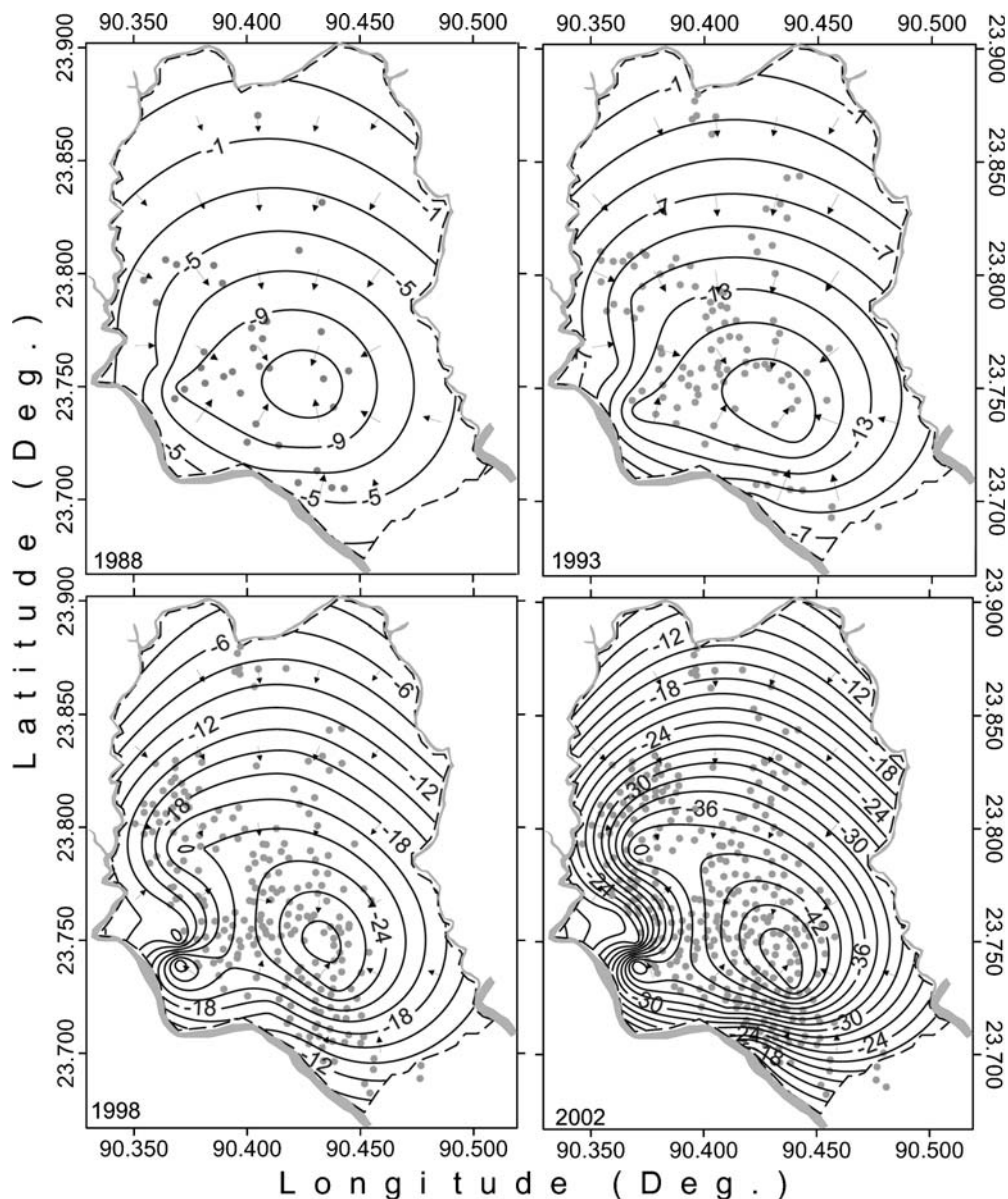
estimated from the dewatered volume. It is assumed that both abstraction and dewatering are steady over the periods 1984–1988, 1989–1993, 1994–1998 and 1999–2002 for simplicity of estimation. The dewatered volume was multiplied by the porosity to find the dewatered pore volume, i.e. contribution of aquifer storage to abstraction. This volume is subtracted from the average yearly abstraction volume to calculate the contribution of the natural recharge and/or decreased discharge (of groundwater to the down gradient) to the abstraction. These results are represented in terms of percentage of abstraction in Table 3.

Results

Abstraction analysis

The total groundwater abstraction rates by DWASA and private wells have been increasing in time (Fig. 4a) with a linear trend ($R^2=0.94$, $n=21$). The volume of water withdrawal from the aquifer was 160–186 million cubic metres (MCM) per year before 1989 and after 1990 it

Fig. 7 Water level contour (with 2-m interval) surfaces showing the development and deepening of cones of depression in the city of Dhaka during the years 1988 to 2002. Active production wells operated by DWASA at that time are overlain on each map (as grey dots)



increased drastically from 264 MCM in 1990 to 592 MCM in 2003. The average daily groundwater abstraction increased by more than a factor of 1,000 between 1970 and 2003. This abstraction scenario is almost identical in the six distribution zones, except zone 2, where abstraction is increasing slightly less over time (Fig. 4b).

DWASA has been increasing its production to keep pace with the demand by installing more wells (Fig. 5). The change in number of tube wells is more than 700% from the 49 wells in 1970 to the 389 wells in 2003. The frequency of installation of new tube wells has increased since 1990. Most of the DWASA production wells were installed after 1995.

Long-term hydrograph

The long-term hydrographs indicate that the water levels are dropping at an increasing rate throughout most of the city with time (Fig. 6a). The water levels have dropped

from 5 m below the PWD datum in the 1980s to more than 45 m below the datum in 2003. The drop in water level has an increasing trend with time. The increasing rate of water-level decline began in different wells from 1980 to 1990. In 2003, the water-level depths ranged from 5.7 m below the datum at DH013 to more than 45 m at DH112 and DH015 (Fig. 6a). Hydrographs for DH013 and DH111 show some seasonal fluctuation and less decline because of their proximity to rivers. The most alarming scenario is depicted in the city-interior observation wells (DH015, DH103 and DH112) where the linear drop in water level with respect to time changed to exponential after 1996–1998. It is also evident that the rate of water-level drop in the city area is about 2.5 m/year in the recent years, which was about 1 m/year during the late 1990s. The huge depression in the water level is within the city area, centring in the abstraction areas. This sort of level drop is not occurring just outside the city

area, as noticed on hydrographs from the observation wells DH073, DH120, and DH087. Hydrographs of these monitoring bores show a seasonal fluctuation (approximately 6 m) with no long-term trend (Fig. 6b). The water level is above the PWD datum outside the city area and below the datum within the city area.

Piezometric surface construction

Piezometric surfaces of 1988, 1993, 1998 and 2002 of the study area are presented in Fig. 7. The potentiometric surface in 1988 shows a cone of depression with a maximum decline of 12 m below the datum in the vicinity of Motijheel and a moderate decline in the Dhanmondi area. The centre of the cone of depression in 1993 had moved southeast and increased to 18 m below the datum. The contour shape and magnitude of the depression changed significantly in the years between 1993 and 1998. The 1998 contour surface shows two cones of depression in the area close to Motijheel and Dhanmondi area. The lateral extent and magnitude of the Motijheel depression are larger than the Dhanmondi depression. The magnitudes of these are about 29 and 27 m below the datum respectively. The shape of contours in 2002 is the same as for 1998, but the maximum decline increased to about 46 m below the datum. The rate of escalating magnitude and extent of the depressions in the

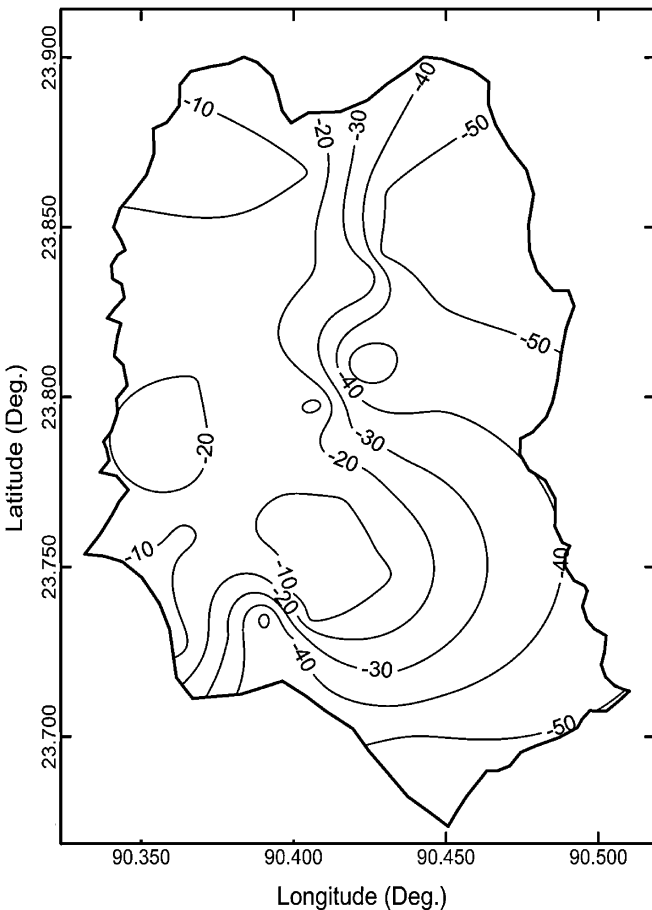


Fig. 8 Surface of the base of top clay layer in the area (metres above PWD)

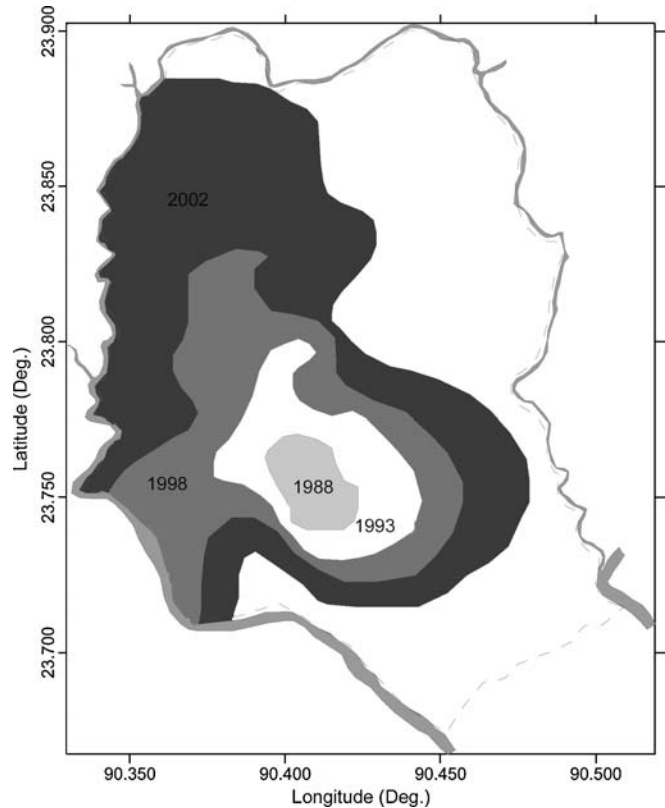


Fig. 9 Aerial extent of aquifer dewatering in the city of Dhaka for December of 1988, 1993, 1998 and 2002

piezometric surface has become non-linear in recent years. All of the temporal contours indicate radial flow of groundwater from the peripheral zone to the city centre; particularly toward the south centre of the city, an area of concentrated pumping.

Dewatered volume

Construction of the base of the top clay layer indicates that the clay layer is much deeper in the northeast and southeast corners of the city (Fig. 8), but there were not enough data in those areas to determine the accurate depth of the base of the top clay layer. However, a different investigation suggests the clay layer is thicker in those areas (M. Rahman, Institute of Water Modelling, personal communication, 2006). It is calculated that 41 MCM of the aquifer

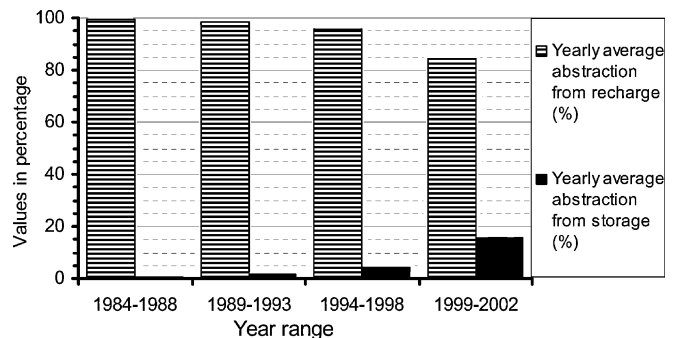


Fig. 10 Fractionation of groundwater abstraction in the city of Dhaka in terms of contribution from recharge and aquifer storage

was dried in the year 1988, and this increased very rapidly to 2,272 MCM in the year 2002 (Table 3). There is a systematic linear ($R^2=0.79$; $n=4$) to exponential ($R^2=0.99$; $n=4$) relationship in dewatered volume with time. The lateral extent of the dewatered area over time is shown in Fig. 9. The upper part of the aquifer in most of the city area has been dewatered, with the exception of the northeast and southeast parts of the city, where the clay layer is the thickest and extends the deepest.

Contribution of the aquifer storage to abstraction is found to be increasing while recharge and discharge are decreasing with time (Fig. 10). It is estimated that almost all the water was coming from recharge and/or decreased natural discharge in 1984–1988 and the contribution of the storage to abstraction was negligible. The contribution of recharge to abstraction decreased to 84.32% in 2002 and storage contribution increased to 15.68% (Table 3) which is causing water-level lowering and dewatering in the aquifer.

Discussion and conclusions

The analysis of groundwater abstraction and water levels reveals that the aquifer hydrology is almost entirely controlled by excessive abstraction of water in the area. The pattern of water-level change in the city of Dhaka from the 1980s onward largely follows the patterns of change in groundwater abstraction (Fig. 11).

Groundwater level drop is a city-wide phenomenon in the hydrogeological regime. The rate of decline has reached 2.5 m/year in recent years in the main part of the city. This scenario follows the increasing rate of groundwater withdrawal over the city. The area has been experiencing massive abstraction of groundwater for the last three decades and the density of the wells is increasing with time. The water level in the aquifer is declining because withdrawals are exceeding recharge. Large and prolonged abstraction has modified groundwater flow directions by reversing hydraulic gradients towards the city centre producing cones of depression in the piezometric surface around large pumping centres (Fig. 7). The cones of depression are lowering vertically and widening horizontally owing to the increased installation of production wells and to the spread of the production wells into

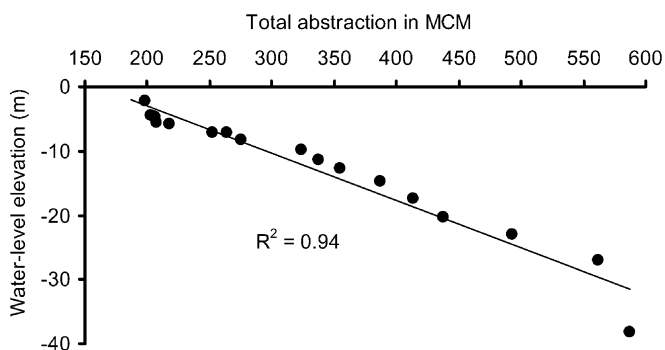


Fig. 11 Scatter plot of average water-level elevation at DH015 and total abstraction of water in MCM for the years 1984–2002. Water-level decline varies linearly with groundwater abstraction in the city

new areas. The positions of the piezometric depressions are largely ruled by the concentrated pumping locations of DWASA. The recent development of a depression in the Dhanmondi area is most likely due to the impact of high pumping associated with the high-rise apartment boom, which started in the early 1990s. This converted the once low-density residential area to a high-density area along with installation of many private abstraction wells for uninterrupted water supply.

The piezometric surfaces and stationary water-level results indicate that the metropolitan area is hydraulically separated from the surrounding region. This standalone hydraulic nature may be controlled by the hydrostructural features and stratigraphic settings. Stratigraphically, the low transmissivity Dupi Tila aquifer may always remain in semi-isolation from the surrounding high transmissivity flood plain aquifer. On the other hand, fault controlled rivers around the metropolis would have a link with the aquifer in the region to establish a more localized hydraulic system in Dhaka by surface water to groundwater interaction. A separate model study for the area shows that connection of the surrounding rivers with the aquifer can generate such a restricted groundwater flow system with existing pumping set up (MA Hoque, Bangladesh University of Engineering and Technology, unpublished data, 2006). If the city aquifer is isolated from the outside aquifer, water cannot be drawn laterally and recharge to the Dupi Tila aquifer can only occur from the surface or from surrounding rivers. This might have been significantly accelerating the drawdown in the city and causing more induced recharge. Due to the lack of site characterization, it remains uncertain whether the water-level data used for outside the city represent the same aquifer as the one inside the city (Dupi Tila aquifer), or whether the outside aquifer, in connection with the Dupi Tila aquifer, is underlain by the aquifer represented by the data.

Rivers around Dhaka appear to be recharging the aquifer to a new hydrodynamic equilibrium in response to pumping indicated by the water-level contours and associated flow pattern. The flow pattern in the shallower horizon would primarily be from the surrounding rivers towards the cones of depression, and water in the deeper horizon may be slow-moving and very old. Oxygen (O) and Hydrogen (H) stable isotope studies (Darling et al. 2002) confirm the large-scale leakage of river water in the upper part of the aquifer beneath the city of Dhaka and $^3\text{H}/^3\text{He}$ isotope data demonstrate that the water at 75 m in the area between Motijheel and south of Dhanmondi is younger than 20 years (Darling et al. 2002), indicating that water from this depth has recently been recharged. Another earlier study (Hasan 1999) used temporal patterns in EC (electrical conductivity) distribution to prove that pumping has induced recharge in the southern part of the aquifer from the polluted Buriganga River. These earlier studies also support the water-level contours that show flow directions towards the city centre from the surrounding rivers (Fig. 7).

The rate of drawdown is increasing with abstraction even though the aquifer is recharged from the surrounding river. Abstracted water is usually supplied by more water entering the groundwater system (increased recharge), less

water leaving the system (decreased discharge), and removal of the water from the storage, or some combination of these (Alley et al. 1999). In the case of the Dhaka groundwater system, abstraction water is coming from all three sources as indicated by the hydraulic gradients towards the city centre, facilitating enhanced recharge and decreased discharge and dewatering of the aquifer due to contribution of the aquifer storage. BWDB (1991) quantify the groundwater withdrawal in terms of recharge: 94% of the withdrawal is dependent on recharge (vertical and horizontal recharge and decreased discharge), and the remaining 6% of the withdrawal comes from storage, causing permanent decline in the water level. The present study found 0.61 and 1.86% of the abstraction to be derived from the aquifer storage in the years 1988 and 1993, respectively. The proportion of average yearly abstraction from recharge decreases in favour of the proportion from the storage. The contribution of the storage is increasing with time and reached 15.68% of abstraction in the year 2002, which is most alarming and causing substantial dewatering of the aquifer. Dewatering is attaining a maximum vertical recharge rate that is proportional to the water-level difference between the water-table elevation in the top clay layer and the elevation of the bottom of the top clay layer in the city of Dhaka. The abstraction from storage will increase non-linearly where dewatering of the aquifer occurs, as the vertical recharge rate reaches its maximum.

This study concludes that the pattern of water-level change in the city largely follows the rate and spread of groundwater abstraction. This increasing nature of the groundwater abstraction could restrict the sustainability of the hydrogeologic regime because the contribution of aquifer-storage is non-linearly increasing, vertical recharge has reached its maximum in most parts of the city, and pumping induced recharge from rivers may, in turn, pollute the aquifer.

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