REPORT

Development of unconfined conditions in multi-aquifer flow systems: a case study in the Rajshahi Barind, Bangladesh

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Abstract Identifying flow processes in multi-aquifer flow systems is a considerable challenge, especially if substantial abstraction occurs. The Rajshahi Barind groundwater flow system in Bangladesh provides an example of the manner in which flow processes can change with time. At some locations there has been a decrease with time in groundwater heads and also in the magnitude of the seasonal fluctuations. This report describes the important stages in a detailed field and modelling study at a specific location in this groundwater flow system. To understand more about the changing conditions, piezometers were constructed in 2015 at different depths but the same location; water levels in these piezometers indicate the formation of an additional water table. Conceptual models are described which show how conditions have changed between the years 2000 and 2015. Following the formation of the additional water table, the aquifer system is conceptualised as two units. A pumping test is described with data collected during both the pumping and recovery phases. Pumping test data for the Lower Unit are analysed using a computational model with estimates of the aquifer parameters; the model also provided estimates of the quantity of water moving from the ground surface, through the Upper Unit, to provide an input to the Lower Unit. The reasons for the substantial changes in the groundwater heads are identified; monitoring of the recently formed additional water table provides a means of testing whether over-abstraction is occurring.

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Introduction

When monitoring heavily exploited aquifers, significant falls in water levels are often observed; however, it may be difficult to interpret the hydrographs and determine whether too much groundwater is being abstracted. The graphs in Fig. 1, of non-pumping water levels at three locations in the Rajshahi Barind multi-aquifer system in northwest Bangladesh, illustrate the uncertainties. At one of the locations, seasonal fluctuations follow a fairly regular pattern, at a second there is a significant decline but at the third location there is a substantial and increasing fall in non-pumping water levels together with smaller seasonal fluctuations. This report considers each of these hydrographs but focuses on the third location. By considering the lithology, constructing monitoring piezometers, and conducting and analysing a pumping test, evidence is gained which allows an assessment to be made of whether over-exploitation could be occurring.

There are many examples of uncertainties about the long-term sustainability of abstraction from multi-aquifer flow systems. The High Plains aquifer in the United States, which consists of discontinuous clay, silt, sand, and gravel layers, is an important example of an aquifer system where both the water levels are declining and the quality of groundwater is deteriorating (Dennehy et al. 2002; Sophocleous 2012; Butler et al. 2013; Haacker et al. 2015; Whittemore et al. 2016). Of particular significance is a contribution by Butler et al. (2013) who demonstrate that the interpretation of hydrographs from continuously monitored wells can enhance the understanding of aquifer behaviour. Other multi-layer aquifer systems which have been investigated by monitoring groundwater heads
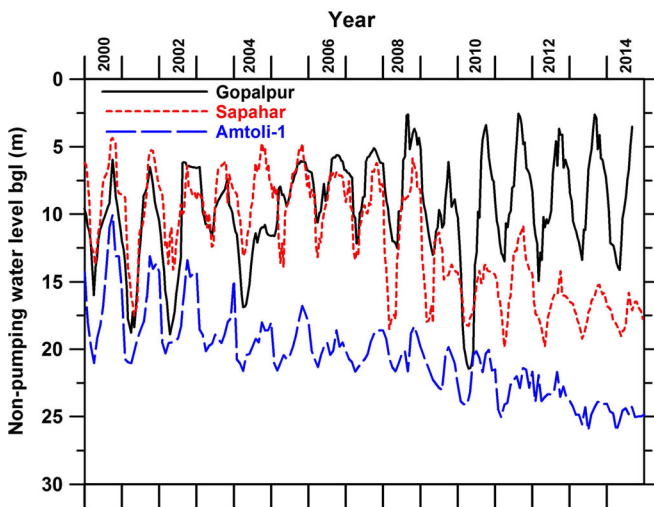
Fig. 1 Groundwater fluctuations monitored at three locations in the Main aquifer in the Rajshahi Barind. *bgl* below ground level

include the Paris Basin (Contoux et al. 2013), the Gdansk hydrogeological system in Poland (Jaworska-Szulc 2009) and an aquifer system of overlapping layers in southern Spain (González-Ramón et al. 2013).

Important insights have been gained from studies of the multi-aquifer flow systems of the Bengal basin, which is where the field example discussed in this report is located. Michael and Voss (2009) developed a regional groundwater model for the whole of the Bengal Basin of India and Bangladesh. Due to the difficulty in estimating the recharge, specified heads are used as an upper boundary condition; this is an acceptable approximation since deeper groundwater flows are their main concern. They also comment that the study would be greatly improved by the collection of new hydrogeologic data. Morris et al. (2003) have examined the consequences of intensive pumping in Dhaka, Bangladesh; conceptual models are presented which illustrate the formation of a water table beneath a near-surface low-permeability aquitard; however, they conclude that the lack of data, such as the geometry of the aquifer, seriously hampers water management. Hoque et al. (2007) examine the declining groundwater levels and aquifer dewatering in the Dhaka metropolitan area. They compare the considerable and continuing decline in groundwater levels beneath Dhaka city due to heavy pumping, with locations outside the city where regular seasonal fluctuations still occur.

Studies of groundwater head fluctuations at different depths have led to an understanding of the complex behaviour of multi-aquifer flow systems; two examples are the Mehsana alluvial aquifer in Gujarat, India and the Braintree aquifer system in Essex, UK. In the heavily exploited multi-layered Mehsana alluvial aquifer, abstraction wells penetrate 100–200 m (Rushton and Srivastava 1988; Kavalanekar et al. 1992, and section 10.2 of Rushton 2003). Over a 5-year period, the water table fell by more than 15 m and the non-

pumping groundwater heads in the main aquifer by 30 m; additionally, seasonal fluctuations were not in phase since the water table responds mainly to recharge but groundwater head fluctuations in the main aquifer are primarily due to pumping. In the Braintree area, water is pumped from a Chalk aquifer which is overlain by the Lower London Tertiaries which are beneath the very low permeability London Clay (Rushton and Senarath 1983, and section 5.16 of Rushton 2003). Initially the aquifer system behaved as a confined aquifer but, due to substantial pumping, a water table formed in the Lower London Tertiaries. Computational modelling of the aquifer system replicated the groundwater head hydrographs, including the formation of the water table.

The detailed analysis in this report relates to the Rajshahi Barind in northwest Bangladesh where there has been substantial groundwater development. An investigation by United Nations Development Programme (UNDP) concluded that the relatively thin fine-grained sand zones, within a clay sequence, would only be suitable for small domestic demands (UNDP 1982); however, the Barind Multipurpose Development Authority (BMDA) has constructed numerous deep tubewells (DTW) into the sand layers which penetrate to depths of between 30 and 70 m. An examination of the groundwater head fluctuations, in the layers from which deep tubewells pump water, showed that full recovery occurred most years during the wet season up to the year 2002. Since then, significant changes have occurred with a substantial decline in water levels in some of the monitoring wells; additionally, the seasonal fluctuations are much smaller. These changes have been considered in a number of publications which are reviewed in the section that follows; none of the papers provide convincing explanations for these changes.

Previous studies of the Rajshahi Barind groundwater flow system

The Barind Tract is a physiographic unit located in northwestern Bangladesh which consists of Pliocene-Pleistocene terrace deposits typically located in slightly elevated positions, 15–40 m above sea level. Deposits are generally highly weathered, and more compacted than floodplain and deltaic deposits. The deposits include clay, sand and occasionally gravel.

Despite previous estimates of low yields from Rajshahi Barind aquifers (UNDP 1982), the Barind Multipurpose Development Authority (BMDA) has constructed many successful deep tubewells which supply groundwater to irrigate at least one dry season crop (Asad-uz-Zaman 2013); the current area of responsibility for BMDA is indicated in Fig. 2. Of particular importance is the use of an alternative form of well construction in which inverted screens extend vertically

Fig. 2 **a** Map of Bangladesh including contours of mean annual rainfall; **b** Area of responsibility of the Barind Multipurpose Development Authority and locations of the three hydrographs in Fig. 1
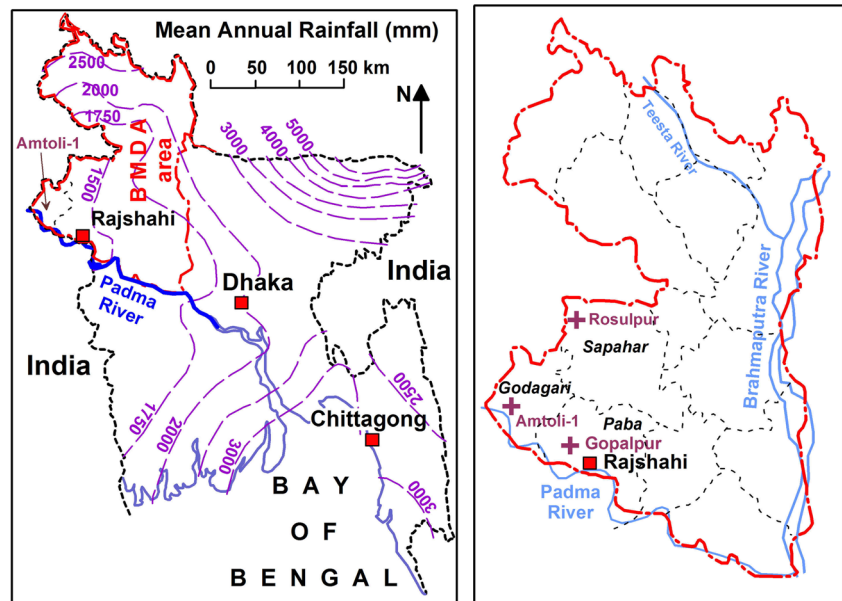
upwards alongside the well casing from a connector at the bottom of the well assembly; this form of construction is illustrated in some of the subsequent figures. The introduction of inverted screens has led to substantial improvements in the specific discharge (discharge per unit drawdown) of the boreholes (Asad-uz-Zaman and Rushton 2006).

Questions have been raised about the sustainability of this abstraction—for example, Hasan et al. (1998) suggest that the low vertical hydraulic conductivity of the Barind Clay, which is the uppermost of the Pliocene–Pleistocene sediments with thicknesses of 5–30 m, limits the recharge to the sand layers from which the DTWs pump water. However, Alam (1993) conducted a thorough field examination of the undisturbed deposits of the Barind Clay from within large diameter wells and his observations indicate that the Barind Clay was laid down during a series of periods with different climatic conditions. There is evidence that the decayed roots of the vegetation and other disturbances provide pathways for preferential vertical flow. Alam concludes that significant vertical flows can occur through the Barind Clay.

On a map of Bangladesh (Fig. 2a) the distribution of mean annual rainfall is plotted; it is lowest in the northwest which is where the Rajshahi Barind is located. Figure 2a,b shows the area of responsibility of the Barind Multipurpose Development Authority; the locations of the sites of the three hydrographs in Fig. 1 are also shown in Fig. 2b. Important features of these three locations, which strongly influence the non-pumping water levels of Fig. 1, are summarised in the following; note that these sites are in the lowest annual rainfall zone in Bangladesh.

1. *Gopalpur, Paba.* There has been no major change in this hydrograph although the recovery in the wet season is closer to the ground surface and there are more erratic seasonal variations. This location is 3 km from the Padma River (Ganges), and the surface irrigation from the river is significant.

2. *Rosulpur, Sapahar.* The fluctuations in depth to water level follow a similar pattern until 2008; from then onwards there has been a fall of about 7 m with generally smaller seasonal fluctuations. This location is at a higher elevation than Gopalpur and has a lower rainfall. There is some surface water irrigation from a lake, the Jobai Beel.

3. *Amtoli-1, Godagari.* Throughout the period 2000 to 2014 there has been a fall in the water level in the aquifer from which tubewells draw water; the seasonal non-pumping water level fluctuations have also become smaller. Irrigation for the command area is primarily from the tubewell.

The analysis in this report will focus on Amtoli-1 because of the substantial and rapid increase in the depth to non-pumping water levels in the Main aquifer and the smaller seasonal fluctuations.

Recently there have been several publications concerning the declining water levels in the Rajshahi Barind; the following summary is a selection from the varied approaches adopted to explore the decline. Shahid and Hazarika (2010) consider the spatial distribution of groundwater droughts, trends in groundwater hydrographs and the relation between groundwater level and meteorological droughts; however, their data sets do not extend beyond 2002 and therefore fail to include the major declines in non-pumping water levels. Selim Reza et al. (2011) correctly identify seven potential sources of recharge but use a water-table-fluctuation method to estimate recharge, which relies on an assumed constant

specific yield. Islam et al. (2014) also consider some of the important processes but then use a recharge coefficient which is defined as the ratio of recharge to rainfall and expressed as a percentage. Adham et al. (2010) use remote sensing along with a geographic information system for groundwater recharge potential which reflects hidden hydrogeologic characteristics and deals with indicative elements at the surface such as lineaments, drainage frequency and density, lithologic character, land cover/land use etc. This provides an estimate and qualitative assessment of the recharge potential concluding that only 8.6 % of the total average annual precipitated water percolates into the subsurface, a value which is far too small to maintain the historical abstraction which is typically 20–30 % of the annual precipitation. Shamsudduha et al. (2011), in a study of the whole of Bangladesh, consider how actual recharge has increased due to the lowering of water tables, resulting in increases in the volume of the aquifer in which water can be stored during the recharge season. In their study, which includes the Barind Tract, they present a hydrograph of the falling water level and suggest that recharge has increased by about 15 %, whereas abstraction is almost double their recharge estimate.

These methods of analysis are not appropriate for the actual groundwater conditions in the Rajshahi Barind aquifer system. The lithology is ignored—for example, no reference is made to the Barind Clay which overlies the more permeable strata—and there is no attempt to define the groundwater conditions in terms of the conventional classifications of confined, unconfined and leaky. Also, there is a failure to recognise that the hydrographs refer to the groundwater head (piezometric head) in the permeable layer from which water is pumped, which is usually under a confining pressure. Consequently, the estimation of "recharge" using the water-table-fluctuation method is inappropriate because the hydrographs do not refer to a water table. Before any analysis is attempted, preliminary conceptual models of all the inter-related processes must be developed; none of the aforementioned papers have included this aspect.

Study of deep tubewell, Amtoli-1

Relationship between non-pumping water levels and lithology

In Fig. 3, water levels in the pumped aquifer in the vicinity of Amtoli-1, recorded when pumps were not operating, are compared with the lithology. From the lithological logs, it is possible to identify three aquifers, the Upper aquifer, the Middle aquifer and the Main aquifer from which water is pumped by the tubewell. Separating these aquifers are three aquitards, the Barind Clay, Aquitard A and Aquitard B. The diagram also contains a bar chart indicating the hours of pumping each month.

The hydrograph in Fig. 3 indicates that from 2000 to 2002 the fluctuations were of a similar form to those for the 1980s–1990s reported by Asad-uz-Zaman and Rushton (2006); however, after 2002, a steady decline occurred in the average value and magnitude of fluctuations of the water levels, while from 2009 onwards, most fluctuations were at the elevation of the Middle aquifer. To understand more about the aquifer system, piezometers were installed in each of the aquifers.

Construction and monitoring of piezometers

Three piezometers were installed (Fig. 4)—piezometer P1 monitors the Upper aquifer, piezometer P2, the Middle aquifer and piezometer P3 has a slotted screen in the Main aquifer. Information from the Main aquifer is also obtained by monitoring the DTW. Details of the DTW and piezometers are included in Table 1. Figure 4 shows the depth to the water columns in the piezometers and in the DTW during non-pumping and pumping periods in December 2015, which is after the wet season and before heavy pumping for irrigation commences.

The water column in P1 is about 9 m above the base of the Barind Clay, while the top of the water column in P2 is within the Middle aquifer. From the readings in P3 and the DTW, it is possible to construct an approximate distribution of the piezometric head in the Main aquifer during non-pumping and pumping conditions (Fig. 4). Note that the blue line, representing the non-pumping groundwater head in the Main aquifer, is very close to the reading for piezometer P2 in the Middle aquifer. This means that conditions in the Middle aquifer can be identified approximately by examining non-pumped water levels in the Main aquifer. Consequently, the hydrograph in Fig. 3 of the non-pumping levels in the Main aquifer indicates that, since 2010, unconfined conditions have been maintained in the Middle aquifer.

Development of conceptual models

From the available field evidence, conceptual models of the flow processes are developed; it is essential to develop preliminary conceptual models before any computational modelling is attempted. When preparing the conceptual models of Fig. 5 for pumping from Amtoli-1, the initial focus is the identification of the vertical volumetric fluxes as water moves from the ground surface to the Main aquifer.

Information and data from which the conceptual models of Fig. 5 are developed include:

Fig. 3 Depth to non-pumping groundwater levels in Main aquifer near Amtoli-1 deep tubewell; the diagram also shows the lithology and the elevation of the *Upper* and *Middle* aquifers and the *Main aquifer* where the inverted screens of the tubewell are located. The *lower diagram* shows hours pumping per month at a discharge rate of 136 m^3/h
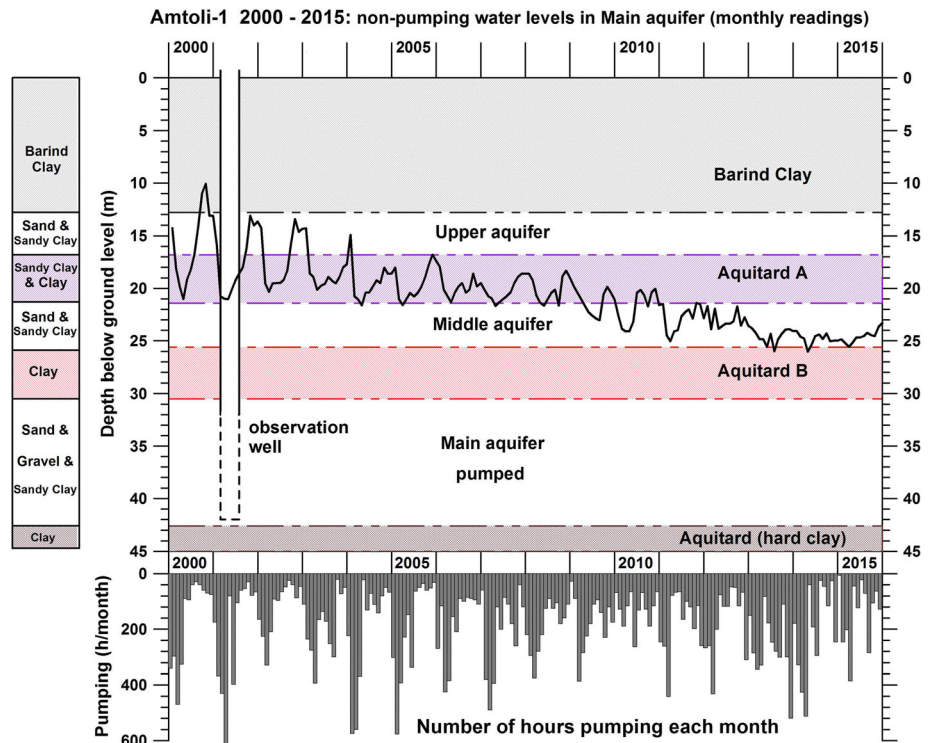
1. Depth to non-pumping groundwater levels in the vicinity of Amtoli-1 DTW from 2000 to 2015 (Fig. 3)
2. Lithology for Amatoli-1 DTW and piezometers (Figs. 3 and 4)
3. Depth to water level for Amatoli-1 DTW and piezometers in December 2015 (Fig. 4)

Conditions in the aquifer system change substantially between the years 2000 and 2015. Initially, a conceptual model is prepared for the year 2000 (Fig. 5a); subsequently, a modified conceptual model is developed for 2015 (Fig. 5b).

Conceptual model for conditions in the year 2000

1. For the year 2000, a typical groundwater head in the Main aquifer, deduced from Fig. 3, is 17.5 m below ground level; this groundwater head is shown in Fig. 5a by the horizontal broken red line.
2. The groundwater head falls from zero at the ground surface to −17.5 m in the Main aquifer. There is a continuous vertical flux through the aquifer system.

This vertical flux is indicated by the double-headed green vertical arrows in Fig. 5a. In this analysis, it is assumed that the water table is at the ground surface; field records indicate that at Amtoli-1 it is within 1 m of the ground surface.

Conceptual model for conditions in the year 2015

1. A similar procedure is followed in Fig. 5b for the conditions in 2015 when the abstraction from the Main aquifer is higher than for 2000. Since the water level in piezometer P2 (Fig. 4) is within the Middle aquifer, a water table forms in the Middle aquifer at this elevation. Consequently, vertical fluxes from the ground surface to
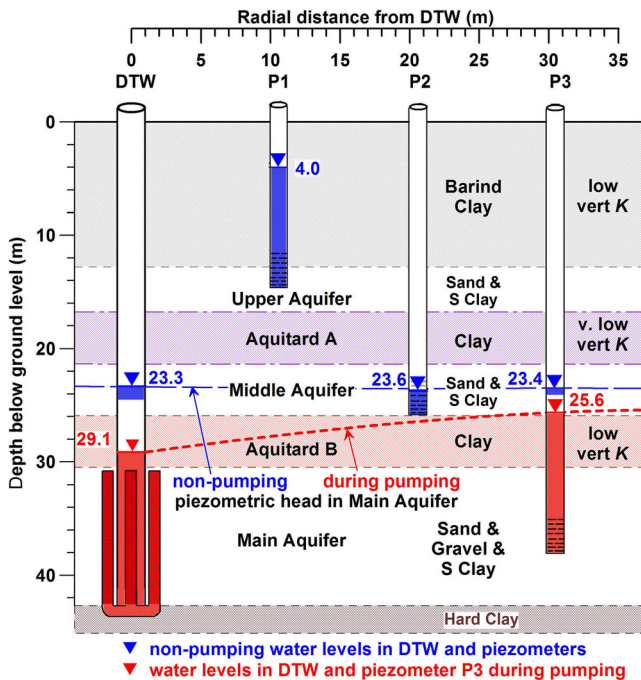

Fig. 4 Water levels in DTW and piezometers in December 2015 during the dry season

Table 1 Details of deep tubewells (*DTW*) and monitoring piezometers. *bgl* below ground level

	Distance from DTW (m)	Depth bgl (m)	Length of screen (m)	Water level bgl during pumping (m)
DTW	–	42.5	4 inverted at 12.2	29.1
P1	10.1	14.6	3.05	4.0
P2	20.3	25.9	3.05	23.7
P3	30.5	38.1	3.05	25.6

the Middle aquifer and from the Middle aquifer to the Main aquifer are considered separately.

2. At the top of the Middle aquifer (21.4 m below ground level), the pressure is atmospheric; hence, the

a 2000 uniform flow to Main aquifer
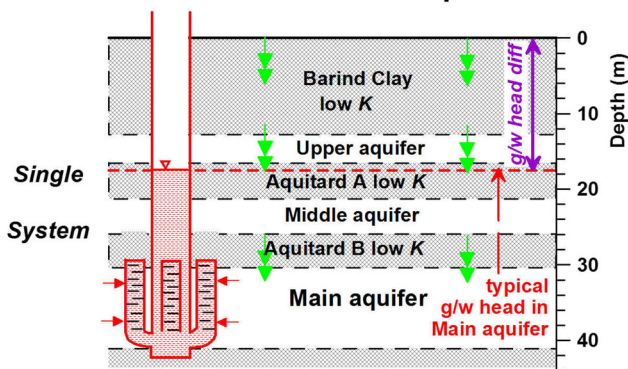
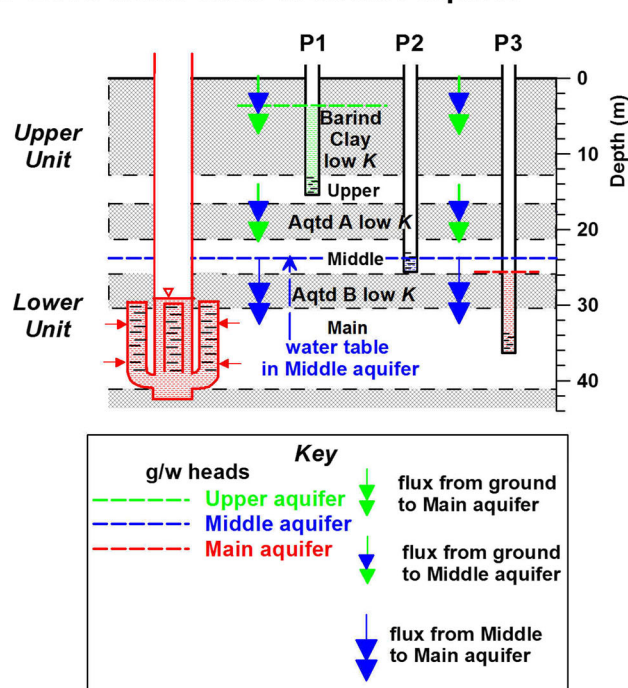## b 2015 water table in Middle aquifer

Fig. 5 Conceptual diagrams illustrating changed conditions in aquifers from 2000 to 2015; **a** uniform flow to Main aquifer, and **b** water table in Middle aquifer. These diagrams assume that there is a water table close to the ground surface

groundwater head at this location is −21.4 m. The vertical flux from the ground surface to the Middle aquifer is indicated in Fig. 5b by the blue-green double-headed arrows.

3. A separate analysis is required for the vertical flux from the Middle to the Main aquifer. This vertical flux depends on the elevation of the water table in the Middle aquifer and the groundwater head in the Main aquifer, which changes as pumping occurs. This flux is represented in Fig. 5b by the blue double-headed arrows. The computational model of section 'Computational model for Lower Unit' is used to explore this flux.

Do the two conceptual models explain groundwater heads and fluctuations?

The conceptual models in Fig. 5 demonstrate that the flow processes have changed significantly between the years 2000 and 2015. In 2000 there was a continuous vertical flux from the ground surface to the Main aquifer, with pressure heads positive (above atmospheric) for the whole of the vertical section; consequently, a second water table did not form, which is described in Fig. 5a as a "single system".

Water level fluctuations in the Main aquifer, from 2000 to 2002 in Fig. 3, are due primarily to pumping from the Main aquifer. As water is withdrawn from the Main aquifer, the vertical flux through the single system increases to meet the demand; this increase in vertical flux is achieved by a fall in the groundwater (piezometric) head in the Main aquifer. Then, when the pumping rate decreases, the vertical flux decreases leading to a rise in the groundwater head. These seasonal fluctuations can be up to 15 m because the vertical flux occurs across a distance of about 30 m which includes three aquitards.

Between 2002 and 2015, more water was taken from the Main aquifer, resulting in a greater vertical flux, whereby eventually the pressure head fell to zero in the Middle aquifer. The hydrograph of Fig. 3 suggests that this probably occurred in 2009. Since then the aquifer system behaves as an "Upper Unit" and a "Lower Unit" with the Upper Unit providing a vertical flux to the Lower Unit (Fig. 5b). Conditions in the Lower Unit are explored in section 'Pumping test and computational model' using information from a pumping test.

For the period 2013 to 2015, there is little change throughout the year in the vertical flux through the Upper Unit, since it depends on the difference in elevation between the water table in the Middle aquifer and the water table near the ground surface, which is also at an approximately constant elevation due to rainfall during the wet season and irrigation during the dry season. However, for the Lower Unit, water level fluctuations occur due to pumping from the Main aquifer. They depend on the approximately constant water-table elevation in the Middle aquifer and the thickness and vertical hydraulic conductivity of Aquitard B. Aquitard B is less than 5 m thick; hence, pumping from the Main aquifer results in seasonal fluctuations during 2013 to 2015 which are typically 2–3 m (Fig. 3).

Pumping test and computational model

Details of pumping test

Pumping tests can be used to estimate groundwater parameters (Kruseman and de Ridder 1990). For a pumping test at Amtoli-1, water levels were monitored during pumping and recovery in the DTW and the three observation piezometers; details of their location and construction are noted in Table 1. Pumping continued for 245 min (0.170 day); water levels were also recorded during recovery for a further 155 min (0.108 day). Measurements of the discharge from the well show that the initial discharge rate was 4,000 m^3/day but fell to a steady value of 3,255 m^3/day after 30 min.

Water levels in the piezometers and DTW were recorded initially at 1-min intervals during the pumping phase and the recovery, but increased to 15 min for later times. Field results, presented as drawdowns below the water levels when pumping started, are plotted to a logarithmic time scale in Fig. 6. Since basic equipment was used to monitor the water levels, there are some inconsistencies; to aid interpretation of the field results, smooth lines have been drawn to pass approximately through most of the discrete readings.

Examination of the results from individual piezometers provides the following insights:

1. At piezometer P3 in the Main aquifer, 30.5 m from the tubewell, the water level fell 0.3 m after 1 min (Fig. 6a). Later in the pumping phase, the rate of fall of the water level decreased appreciably, approaching a constant drawdown of about 2.2 m at the end of the pumping period. During recovery, the reduction in drawdowns was almost a mirror image of the drawdowns during pumping. Almost complete recovery occurred after 0.1 day. This response is similar to the classical leaky aquifer response, shown in Figure 5.18 of Rushton (2003).

2. Water levels in piezometer P1 in the Upper aquifer rise during the pumping test. This response is consistent with the conceptual model of Fig. 5b where the strata from the ground surface to the top of the Middle aquifer respond as a separate unit.

3. For piezometer P2 in the Middle aquifer, at 20.4 m from the pumped well, there was no measurable drawdown until 0.01 day (about 15 min; Fig. 6c). The drawdown then increased significantly; however, the rate of change in drawdown with respect to time did not decrease toward the end of the pumping phase; the maximum drawdown is 0.18 m, less than 10 % of P3. Recovery occurs only slowly and is almost 50 % complete at the end of the monitoring period. The slow and then rapidly increasing drawdowns in P2 during pumping are consistent with an unconfined aquifer response; however, the observed recovery can only occur if there is some form of inflow to the Middle aquifer.

4. There were some practical difficulties in obtaining drawdown measurements during the early stages in the pumped well (Fig. 6d). Nevertheless, the drawdown and recovery curves are of similar shape to P3, which also monitors the Main aquifer, and is located 30.5 m from the pumped well. The maximum drawdown in the DTW is nearly three times the drawdown in P3.
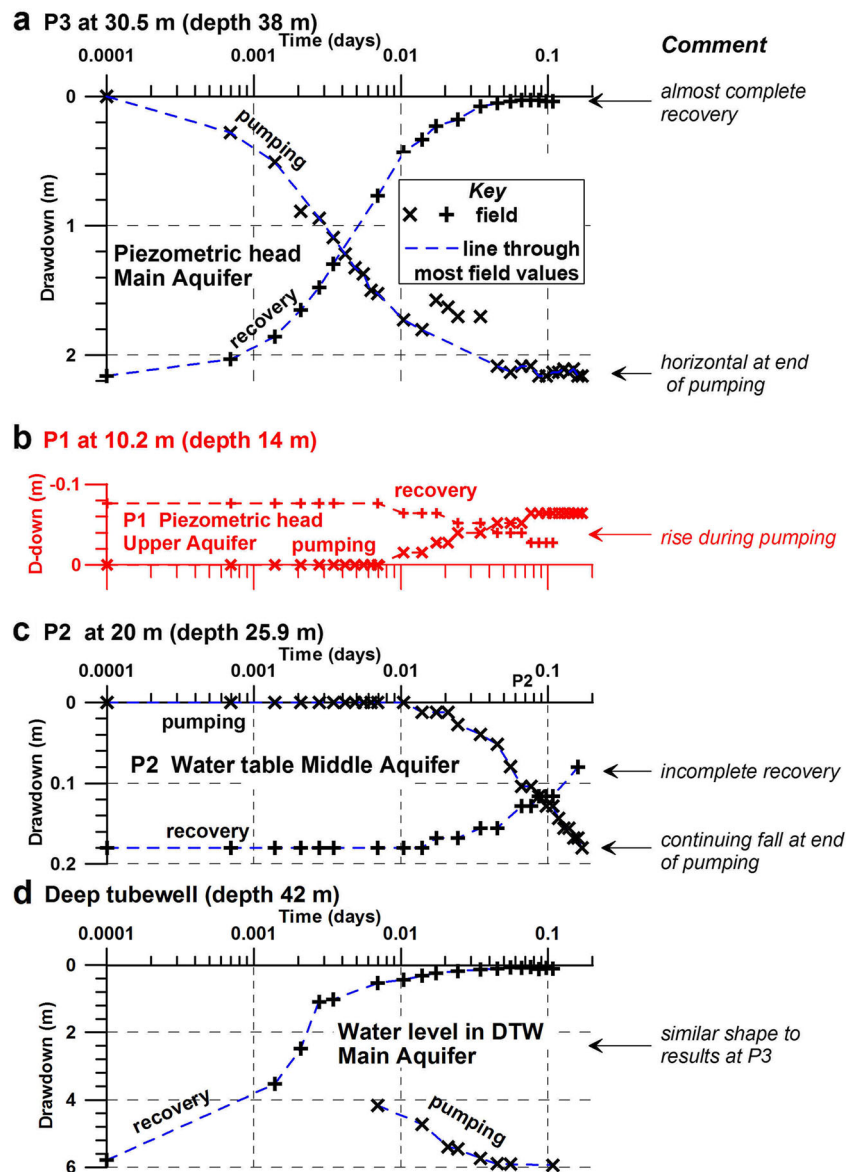
This examination of the responses in the observation wells and the DTW due to pumping is consistent with the conceptual model of Fig. 5b; therefore, a computational model has been prepared to represent flows in the Lower Unit which includes the Middle aquifer, Aquitard B and the Main aquifer. Fluxes from the strata above the Middle aquifer are represented as a vertical flux to the Middle aquifer; the magnitude of this flux is initially unknown.

Computational model for Lower Unit

The purpose of the computational model is to represent conditions, during the pumping test and subsequent recovery, in the Lower Unit of the conceptual model (Fig. 5b). The flow processes which must be incorporated in the computational model are illustrated in Fig. 7a, they include:

- Varying pumping rate and zero pumping rate during recovery
- Well loss as water passes from the aquifer into the well, which has a finite radius
- An outer no-flow boundary to represent other wells pumping from the same aquifer
- Lateral flow through the Main aquifer to the well and the inclusion of confined storage
- Vertical flow through Aquitard B

Fig. 6 a–d Field results from the pumping test; the *broken lines* represent approximate fits through the field values

a P3 at 30.5 m (depth 38 m)

b P1 at 10.2 m (depth 14 m)

**c** P2 at 20 m (depth 25.9 m)

d Deep tubewell (depth 42 m)

- Horizontal flow in the Middle aquifer with water released from unconfined storage as the water table falls
- Flux (recharge) to the water table from the overlying strata

The movement of groundwater from the Middle aquifer, through Aquitard B to the Main aquifer can be described as a leaky aquifer flow process. The original analyses of pumping in leaky aquifers systems assumed an infinitely small well radius, an aquifer of infinite extent and a constant water-table elevation in the overlying aquifer (Jacob 1946; Hantush and Jacob 1955); however, in practice, the groundwater head in the overlying aquifer will fall as water is drawn through the aquitard, a situation which was studied by Neuman and Witherespoon (1969). In recent studies, analytical solutions have been developed for a range of additional conditions—for example, Feng and Zhan (2015) have

developed a mathematical model for groundwater flow to a partially penetrating pumping well of a finite diameter in an anisotropic leaky confined aquifer, the model also accounts for the effects of aquitard storage, aquifer anisotropy, and wellbore storage. The article also summarises many of the other studies of leaky aquifer behaviour. Although there are now many analytical solutions for leaky aquifer behaviour, they are not suitable for the current problem, primarily because they are unable to represent a varying well discharge followed by zero discharge or the vertical flux from the overlying strata.

Since analytical solutions cannot include all of the flow processes listed already, a numerical method is selected. The two-zone radial flow model (Fig. 7b) can include all these flow processes; the model is described in detail in Rathod and Rushton (1991) and section 7.4 of Rushton (2003). The

Fig. 7 **a** Conceptual model for Lower Unit and **b** computational model used for the interpretation of the pumping test

a Lower Unit of conceptual model

b Computational model
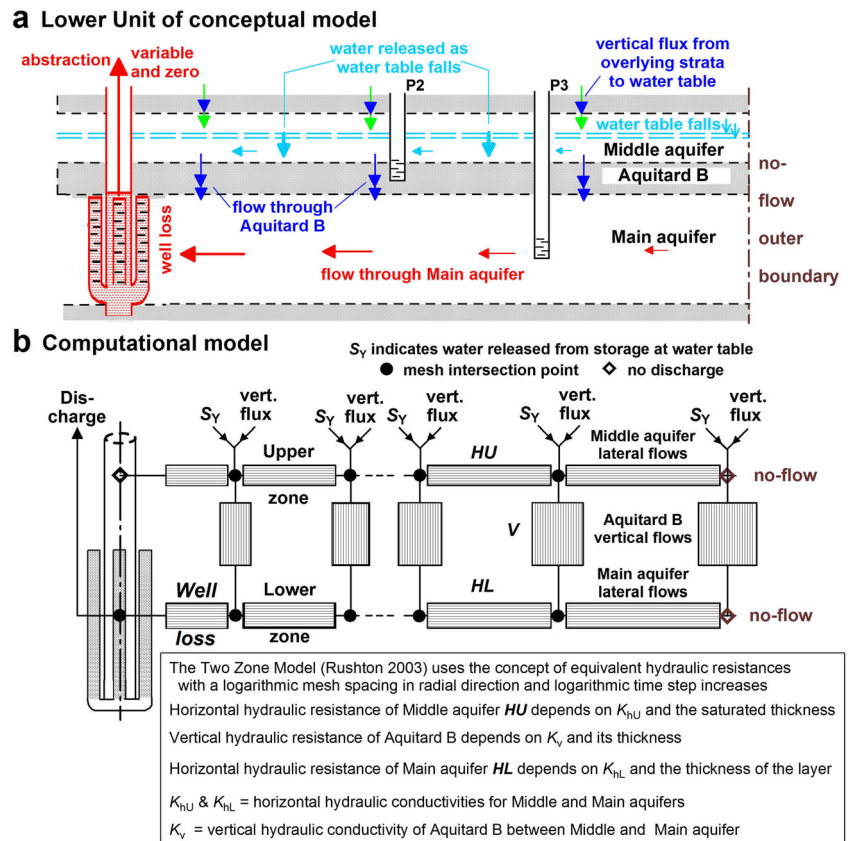
model uses an arrangement of equivalent hydraulic resistances which are defined at the bottom of Fig. 7b; these hydraulic resistances are the inverse of conductances used in the MODFLOW computational model. In the two-zone radial flow model, flows in the Middle aquifer are represented by the Upper zone, flows in the Main aquifer by the Lower zone and flows between the Upper and Lower zones by vertical hydraulic resistances. There is a logarithmic mesh spacing in the radial direction; time steps also increase logarithmically with an initial time step of 0.00001 day. The pumping rate varies corresponding to the measured discharge; when recovery starts, the pumping rate is set to zero and the time step returns to its low initial value. Calculated values of the drawdown are output at the pumped well and at the radial distances of P2 and P3.

Parameter values required for this computational model are listed as follows:

Middle aquifer. Horizontal hydraulic conductivity, specific yield, saturated thickness.
Main aquifer. Horizontal hydraulic conductivity, confined storage coefficient, thickness of aquifer.
Vertical flow through Aquitard B. Vertical hydraulic conductivity and thickness of Aquitard B.
Well loss factor. As the groundwater passes from the aquifer, through the gravel pack and into the well screens,

the flow paths become disturbed (Clarke 1977) resulting in head losses. This phenomenon is described as 'well loss' (Fig. 7b), which is represented in the computational model by increasing the horizontal hydraulic resistance for the mesh interval adjacent to the well (section 8.2 of Rushton 2003). The introduction of a well loss factor is equivalent to reducing the effective hydraulic conductivity.
Recharge (*vertical flux*) *from Upper Unit.* This is determined during the model refinement process; it is likely to be in the range 1–4 mm/day (about 25–100 % of the average annual precipitation).
Radial distance to lateral outer boundary. This depends on interference from surrounding tubewells. In an area of 10 km^2 surrounding Amtoli-1 there are 15 operating tubewells; hence, the average distribution is one tubewell per 0.667 km^2. An outer no-flow boundary at a radius of 460 m is equivalent to a plan area of 0.665 km^2.

Refining (calibrating) the computational model

Refining the computational model involves making modifications to the aquifer parameters to improve the agreement between model and field results. A systematic approach is adopted considering individual field results in turn. The

computational model output includes drawdowns for both the pumping and recovery phases.

1. The first stage is to consider observation piezometer P3 where the groundwater head fluctuations depend primarily on the horizontal hydraulic conductivity and confined storage coefficient of the Main aquifer and the vertical hydraulic conductivity of Aquitard B. Initial drawdowns are sensitive to the horizontal hydraulic conductivity; however, later in the pumping phase and for the entire recovery, the model response at P3 is principally dependent on the vertical hydraulic conductivity of Aquitard B as water is drawn from the Middle aquifer. A careful examination of Fig. 8a shows that the continuous lines of the computational model output generally pass through, or close to, the field results. However, there are some inconsistencies in the field measurements, such as the four readings during the pumping phase after 0.01 day, which arise due to the limitations of the measuring equipment and the limited experience of the operators.

2. The next stage is to consider the response of piezometer P2 in the Middle aquifer (Fig. 8b). Water is drawn from the Middle aquifer and transmitted through Aquitard B to the Main aquifer. For the pumping phase, the initial drawdowns depend on the water moving downwards through Aquitard B and the horizontal hydraulic conductivity of the Middle aquifer. However, the continuing drawdown towards the end of the pumping phase results from the increasing impact of the specific yield. When the pump is switched off, there is a partial recovery in drawdowns even though water continues to be drawn from the Middle aquifer, through Aquitard B to the Main aquifer. This partial recovery can only occur if there is a vertical flux (recharge) from the overlying Upper Unit. The red unbroken line in Fig. 8b shows that the drawdowns at P2 would remain at a relatively constant value if this vertical flux did not occur.

3. Field and modelled drawdowns in the deep tubewell are plotted in Fig. 8c. The field results have limited reliability due to the difficulty of dipping in a pumping well while the pump is operating. The horizontal hydraulic conductivity and confined storage coefficient remain as determined from the first stage already mentioned; the well loss factor is adjusted for a best fit to the field results. A well loss factor of 1.8 resulted in a satisfactory reproduction of the general form of the drawdowns and recovery in the DTW (Fig. 8c).

Parameter values estimated from the computational model

Parameter values deduced from the computational model are listed in columns 2 and 3 of Table 2. Column 2 refers to the
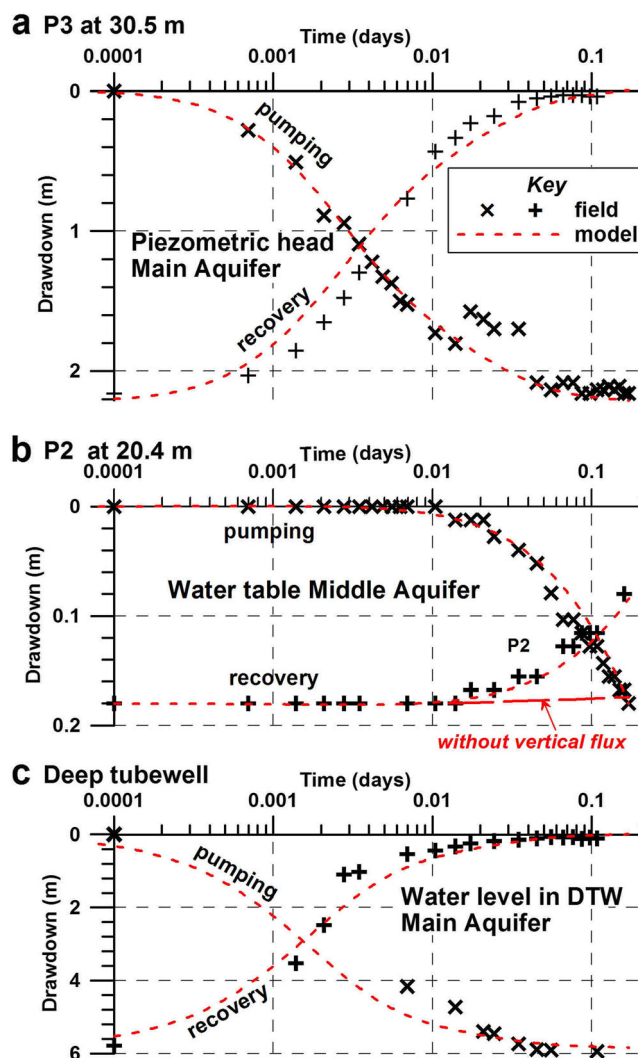

Fig. 8 a–c Comparison between field results (*discrete symbols*) and groundwater flow model (*continuous lines*)

situation of 15 tubewells in an area of 10 km² or the DTW collecting water from an area of 0.667 km² (see section 'Computational model for Lower Unit'), which corresponds to an outer boundary at 460 m. However, it is possible that the area from which Amtoli-1 collects water is larger due to greater distances to the surrounding tubewells and some of the tubewells not operating; consequently, in a second simulation with only half the tubewells operating, the DTW collects water from an area of 1.33 km² with an equivalent outer boundary at 652 m. The following discussion refers mainly to results for the outer boundary at 460 m with additional comments when the outer boundary is at 652 m.

Main aquifer. The horizontal hydraulic conductivity of 92 m/day is appropriate for a permeable material of sand and gravel with some sandy clay. It is also close to the value of 70 m/day calculated by Rashid (2005) for the same location using leaky aquifer theory, and consistent

with the values of Michael and Voss (2009). The confined storage coefficient is similar to other studies although the model response is not sensitive to this parameter. For the lateral boundary at 652 m, the required horizontal hydraulic conductivity is slightly higher.

Aquitard B. The vertical hydraulic conductivity of 0.042 m/day is consistent with values quoted by Fetter (2001) for silt, sandy silt with clayey silt. When the Main aquifer extends to 652 m, the vertical hydraulic conductivity is lower at 0.030 m/day, which occurs because the Main aquifer can collect water over a larger area.

Middle aquifer. The horizontal hydraulic conductivity of 27 m/day is lower than for the Main aquifer but the lithological logs indicate that it consists of medium and fine sand. The unconfined storage (specific yield) of 0.012 is low compared with normal values for sands; however, this relatively low value is supported by an investigation of a similar situation where the Lower London Tertiaries in Eastern England were partially dewatered; the specific yield of 0.01 was thought to occur due to air-entrapment (Rushton and Senarath 1983, and section 5.16 of Rushton 2003). The low value can also be due to slow drainage from the pore space; insights into the estimation of the specific yield can be found in Moench (2004). With the aquifer extending radially to 652 m, the required specific yield is 70 % of the value for the 460-m boundary.

Vertical flux from the Upper Unit. To represent the partial recovery in drawdowns for the Middle aquifer, a vertical flux of 3.9 mm/day is required. If this rate is maintained for a whole year, it is equivalent to 1,423 mm, which is a significant proportion of the average rainfall. However, until monitoring of the three piezometers has continued for a year, this value of 3.9 mm/day must be treated as preliminary. For an outer radius of 652 m the required vertical flux is 2.2 mm/day.

Well loss factor. Reducing the horizontal hydraulic conductivity for the mesh interval adjacent to the well to 1/1.8 of the standard value is appropriate due to the large volume of the gravel pack for the inverted well.

Since this is a short duration test, the parameter values represent local conditions. Furthermore, as already indicated, parameters such as the specific yield may not represent long-term values; nevertheless, the pumping test analysis does confirm the validity of the conceptual model, especially the significance of the vertical flux through the overlying strata.

Implications for the Rajshahi Barind aquifer system

A methodology for assessing the resilience of tubewells in the Rajshahi Barind aquifer system is proposed based on insights from the study of Amtoli-1. The investigation at Amtoli-1 has shown that significant changes can occur in the flow processes within the aquifer system. Up to, and including the year 2000, the aquifer responded as a single system, whereby pumping from the Main aquifer caused a vertical flux through all the overlying layers drawing water from the water table near the ground surface to the pumped layer. Throughout the full depth of the multi-layered aquifer, pressure heads were above atmospheric. Due to the varying pumping throughout the year, the piezometric heads (water levels) varied seasonally by 10 m or more.

By 2015, the flow processes at Amtoli-1 had changed significantly. Due to an increase in the vertical flux through the aquifer system, the pressure head in the Middle aquifer fell to zero, leading to the formation of an additional water table. The aquifer now responds as two units. For the Lower Unit, from the water table in the Middle aquifer to the Main aquifer, pressure heads are above atmospheric, with the piezometric head in the Main aquifer fluctuating as the pumping varies; however, the fluctuations are typically only about 2 m because the vertical groundwater head gradient is across Aquitard B, which is 4.6 m thick. For the Upper Unit, the vertical flux is from the near-surface water table to the bottom of Aquitard A where the pressure is also atmospheric. Although flows in the Lower Unit have been represented by the computational model of section 'Computational model for Lower Unit', there is

Table 2 Parameter values for computational model for average tubewell distribution of 15 tubewells in 10 km^2 and also double that area. Initial parameter values for *average tubewell distribution* are shown *in brackets*

Parameters	Average tubewell distribution	Doubled area
Radial distance to outer boundary (m) area associated with tubewell (km^2)	460	652
	0.667	1.33
Main aquifer K_{hL} (m/day)	92 (50)	94
Main aquifer confined storage (dimensionless)	0.00015 (0.0005)	0.00015
Aquitard B K_V (m/day)	0.042 (0.015)	0.030
Middle aquifer K_{hU} (m/day)	27 (35)	29
Middle aquifer unconfined storage (dimensionless)	0.012 (0.05)	0.0085
Vertical flux from Upper Unit (m/day)	0.0039 (0.004)	0.0022
Well loss factor	1.8 (3.0)	1.8

not yet sufficient field information to quantify the vertical flux through the Upper Unit.

To assess whether over-abstraction is occurring at Amtoli-1, two important issues must be considered—whether there is sufficient water stored in the Middle aquifer and whether the replenishment from the Upper Unit is adequate. Monitoring of the water table in the Middle aquifer using piezometer P2, which commenced in December 2015, will allow an assessment of the quantity of water stored in the Middle aquifer; however, the long record of non-pumping water levels in the Main aquifer (Fig. 3) provides an approximation to the water-table elevation in the Middle aquifer. An examination of the hydrograph in Fig. 3 shows that there are periods, especially from 2013 onwards, when the water level is close to the base of the Middle aquifer; note that the line indicating the base of the Middle aquifer is only approximate. At present, the abstraction appears to be sustainable.

A more detailed analysis is required of the vertical flux through the Upper Unit which supplies inflows to the Lower Unit. The lithology is idealised into layers of constant thickness with estimated vertical hydraulic conductivities. Currently a field study is being conducted related to the Upper Unit. There are several potential sources of inflow to the Upper Unit. Apart from conventional rainfall recharge (Rushton et al. 2006), there are many ponds which originally stored water, which have now been renovated mainly for fish farming. The surface area of the ponds is about 4 % of the total command area; furthermore, substantial quantities of water pass through the bunds of flooded ricefields into the underlying aquifer system—Walker and Rushton 1984; note Rashid (2005) has obtained field estimates for these losses. Vertical fluxes through Upper Unit also depend on the properties of the Barind Clay and Aquitard A. Pathways through the Barind Clay have been identified by Alam (1993). It is possible that a preferential flow mechanism occurs in the Barind Clay; an example of the importance of preferential flow through clay layers is described in Tediosi et al. (2012).

This detailed study of Amtoli-1 provides guidance for an assessment of the reliability of other tubewells in the Rajshahi Barind. Monitoring water levels in the layers from which water is pumped is essential. When, as for Gopalpur in Fig. 2b, seasonal fluctuations follow an approximately regular pattern, with recovery most years to a consistent level, there is unlikely to be any difficulty in maintaining the current abstraction pattern; however, if substantial declines occur in the average water level and in the magnitude of the fluctuations, such as at Sapahar and Amtoli-1 in Fig. 2b, further investigations are necessary. Hydrographs should be superimposed on diagrams of the lithology, which may indicate whether an additional water table could have formed. If this is a possibility, it can be investigated further by constructing piezometers to monitor the permeable strata.

Conclusions

This investigation has highlighted the importance of developing conceptual models based on the lithology and groundwater head fluctuations for the Amtoli-1 tubewell in the Rajshahi Barind aquifer. Monitoring of piezometers at different depths, but at the same location, provides crucial information. The aquifer system is idealised as three aquifers, Upper, Middle and Main with three aquitards, the Barind Clay, Aquitard A and Aquitard B. Two alternative conceptual models are prepared which illustrate the formation of an additional water table in the Middle aquifer after many years of pumping. Consequently, the aquifer system now responds as an Upper Unit and a Lower Unit.

Aquifer parameters for the Lower Unit have been estimated, using a radial numerical flow model to simulate a pumping test, with monitoring during both the pumping and recovery phases; nonetheless, a complete computational model simulation can only be achieved when the flux from the Upper Unit is input to the water table of the Lower Unit. At present, there is insufficient information to calculate this flux; however, there is a field study that is on-going to provide data and information for this task.

The Rajshahi Barind study provides insights which could be adapted for investigations of other heavily exploited multi-aquifer flow systems. It is essential to collect and collate all available information—for example, lithological logs are generally available; the quality of the record may be questionable, but it is usually possible to develop an adequate representation of the lithology. Further information is frequently available about water levels in the aquifer system over a considerable period of time; however, the provenance of these water levels must be identified—are they from specially constructed piezometers or from abstraction wells when they are not pumping; do they refer to confined or unconfined layers? From all the available data and information, conceptual models should be prepared. For heavily exploited multi-aquifer flow systems, several conceptual models may be required since conditions within individual layers often change with time. Uncertainties can usually be resolved by carrying out supplementary field work including the drilling of additional piezometers.

In groundwater investigations, working at different scales in both space and time is usually beneficial. The Rajshahi Barind investigation has involved a regional response over decades, during which there were significant changes including increased abstraction and the formation of an additional water table in some locations. Additionally, a small-scale, short-time study, monitoring the response of pumping from an individual well over a period of less than a day, has provided insights about the aquifer behaviour and properties.

Further work is required to estimate the contribution of surface water to the groundwater system at Amtoli-1 and at similar locations. Low permeability layers close to the ground surface complicate the assessment. Indirect techniques such as the water-table fluctuation method are unlikely to be appropriate for multi-aquifer flow systems because simple unconfined conditions rarely occur and fluctuations are more likely to be due to abstraction than conventional recharge. Account must be taken of all the components of the water balance and also the downwards movement of water from the ground surface to the underlying aquifers. When the abstracted water is used for irrigation, the estimated return flow must be based on actual monitoring—for example, losses from irrigated fields and through the bunds of ricefields may be significant components. Finally, in locations with a wet season, periods of intense rainfall often lead to substantial runoff; however, the runoff may be routed to ponds and lakes rather than being lost from the catchment.

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