ORIGINAL ARTICLE

Monitoring groundwater heads and estimating recharge in multi-aquifer systems illustrated by an irrigated area in north-west Bangladesh

K. R. Rushton[1] · M. Asaduz Zaman[2] · Mehedi Hasan[3]

Abstract

The impact of groundwater abstraction in multi-aquifer systems can be identified by monitoring variations of groundwater heads with depth and with time. Equally important are estimates of recharge to the groundwater system including contributions from irrigation. A case study from the Rajshahi Barind in Bangladesh illustrates the methodologies. Abstraction of groundwater from deep tubewells has resulted in substantial increases in agricultural production but also significant falls in groundwater heads in the aquifers. Monitoring of the groundwater heads at different depths and relating these to the lithology has indicated the formation of an additional water table in an intermediate aquifer; this leads to the conceptualisation of the aquifer system as two Units, Upper and Lower. Estimates of the potential recharge to the aquifer system are obtained from a daily soil water balance which is enhanced to include the representation of recharge from standing water in flooded ricefields. Detailed fieldwork, over a period of more than 2 years, includes daily records of groundwater heads, rainfall, temperature and hours of pumping for irrigation; information about the crops grown in the command area is also collected. Individual, but interconnected, conceptual and computational models for the two Units are developed. The outputs of the computational models show good agreement with measured groundwater head fluctuations. Using information from the computational models, the sustainability of the current abstraction patterns is considered.

Keywords Groundwater hydraulics · Multi-aquifer · Bangladesh · Conceptual models · Recharge

Introduction

Exploitation of an aquifer generally leads to a fall in groundwater heads, but an important question is whether too much water is being abstracted; this problem is especially challenging for multi-aquifer systems. Groundwater heads can be monitored, but do significant declines in groundwater head necessarily mean that too much water is being abstracted? Although reliable records may be available of the quantity

of water pumped from an aquifer system, estimating the recharge to a multi-aquifer system requires detailed investigations coupled with an understanding of the near-surface processes in the cultivated layer and the subsequent movement of water through underlying strata.

When investigating groundwater conditions in multi-aquifer situations, monitoring the variation of groundwater heads with time in piezometers tapping individual aquifers provides valuable information. This is illustrated in Fig. 1 which shows the groundwater heads in an alluvial aquifer located in a broad river flood plain in Gujarat, India (Kavalanekar et al. 1992; Rushton 2003, p 304). The red line indicates the groundwater head fluctuations in the shallow aquifer, while the green line represents the fluctuations at a depth of 200 m. These hydrographs are not in phase. The groundwater heads in the shallow aquifer (the water table) recover during the monsoon season with a slow fall during the dry season; they recover each year to a similar level because of their location in a river flood plain. However, the heads in the deeper aquifer fall during the

✉ K. R. Rushton
   kenrrushton@btinternet.com

1   Cranfield University, 106 Moreton Road,
    Buckingham MK18 1PW, UK

2   Centre for Action Research-Barind (CARB), UN Road,
    House # 4, Flat # A-5, Baridhara, Dhaka 1212, Bangladesh

3   Groundwater Monitoring, Resource Assessment
    and Management Unit, CARB, Amtoli, Godagari, Rajshahi,
    Bangladesh

Fig. 1 Groundwater heads at different depths within a multi-aquifer system: example from Linch borehole in Mehsana alluvial aquifer, Gujarat, India
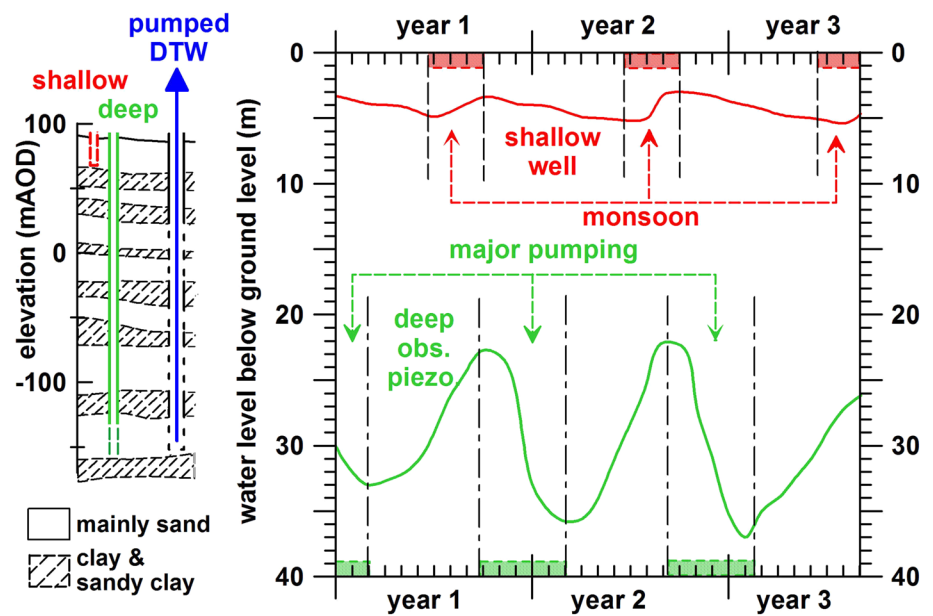
main pumping season which follows the monsoon, with recovery starting in the latter part of the dry season when no crops are grown. The flux through the clay and sandy clay aquitards depends on the difference between the red and green groundwater heads. Failure to distinguish the different features of these hydrographs often leads to invalid conclusions. Further examples of the use of multiple piezometers to explore groundwater conditions in multi-aquifers include Walthall and Ingram (1984), Gerber et al. (2001) and Post and von Asmuth (2013).

The estimation of the quantity of water which enters the aquifer system due to rainfall and irrigation is another important factor when seeking to quantify the resources of multi-aquifer systems. Recharge estimation techniques are described in a special issue of the Hydrogeology Journal (Scanlon and Cook 2002) and in a book by Healy (2010). When estimating recharge, it is essential to consider in detail the nature of the physical processes. For example, Fitzsimons and Misstear (2006) consider recharge through tills and highlight the importance of developing a conceptual understanding of the influence of the geology on recharge mechanisms and recharge rates. Irrigated areas present distinctive challenges. Information from the FAO report, Crop Evapotranspiration (Allen et al. 1998), combined with a soil water balance, can be used to estimate recharge under different cropping patterns. Eilers et al. (2007) describe how this approach is used to estimate recharge for a semi-arid area in Nigeria; de Silva and Rushton (2007) adapt the technique for an upland area in Sri Lanka with a tropical climate. Irrigated flooded ricefields are often the source of significant recharge through the puddled bed and bunds (Walker and Rushton 1984); consequently, direct precipitation may not be the principal source of recharge.

When studying multi-aquifer situations, it is vital to identify the important physical processes and develop valid conceptual models. This requires an understanding of the precipitation, farming practices, irrigation and the routes by which water enters the aquifer system. Additional information is required about the transfer of water through low-permeability deposits and intermediate aquifers to the pumped aquifer. The conceptual models form the basis of computational models which are refined; their adequacy is confirmed by comparisons with field data.

A specific case study of the Barind Tract in north-western Bangladesh is selected to illustrate the importance of monitoring groundwater heads at different depths in multi-aquifer systems and estimating how much water enters through the cultivated layer. Exploitation of the Rajshahi Barind aquifer has resulted in a major improvement in the availability of water for irrigation. However, as pumping from the deep tubewells (DTWs) has increased, there have been significant falls in the non-pumping water levels in the DTWs and also a reduction in the seasonal fluctuations. Using the piezometers constructed in the vicinity of a DTW to determine the lithology (Rushton and Asaduz Zaman 2017), a short-term pumping test was conducted and analysed. Nevertheless, many questions remained about the sustainability including the recharge processes and how water moves from the ground surface to the deeper aquifer from which pumping occurs. For this case study, a comprehensive understanding of the aquifer system is developed by studying an individual tubewell and its command area rather than a larger area.

The first section of this paper provides an introduction to the Barind aquifer system and includes brief reference to earlier studies. This is followed by a description of the fieldwork associated with the Amtoli-1 DTW. An examination

of the groundwater heads indicates that an additional water table has formed in an intermediate aquifer; consequently, the aquifer system is considered as two Units. Of special significance is a methodology developed for estimating the recharge and in particular identifying the contributions through the bed and bunds of flooded ricefields. Conceptual models are prepared, and computational models are developed to represent groundwater flows in the aquifer system over a period of more than 2 years. Using information from the computational models, the sustainability of the current abstractions is assessed.

Case study on the Barind tract

Background

The Barind Tract is located in north-west Bangladesh, as shown in Fig. 2. It consists of Pliocene–Pleistocene terrace deposits, roughly equivalent to the 'Older Alluvium' of the Indian literature, typically located in slightly elevated positions, 15–40 m above sea level. Deposits are generally highly weathered and include clay, sand and occasionally gravel (Brammer 2016). The tract is one of the direst and hottest parts of the country with a mean annual rainfall of about 1500 mm and temperatures up to 50 °C in the summer.
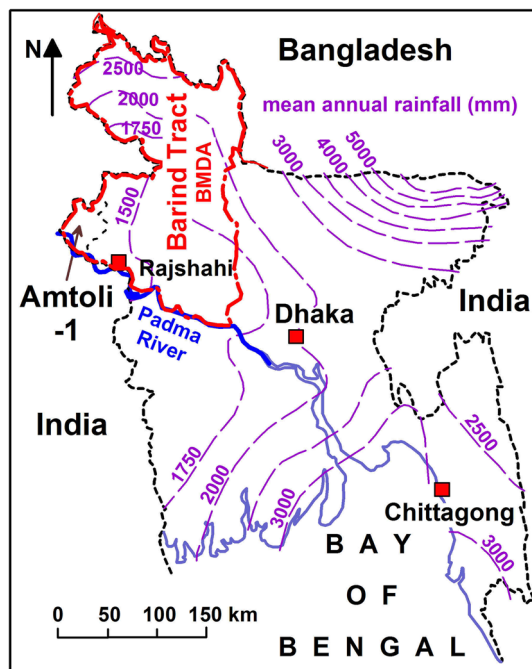

Fig. 2 Location map of Amtoli-1 tubewell in Bangladesh; BMDA indicates the area covered by the Barind Multipurpose Development Authority

Despite predictions by UNDP (1982) of low yields from the Rajshahi Barind aquifers, the Barind Multipurpose Development Authority (BMDA) has constructed many successful deep tubewells which supply groundwater to irrigate one or more dry season crop (Faisal et al. 2005); the current area of responsibility for BMDA is indicated in Fig. 2. One significant feature which has improved the yield of the DTWs is the introduction of an alternative form of well construction for aquifers of limited thickness, in which inverted screens extend vertically upwards alongside the well casing from a connector at the bottom of the well assembly (Asad-uz-Zaman and Rushton 2006); this form of construction is illustrated in some of the subsequent figures.

Several papers consider the groundwater resources of the Barind Tract; the adequacy of these studies is assessed by determining whether they recognise that it is a multi-aquifer system and whether the recharge estimates are based on the actual field conditions including the substantial losses from flooded ricefields. Shahid and Hazarika (2010) attempt to identify groundwater droughts by comparing rainfall with groundwater levels in the deeper aquifer; they note a lag between maximum groundwater level and the monsoon rainfall but do not recognise that the deep groundwater fluctuations depend primarily on abstraction. Adham et al. (2010) use GIS and remote sensing to estimate the recharge in the Barind Tract; they fail to consider the actual recharge processes and consider that only 8.6% of the total average annual precipitated water contributes to recharge. Islam et al. (2014) base their recharge estimates on annual water balances; their estimated recharge is 10% of the annual rainfall, whereas abstraction from the DTWs is actually more than 30% of the annual rainfall.

Investigations by Shahid et al. (2015) and also Rahman et al. (2016, 2017) ignore the multi-aquifer nature of the Barind aquifers; water levels in the deeper wells are assumed to represent the groundwater table. When estimating recharge using the water table fluctuation method, data from observation wells, which penetrate 60–75 m and respond to abstractions, are used instead of the actual water table data. Many of the factors which can cause depletion of groundwater in the Barind aquifer are identified by Mustafa et al. (2017); however, features such as losses from flooded ricefields are not included leading to a substantial underestimation of the magnitude of the recharge. Their groundwater model of the multi-aquifer system consists of a single layer.

These, and other assumptions, are not appropriate for the actual groundwater conditions in the Barind aquifer system. Consequently, there can be no confidence in their findings.

Comprehensive fieldwork associated with Amtoli-1 deep tubewell

This study focuses on a single DTW, Amtoli-1, and its associated command area. The reason for concentrating on a

single representative tubewell rather than a larger area is that it is possible to collect the detailed data and information needed to develop a thorough understanding of the flow process. The presence of DTWs in the surrounding area with similar abstraction patters means that Amtoli-1 can be considered on its own. Further examples of focussing on a single well include India (Rushton and Srivastava 1988), Bangladesh (Miah and Rushton 1997) and Sri Lanka (Rushton and de Silva 2016).

The Amtoli-1 tubewell is located in the south-west of the BMDA area, as shown in Fig. 2; the cropping intensity in the BMDA area is currently approximately 2.5. Amtoli-1 is typical of locations in the Rajshahi Barind, where substantial water-level declines have occurred in the aquifer zones from which water is pumped (Rushton and Asaduz Zaman 2017); note that Amtoli-1 is located in an area where the annual average rainfall of 1420 mm is the lowest for Bangladesh.

In the 1980s, during the earlier stages of deep tubewell development, the fluctuations in non-pumping water levels in the deeper aquifer were 3–5 m with recovery to typically 10 m below ground level (bgl) each monsoon season. The non-pumping water-level hydrograph in Fig. 3a indicates that for the years 2000–2002, the annual fluctuations in Amtoli-1 approached 10 m due to increased abstraction. However, by 2015–2017 a significant decline had occurred between 23 and 25.3 m bgl and small seasonal fluctuations of less than 2 m, as shown in Fig. 3b. The distinctive difference between the hydrographs in diagrams (a) and (b) is a clear indication that important changes have occurred in the groundwater flow processes.

In November 2015, small diameter exploratory boreholes, P2 and P3, were constructed in the vicinity of Amtoli-1, as shown in Fig. 3c. In addition to the near-surface aquifer, two distinct aquifers were identified, an intermediate aquifer, which in this study is referred to as the Middle aquifer, located between 21.3 and 25.9 m bgl and the Main aquifer from which pumping occurs extending from 30.4 to 41.2 m.

The Middle aquifer is monitored by piezometer P2 and the Main aquifer by piezometer P3. Water levels, when the pump was not operating, in the DTW and piezometers P2 and P3 were collected on a daily basis; readings for P2 and P3 are plotted in Fig. 4d.

Figure 4a records the rainfall over a 27-month period from December 2015 to February 2018; much of the rainfall occurs during the monsoon season of May to September although there is significant rainfall at other times. Figure 4b records the number of hours when the pump operated at Amtoli-1 for irrigation of the command area; a representative annual pattern of cropping is two crops of rice and one of tomatoes. There is substantial pumping from February to early April for the winter rice crop; some irrigation pumping occurs during September to December for a crop such as tomatoes. If the monsoon rainfall is erratic, supplementary irrigation pumping may be required for the monsoon rice crop.

To monitor near-surface conditions, dug wells were constructed during the fieldwork period. Fluctuations in dug well DW-4 are plotted in Fig. 4c; the well is 0.92 m in diameter, 3.0 m deep and located about 220 m from the DTW, as shown in Fig. 3c, with readings starting from June 2016. A careful examination of the daily readings in Fig. 4c, indicated by + symbol, shows that sudden changes can occur between successive days. This may be caused by irrigation in neighbouring fields. In addition, an earthen channel close to the dug well acts as a drainage channel during times of high rainfall. The broken red line on Fig. 4c indicates the average weekly readings for DW-4.

A comparison of the hydrographs for the dug well (Fig. 4c) and the wells in the deeper aquifers (Fig. 4d) shows that, like hydrographs for the alluvial aquifer of Fig. 1, the responses are significantly different. The water levels in the deeper piezometers P2 and P3 fall during pumping and recover when the pump is not operating. However, the water level in the shallow dug well, as shown in Fig. 4c, does not

Fig. 3 Information about Amtoli-1 tubewell and associated multi-aquifer system; **a** groundwater head fluctuations in Main aquifer from 2000 to 2002, **b** fluctuations from 2015 to 2017 and **c** conceptual models and flow processes in Upper and Lower Units
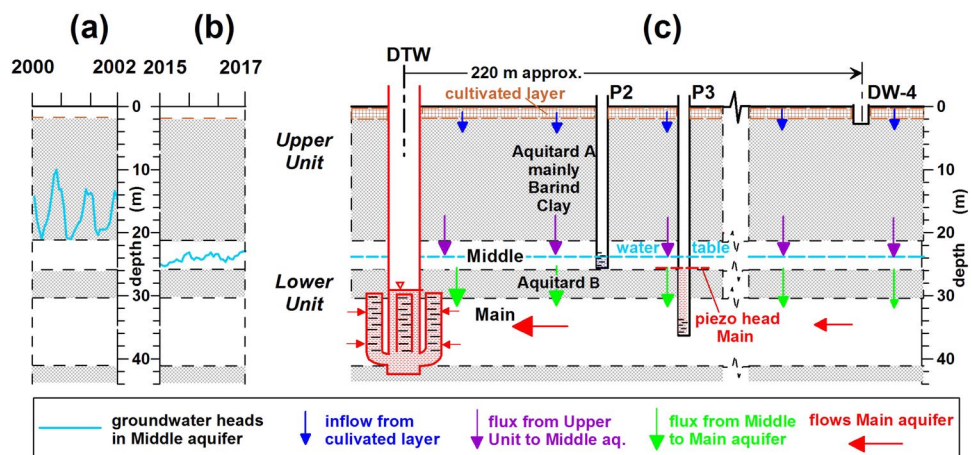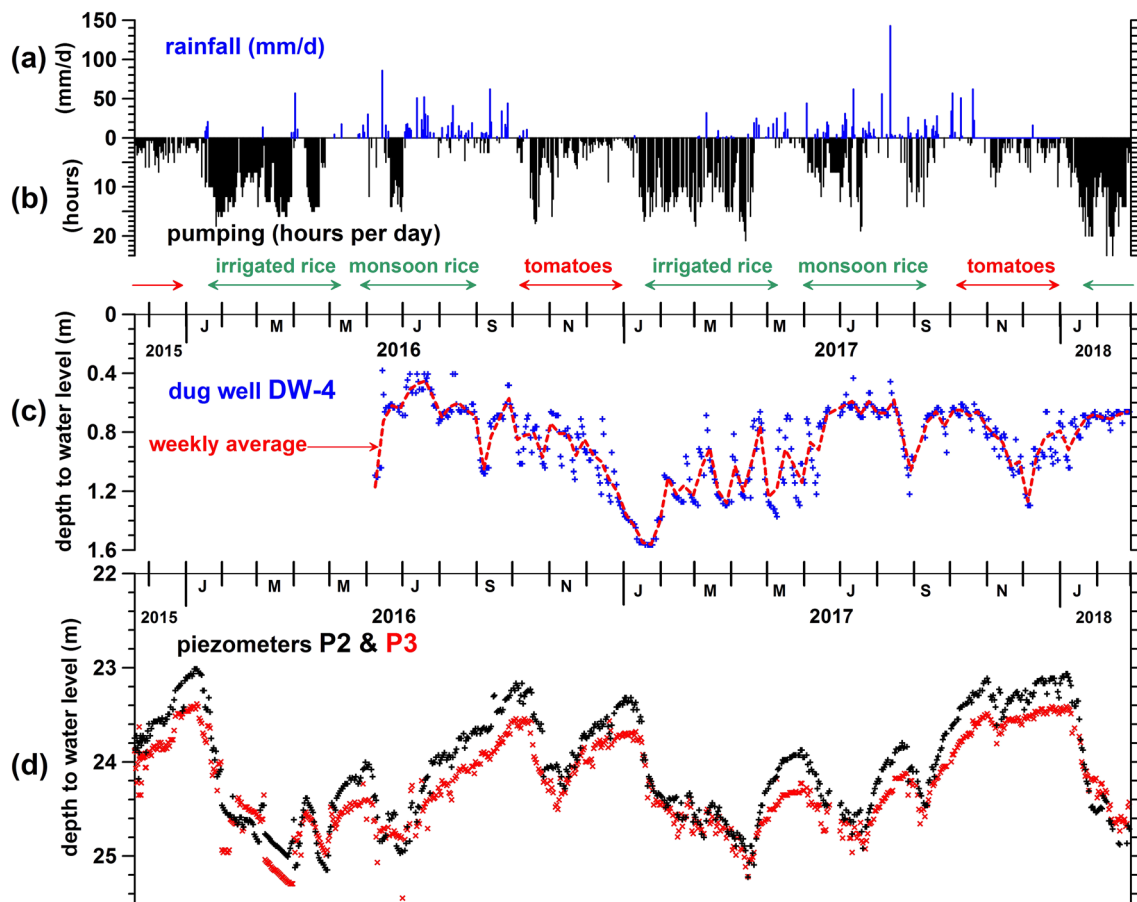
Fig. 4 Data collected during monitoring associated with Amtoli-1 **a** rainfall, **b** hours that Amtoli-1 operates, **c** water-level fluctuations in DW-4 with red line indicating weekly average values (from June 2016), **d** water levels in piezometers P2 and P3

only respond to rainfall (Fig. 4a). In fact, recovery in the dug well water levels occurs mainly during periods of intense pumping, as shown in Fig. 4b, when the abstracted water is used for irrigation of the crops and provides a source of recharge.

Every month, a map of the distribution of crops over the command area was prepared. In addition, photographs and videos of farming practice, especially during very heavy rainfall, provide insights into the actual conditions in the command area.

Aquifer system acts as two units

The small graph in Fig. 3b is of particular significance because it shows that the groundwater level in piezometer P2, which penetrates to the Middle aquifer, is currently between the top and bottom of the Middle aquifer. This indicates that an additional water table is formed in the Middle aquifer. This is a crucial factor when developing the conceptual model of Fig. 3c. Due to the formation of this additional water table, the aquifer system responds as

two units, an Upper Unit and a Lower Unit. A flux from the Upper Unit provides an inflow (recharge) to the water table in the Middle aquifer of the Lower Unit.

The Upper and Lower Units are indicated in Fig. 3c; the flows in and between the Units are shown as coloured arrows. Water from the cultivated layer of the Upper Unit moves predominantly vertically through Aquitard A; this aquitard consists mainly of Barind Clay. When this flux is discharged from the bottom of Aquitard A, it acts as recharge to the water table in the Middle aquifer. Pumping from the tubewell in the Main aquifer causes a vertical flux through Aquitard B in the Lower Unit; this draws water from the water table in the Middle aquifer. The fluctuations of the water table in the Middle aquifer depend on the flux from the Upper Unit, the flux through Aquitard B due to the abstraction and water released from or taken into storage as the water table falls or rises; the specific yield determines the magnitude of these fluctuations.

Conceptual and computational models of the Upper Unit are considered first; the flux from the bottom of

Aquitard A in the Upper Unit acts as an input to the computational model for the Lower Unit.

Conditions in the upper unit

The Upper Unit, as shown in Fig. 5, consists of the cultivated zone which is underlain by Aquitard A. Typically, there are two crops of rice and a third partially irrigated crop, often of tomatoes, after the monsoon season. Water, which moves down from the soil zone, becomes an inflow through the aquitard. The flux q_u from the base of Aquitard A provides an input to the water table in the Middle aquifer. Because a water table is formed in the Middle aquifer, the pressure above this water table and hence at the bottom of the Upper Unit is atmospheric.

Conceptual models

Conceptual models are required for the cultivated layer, including the ricefields, and also for the underlying aquitard, as shown in Fig. 5. Field evidence for substantial losses of water through the bunds of ricefields is presented in Walker and Rushton (1986). The importance of considering both percolation through the bed and seepage through the bund was verified in a number of subsequent studies including Tuong et al. (1994) and Kukal and Aggarwal (2002). Rashid (2005) carried out detailed experiments to estimate water losses through the bed and bunds of ricefields in the Amtoli area; for the irrigated rice crop, the depth of water varied from 1 to 7 cm with typical losses through the bed and bunds of 4 mm/day. The corresponding conditions for the monsoon rice crop were water depths between 4 and 10 cm with losses of 6 mm/day. When crops such as tomatoes are grown or the land is fallow, water can pass through the soil zone due
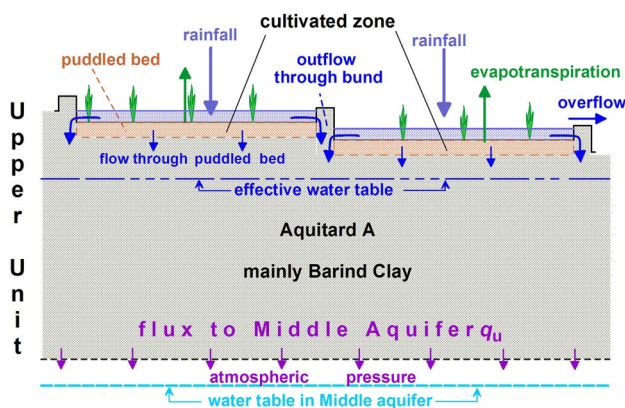

Fig. 5 Conceptual model for Upper Unit illustrating the significant loss of water through the bed and bunds of ricefields and the flow of water through Aquitard A to the water table in the Middle aquifer

to rainfall or irrigation when the soil reaches field capacity (Eilers et al. 2007).

Water from the bunds or bed of ricefields and water transmitted through the soil zone when it is at field capacity combine as inflows to Aquitard A. It is assumed that this water moves predominantly vertically through Aquitard A so that Darcy's Law applies.

Computational models

Two computation models are required, a daily soil water balance model to represent near-surface conditions including growing crops and also a computational model for the vertical flow through the aquitard in the Upper Unit. Groundwater heads at the top of the aquitard calculated from these models are compared with the water-level fluctuations in the dug well, as shown in Fig. 4c.

Soil water balance

Soil water balance models are widely used for estimating crop water requirements in semi-arid areas (Allen et al. 1998); the methodology has been adapted for the estimation of recharge to underlying aquifers (Rushton 2003 p64; Eilers et al. 2007). Moisture conditions within the soil are represented by the soil moisture deficit (*SMD*) which is defined as the quantity of water which needs to be added to the soil to bring it to field capacity. A second important parameter is the total available water (*TAW*) which depends on the depth of the crop roots and the proportion of water that can be withdrawn from the soil by the roots. A further parameter is the readily available water (*RAW*); when the soil moisture deficit is greater than *RAW*, the actual evapotranspiration (*AE*) may be less than the potential rate (*PE*), where *PE* equals the reference crop evapotranspiration (*ET*o) multiplied by the relevant crop coefficient.

Three significant soil moisture conditions in the cultivated layer are illustrated in Fig. 6a; in these diagrams, the vertical downward axis indicates a soil moisture deficit.

For **Case I** the precipitation (*Pr*) is smaller than the potential evapotranspiration *PE*. Since the soil moisture deficit is between *RAW* and *TAW*, the actual evapotranspiration *AE* is less than *PE*. A small run-off (*RO*) may occur. The increase in soil moisture deficit during the daily time step equals the sum of *AE* and *RO* minus the precipitation *Pr*.

For **Case II** of Fig. 6a, the precipitation plus irrigation (*Pr*+*I*) are larger than *PE*. Furthermore, the *SMD* is very close to zero; hence, the actual evapotranspiration *AE*=*PE*. The water balance calculation results in a negative *SMD*. However, a zero value for the *SMD* corresponds to the soil reaching field capacity; at field capacity, the soil becomes free draining. Consequently, the calculated negative value of the *SMD* becomes recharge from the base of the soil zone,

Fig. 6 Diagrams illustrating water balances in the cultivated layer and in the aquitard of the Upper Unit **a** soil water balances for three alternative values of the soil moisture deficit *SMD*; **b** vertical flow through Aquitard A
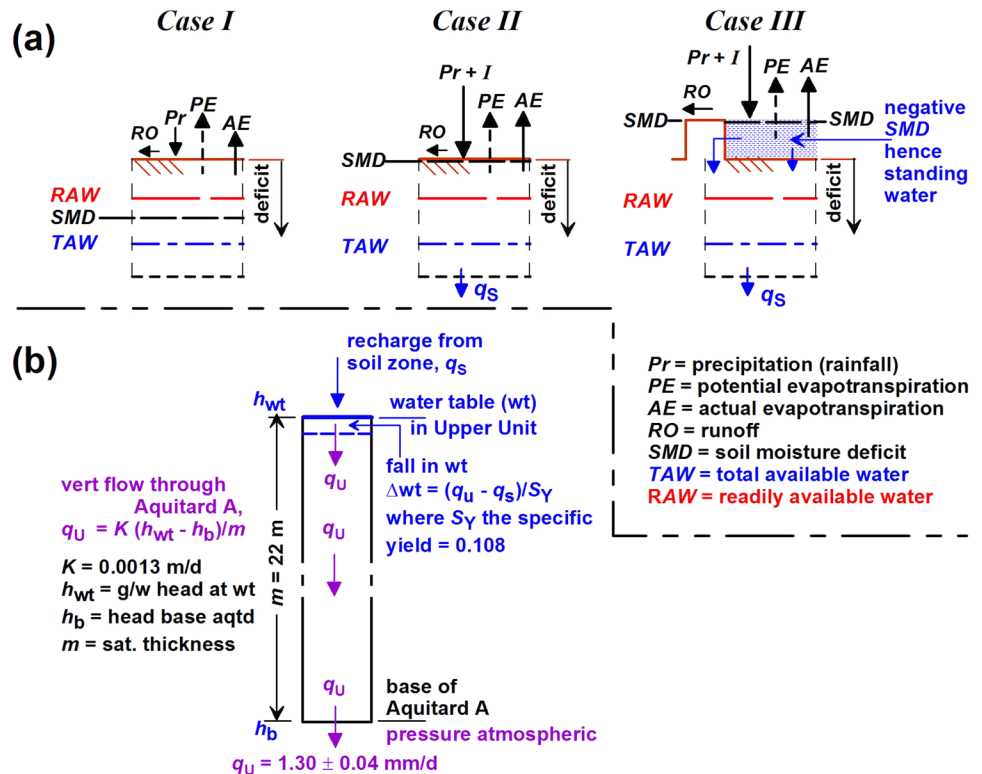
q_S. This condition can apply to crops such as tomatoes and also to fallow land.

Case III of Fig. 6a illustrates the representation of flooded ricefields in terms of the *SMD*. Due to the low-permeability puddled bed of a ricefield, negative values of the soil moisture deficit can occur; they correspond to standing water in the field as indicated by the note on the right of the diagram. If the negative *SMD* becomes too large, excess water flows over the bunds of the ricefield as run-off *RO*. There is a small seepage through the puddled bed of the ricefield and significant flows through the bunds (illustrated in Fig. 5); these flows act as recharge to the Upper Unit aquitard. Losses through the bunds depend on the depth of water in the ricefield; numerical values for a field situation in Indonesia are reported by Walker and Rushton (1986). Ricefields in Sri Lanka are considered by de Silva and Rushton (2008) while Rashid (2005) provides experimental values for the Amtoli area.

The subsurface outflow from ricefields is the principal source of recharge. An algorithm for the calculation of a soil water balance for ricefields is included in de Silva and Rushton (2008).

Typical results from a soil water balance calculation

This discussion focuses on Fig. 7 for the year 2017, with two crops of rice and one of tomatoes; this is part of a simulation from January 2015 to February 2018. The

diagram (Fig. 7) includes: (a) daily rainfall, irrigation and calculated run-off which includes flows over the bunds of ricefields, (b) potential and actual evapotranspiration, (c) *SMD*, *RAW* and *TAW*, (d) estimated recharge q_s.

Data are not available for the actual irrigation applied to individual fields; however, there is a record of the hours of pumping for the whole command area, as shown in Fig. 4a. Additionally, the farmers have regular patterns for the hours and frequency of irrigation for different crops. From this information, estimates are made of the irrigation which is shown by the green bars in Fig. 7a

Comments on the water balance in the cultivated layer are added below; the numbers in Fig. 7 indicate the occasions when these phenomena occur.

1. For irrigated rice, the target depth of water in the paddy is between 40 and 80 mm; this depth of water is indicated by the negative soil moisture deficit in Fig. 7c. For the first crop, this water depth is maintained by regular irrigation since there is only occasional rainfall. The monsoon rice crop requires some irrigation to supplement rainfall, especially to ensure that there is a sufficient depth of water for transplanting.

2. Irrigation is required for the tomato crop which is grown after the monsoon season; the aim is to ensure that the soil moisture deficit is small. When the irrigation results in a negative *SMD*, limited recharge occurs on that day.

Fig. 7 Daily soil water balance in cultivated layer for 2017; numbers refer to notes in the text
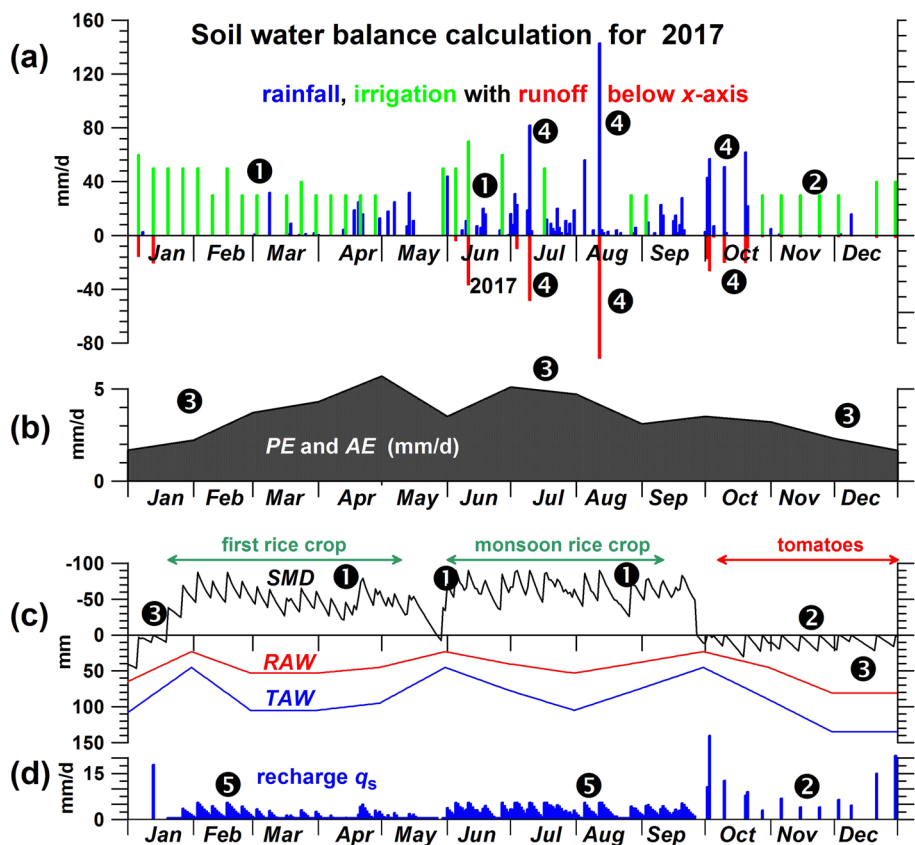
3. For the whole of 2017, the actual evapotranspiration always equals the potential value because there is sufficient precipitation or irrigation to ensure that the *SMD* is smaller than *RAW*.
4. Substantial rainfall results in significant run-off.
5. During the rice cultivation periods, there is recharge on most days, not only on the days on which there is rainfall or irrigation. This recharge through the bunds and beds of ricefields occurs for two periods, each of about 4 months; it provides much of the water which moves through the Upper Unit and allows the abstraction from the DTW to be maintained.

Movement of water through Aquitard A of the upper unit

The soil moisture balance provides estimates of the daily recharge q_s. A separate model is required for the vertical flux q_u through the Aquitard A; this is illustrated and explained in Fig. 6b. The inflow to the vertical column representing the aquitard of the Upper Unit is q_s with the groundwater head at the water table h_{wt}; the outflow q_u emerges at the base of the Upper Unit into the Middle aquifer. At the base of the Upper Unit, the pressure is atmospheric with the groundwater head h_b. The vertical flux through the aquitard q_u is governed by Darcy's Law:

$$q_u = K(h_{wt} - h_b)/m \tag{1}$$

where m, the thickness of the aquitard, is 22 m. The magnitude of the effective vertical hydraulic conductivity of the aquitard K is unknown; however, the fieldwork of Alam (1993) indicates that there are pathways through the Barind Clay (see also Asad-uz-Zaman and Rushton 2006). Lithological logs are available from five boreholes in the vicinity of Amtoli-1; some of the materials in Aquitard A are described as sandy clay or very fine sand although there are also significant deposits of clay. When the effective vertical hydraulic conductivity is set at 0.0013 m/day, the water table at the top of the aquitard is close to the ground surface. Further information about the calculation is included in Fig. 6b.

Figure 8 summarises both the computational model results for the Upper Unit and the readings in dug well DW-4 from June 2016 to February 2018. The rainfall and irrigation are included in Fig. 8a with the recharge calculated from the soil water balance in Fig. 8b. Note that recharge can occur throughout the year.

The fluctuations of the water table at the top of the Upper Unit, h_{wt}, depend on the difference between q_s and q_u and the specific yield. Adjustments were made to the specific yield. With a value of 0.108, the calculated water levels in the dug well, shown by the green line in Fig. 8c, are consistent with the field values; the datum for measurements for DW-4
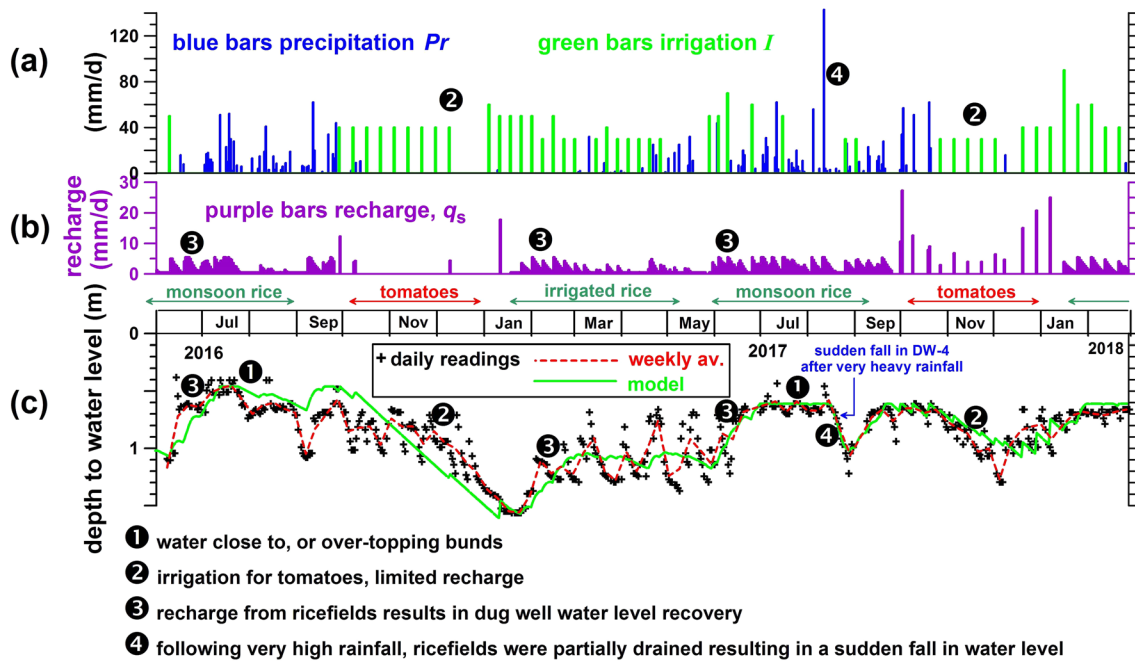
Fig. 8 Water balance and hydrographs for the Upper Unit **a** rainfall and irrigation, **b** recharge from soil water balance model, **c** field and model results for dug well DW-4

is about 0.5 m higher than the top of the ricefield bunds. Comments about certain of these results are recorded in the figure. When account is taken of factors which influence the dug well water levels such as irrigation in neighbouring fields and the flow of water in the channel near to the dug well, the agreement between the model results and field readings suggests that the conceptual and computational models for the Upper Unit are appropriate.

During August 2017, there was an exceptionally high rainfall of 143 mm in 1 day; after an initial rise, there was a substantial fall in the water level in DW-4. The reason for this fall in DW-4 is that farmers cut channels through the bunds to drain away the excess water. Consequently, water levels in the ricefields became much lower. When this feature is represented in the computational model, the changes in groundwater head, including the subsequent recovery, are replicated satisfactorily (see note 4).

The calculated flux through Aquitard A (Fig. 6b) is $q_u = 1.3 \pm 0.04$ mm/day. The variation is small because $h_{wt} - h_b$ in Eq. (1) only changes between 20.72 and 22.0 m. Consequently the flux, which acts as recharge to the additional water table in the Middle aquifer, does not change materially during the monsoon season or during periods of high irrigation. In the computational model for the Lower Unit, this flux is set at 1.3 mm/day.

The calculation of Eq. (1) uses an effective vertical hydraulic conductivity of 0.0013 m/day; this is an idealisation of the complex nature of the aquitard in the Upper Unit. However, the representation of a complex aquitard

as an equivalent low-permeability layer has been adopted elsewhere. In a study of a sandy-silt till aquitard (Gerber et al. 2001), the vertical bulk hydraulic conductivity of the aquitard is estimated to be 0.0005 m/day. For an alluvial aquifer in India, the effective vertical hydraulic conductivity of a complex mixture of sandy clays, silts, clayey sands and sands was deduced to be 0.0009 m/day (Kavalanekar et al. 1992; Rushton 2003, p. 310).

Conditions in the lower unit

The initial investigation at Amtoli-1, reported by Rushton and Asaduz Zaman (2017), introduced conceptual and computational models for the Lower Unit which successfully reproduced the drawdowns in a short-duration pumping test; the ability of these models to represent the long-term groundwater head fluctuations in the Lower Unit is now examined.

Conceptual model

A conceptual model for the flow processes in the Lower Unit is presented in Fig. 9a. At the water table in the Middle aquifer, there is an input of the vertical flux q_u from Upper Unit (purple arrows), additionally if the water table falls, water is released from storage (blue lines). The difference between these two quantities equals the flow through Aquitard B into the Main aquifer (green arrows). Water that passes through

Fig. 9 Lower Unit: **a** conceptual model; **b** corresponding two-zone radial flow computational model (developed from Rushton and Asaduz Zaman 2017)
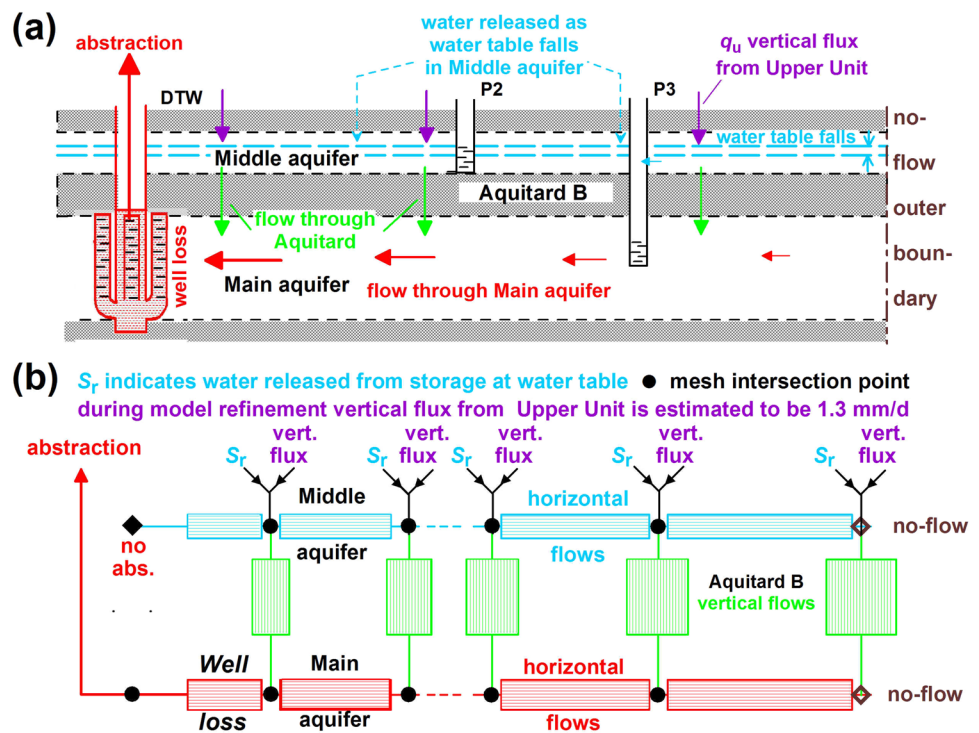
Aquitard B then moves laterally to the pumped well (red arrows).

Since the pump does not operate continuously, flows through the Main aquifer vary from a maximum when the pump is operating to a low value when the pump is switched-off; these changes occur rapidly due to the confined properties of the Main aquifer. Flows through Aquitard B also change rapidly as the pump is switched on and off. However, due to the presence of the water table and unconfined conditions in the Middle aquifer, fluctuations of water table in the Middle aquifer on a daily basis are small. Nevertheless, the water table in the Middle aquifer does fluctuate, falling during periods of heavy pumping when the demand from the Main aquifer is larger than the flux from the Upper Unit, with recovery at times of little or no abstraction.

Computational model simulations

A preliminary computational model was prepared for the initial pumping test which lasted only 6 h with recovery monitored for 3 h (Rushton and Asaduz Zaman 2017). This computational model has been developed further for the simulation of conditions over a period of 27 months. The two-zone radial flow model (Rushton 2003, p. 213) is used to represent pumping from the Main aquifer with the water drawn though Aquitard B from the Middle aquifer, as shown in Fig. 9b; the colours purple, blue, green and red refer to the components of the conceptual model in Fig. 9a. The computational model uses a logarithmic mesh spacing in the

radial direction with time steps increasing logarithmically. Since the well screens are located in the Main aquifer, water is withdrawn only from the lower zone which represents the Main aquifer, as shown in Fig. 9b. The area associated with Amtoli-1 of 0.45 km^2 is deduced from the number of tube-wells in the surrounding area of 10 km^2 and their relative abstraction rates. This area is represented as a circular plan area with a radius of 380 m.

The non-pumping water levels for piezometer P2 in the Middle aquifer and for the DTW and P3 in the Main aquifer are plotted by the symbol + in Fig. 10b, c. Abstraction from the DTW is reported as hours of pumping in a day, as shown in Fig. 10a; this is represented as pumping phases at 3254 m^3/day followed by non-pumping phases with the abstraction at zero. For each phase, the time step is reduced to 0.0001 day and then increased logarithmically to the end of that phase. The only inflow to the Lower Unit is the flux from the Upper Unit.

After model refinement, the computational model results for the end of each non-pumping phase are shown by the green lines in Fig. 10b, c. The computed results are consistent with the field data for both the Middle and Main aquifers. In particular, the lowest water levels in the Middle aquifer in March–April 2016 and in early April 2017 are reproduced satisfactorily, as shown in Fig. 10b.

The following parameter values are used in the computational model:

Middle aquifer: horizontal and vertical hydraulic conductivity = 8 and 6 m/day, specific yield = 0.10
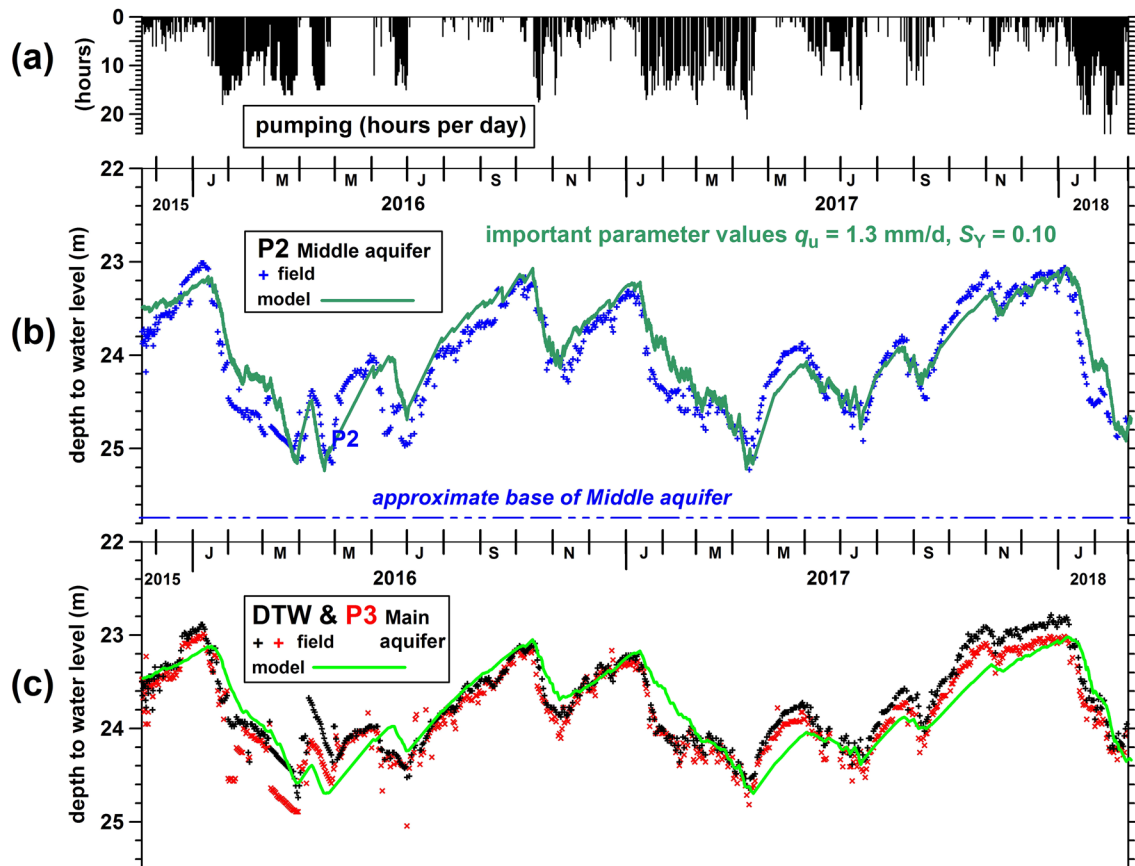
Fig. 10 Comparison for Lower Unit of field and modelled results (green lines) **a** hours for which the pump operates, **b** water levels for P2 in the Middle aquifer, **c** water levels in DTW and P3 in the Main aquifer

Main aquifer: horizontal and vertical hydraulic conductivity = 80 and 25 m/day, confined storage coefficient = 0.0009

Aquitard B: vertical hydraulic conductivity = 0.06 m/day

Vertical flux from Upper Unit = 0.0013 m/day or 1.3 mm/day

There are two parameters which are critical for a satisfactory simulation. If the vertical flux from the Upper Unit is less than 1.3 mm/day, the computed water table falls below the base of the Middle aquifer; this is not consistent with the observed behaviour as recorded by piezometer P2 in Fig. 10b. The fluctuations for both the DTW and P3 in the Main aquifer and for P2 in the Middle aquifer are reproduced satisfactorily only when the specific yield of the Middle aquifer is close to 0.10.

Conclusions

The multi-aquifer system associated with the tubewell Amtoli-1 is investigated by dividing the system into an Upper and a Lower Unit. Due to the presence of the additional water table in the Middle aquifer, these Units are studied individually with the flux from the Upper Unit providing the only inflow to the Lower Unit. For the Upper Unit, conceptual models are described for the near-surface conditions in the cultivated zone and for the movement of water vertically through Aquitard A to the Middle aquifer. The near-surface conditions are represented by daily soil water balance calculations with modifications introduced to represent water losses through the bed and bunds of irrigated ricefields.

The Middle aquifer acts as a 'storage reservoir' providing water during periods of high abstraction and storing inflow from the Upper Unit, especially when there is little abstraction. The water table fluctuations in the Middle aquifer do not fall below the base of the Middle aquifer throughout the study period; this implies that the abstraction from the DTW is balanced by the flux through Aquitard A. Provided that this water table remains above the base of the Middle aquifer, the abstractions can be maintained.

The implications for other *multi-aquifer systems* include the importance of monitoring groundwater heads at different depths using individual piezometers and relating these heads to the lithology. Without the information from the

piezometers, it is unlikely that the formation of the additional water table at Amtoli-1 would have been recognised.

An additional water table can occur in multi-aquifer systems, especially when an upper aquitard having a low vertical hydraulic conductivity overlies an intermediate aquifer. The possibility of the formation of an additional water table can be explored by long-term monitoring of non-pumping water levels in abstraction boreholes and confirmed by the drilling of piezometers to determine the lithology and locate the water table.

When estimating how much water enters the aquifer system, the actual physical situation at the ground surface must be considered. For the Amtoli-1 tubewell, the contribution from flooded ricefields is critical.

References

Adham MI, Jahan CS, Mazumder QH, Hossain MMA, Haque A-M (2010) Study on groundwater recharge potentiality of Barind Tract, Rajshahi District, Bangladesh using GIS and remote sensing technique. J Geol Soc India 75:432–438

Alam MS (1993) Stratigraphical and paleo-climatic studies of the quaternary deposits in north-western Bangladesh. PhD Thesis, Free University of Brussels, Belgium

Allen R, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. Irrigation and Drainage paper 56, FAO, Rome

Asad-uz-Zaman M, Rushton KR (2006) Improved yield from aquifers of limited saturated thickness using inverted wells. J Hydrol 326:311–324

Brammer H (2016) Bangladesh's diverse and complex physical geography: implications for agricultural development. Int J Environ Stud. https://doi.org/10.1080/00207233.2016.1236647

de Silva CS, Rushton KR (2007) Groundwater recharge estimation using improved soil moisture balance methodology for a tropical climate with distinct dry seasons. Hydrol Sci J 52(5):1051–1067

de Silva CS, Rushton KR (2008) Representation of rainfed valley ricefields using a soil–water balance model. Agric Water Manag 95:271–282

Eilers VHM, Carter RC, Rushton KR (2007) A single layer soil water balance model for estimating deep drainage (potential recharge): an application to cropped land in semi-arid North-east Nigeria. Geoderma 140:119–131

Faisal IM, Parveen S, Kabir MR (2005) Sustainable development through groundwater management: a case study on the Barind Tract. Int J Water Resour Dev 21:425–435

Fitzsimons VP, Misstear BDR (2006) Estimating groundwater recharge through tills: a sensitivity analysis of soil moisture budgets and till properties in Ireland. Hydrogeol J 14:548–561

Gerber RE, Boyce JI, Howard KWF (2001) Evaluation of heterogeneity and field-scale groundwater flow regime in a leaky till aquitard. Hydrogeol J 9:60–78

Healy RW (2010) Estimating groundwater recharge. Cambridge University Press, Cambridge. ISBN 978-0-521-86396-4

Islam MN, Chowdhury A, Islam KM, Rahaman MZ (2014) Development of rainfall recharge model for natural groundwater recharge

estimation in Godagari Upazila of Rajshahi District, Bangladesh. Am J Civil Eng 2(2):48–52. https://doi.org/10.11648/j.ajce.20140 202.16

Kavalanekar NB, Sharma SC, Rushton KR (1992) Over-exploitation of an alluvial aquifer in Gujarat, India. Hydrol Sci J 37:329–346

Kukal SS, Aggarwal GC (2002) Percolation losses of water in relation to puddling intensity and depth in a sandy loam rice (*Oryza sativa*) field. Agric Water Manage 57:49–59

Miah MM, Rushton KR (1997) Exploitation of alluvial aquifers having a low permeability overlying zone with examples from Bangladesh. Hydrol Sci J 42:67–79

Mustafa SMT, Abdollahi K, Verbeiren B, Huysmans M (2017) Identification of the influencing factors on groundwater drought and depletion in north-western Bangladesh. Hydrogeol J 25:1357–1375

Post VEA, von Asmuth JR (2013) Review: hydraulic head measurements—new technologies, classic pitfalls. Hydrogeol J 21:737–750

Rahman ATMS, Kamruzzaman M, Jahan CS, Mazumder QH (2016) Long-Term trend analysis of water table using 'MAKESENS' model and sustainability of groundwater resources in drought prone Barind Area, NW Bangladesh. J Geol Soc India 87(2):179–193

Rahman ATMS, Jahan CS, Mazumder QH, Kamruzzaman M, Hosono T (2017) Drought analysis and its implication in sustainable water resource management in Barind Area, Bangladesh. J Geol Soc India 89:47–56

Rashid MA (2005) Groundwater management for rice irrigation in Barind area of Bangladesh. PhD Thesis, Bangladesh Agricultural University, Mymensingh, Bangladesh

Rushton KR (2003) Groundwater hydrology: conceptual and computational models. Wiley, Chichester

Rushton KR, Asaduz Zaman M (2017) Development of unconfined conditions in multi-aquifer flow systems: a case study in the Rajshahi Barind, Bangladesh. Hydrogeol J 25:25–38

Rushton KR, de Silva CS (2016) Sustainable yields from large diameter wells in shallow weathered aquifers. J Hydrol 539:495–509

Rushton KR, Srivastava NV (1988) Interpreting injection well tests in an alluvial aquifer. J Hydrol 99:49–60

Scanlon BR, Cook PG (2002) Preface: theme issue on groundwater recharge. Hydrogeol J 10:3–4

Shahid S, Hazarika MK (2010) Groundwater drought in the northwestern districts of Bangladesh. Water Resour Manag 24:1989–2006

Shahid S, Wang XJ, Rahman MM, Hasan R, Haruni SB, Shamsudin S (2015) Spatial assessment of groundwater over-exploitation in northwestern districts of Bangladesh. J Geol Soc India 85:463–470

Tuong TP, Wopereis MCS, Marquez JA, Kropff MJ (1994) Mechanisms and control of percolation losses in irrigated puddled rice fields. Soil Sci Soc Am J 58:1794–1803

UNDP (1982) Ground water survey: the hydrogeological conditions of Bangladesh, Technical report. United Nations Development Program, New York

Walker SH, Rushton KR (1984) Verification of lateral percolation losses from irrigated rice fields by a numerical model. J Hydrol 71:335–351

Walker SH, Rushton KR (1986) Water losses through the bunds of irrigated rice fields interpreted through an analogue model. Agric Water Manag 11:59–73

Walthall S, Ingram JA (1984) The investigation of aquifer parameters using multiple piezometers. Ground Water 22(1):25–30