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ORIGINAL ARTICLE

Hydrogeological framework and its implication on water level rise in Eastern ArRiyadh, Saudi Arabia

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Abstract Excessive water usage together with limited capacity of local hydrogeological environment to dispose excess water or waste water has emerged as a problem of water level rise in many parts of ArRiyadh, the capital city of Saudi Arabia. In the past, groundwater rise to shallow horizons has caused considerable impact on public health, environment and infrastructure. In order to reduce and maintain groundwater to safe level, ArRiyadh Development Authority has constructed a gravity drainage system in the affected areas. During the initiation of the gravity drain project, water level in eastern ArRiyadh was >15 m; therefore, the area was not included in the project but was subjected to regular groundwater monitoring. During the recent decade, eastern ArRiyadh has witnessed quick water level rise, with an average rate of 0.55 m/year. This water level rising trend seems persistent with time which may impart serious damage to the environment and infrastructure. The study shows that the presence of thick clays within eastern alluvium retards hydrodynamic connectivity and inhibits vertical groundwater movement.

Keywords Water level rise · Electrical resistivity tomography · Pump tests · Eastern ArRiyadh · Saudi Arabia

Introduction

Arid and semi-arid regions of the world are rapidly developing and placing greater demands on the environmental systems. ArRiyadh, the capital city of Saudi Arabia, is among the fastest growing cities in the world. Unprecedented growth in population, urbanization and production sectors has led to escalated water consumption (Al-Zahrani 2009).

Desalinated sea water from Al-Jubail on the Arabian Gulf became the major source of domestic water supply for ArRiyadh. The pipeline system transports about 1.21 million m^3 of water per day. Water supply in ArRiyadh is also through groundwater pumping from nearby local aquifers. The shallow wells are located in Nesah, Nemar and Al-Hair valleys. The deep wells are tapping the Minjur and Wasia aquifers. This groundwater is treated in six treatment plants before domestic supply in ArRiyadh (Al Rehaili and Al-Abdula'aly 1999).

Per capita water consumption within ArRiyadh is high, estimated to be 320 l/day which is continuously increasing due to population growth together with improved living standards (Ministry of Water and Electricity 2009). Excessive water usage has induced infiltration to the ground. The capability of the local environment to dispose excess water or waste water by means of the mechanisms of infiltration, natural drainage and evaporation, is limited. Therefore, due to rapid expansion of residential areas, new localities lack proper sewage disposal and other sanitary services. Consequently, such areas have begun to experience rise in groundwater level.

Groundwater rise to shallow levels is particularly dangerous for high buildings, pavements, roads and public utility services. There is often groundwater pollution with sewage and chances are that polluted groundwater may contaminate underground potable water tanks. ArRiyadh Development Authority (ADA) conducted rising groundwater management study (RGMS), aimed at analyzing the sources and mitigation of rising groundwater levels within the affected parts of the city. The RGMS concluded that

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infiltration from leaks in the potable water system; septic tanks and irrigation return flows are principle sources of recharge to the city's groundwater. In order to mitigate water level rise, gravity drainage networks were installed within the affected areas. The performance of these gravity drains is largely governed by permeability of shallow depths (0–5 m) which is generally very low (Al-Othman 2011).

Eastern part of ArRiyadh was not included in the RGMS due to the reason that prior to the year 2000, average water level in eastern ArRiyadh was >15 m below ground level (mbgl). However, during the recent past, i.e., from 2000 to 2009, eastern ArRiyadh has experienced quick rise in water level. The possible solutions like dewatering through pumpage and installing gravity drains to lower groundwater have their own limitations. Thus, prior to executing any corrective program understanding of subsurface environment and groundwater dynamics remain crucial.

This paper aims at detailed hydrogeological assessment of the problem of water level rise to shallow depths. The probable subsurface geometry and its possible linkup with water level rise have also been addressed. Efforts have been made to quantify various components of groundwater budget at local scale.

Study area

The city of ArRiyadh is situated in the middle of Arabian Peninsula. The study area forms a part of Eastern ArRiyadh, falls between the UTM coordinates 2731440 and 2739749 m N and 678816 and 688013 m E (Fig. 1). The topographic elevations range from 645 m above mean sea level (amsl) in the SW to 570 m amsl in the NE. General topographic slope is from west to east direction. Most of the eastern ArRiyadh is located in alluvial sediments. The study area constitutes Manar and Naseem districts covering an area of about 42 km^2. These two districts witnessed high population growth rates in the recent past.

Methodology

A systematic hydrogeological study was carried out in parts of Eastern ArRiyadh. The hydrogeological investigations include acquisition and processing of digital elevation model (DEM), water level monitoring, Pump test analysis, resistivity survey and lithologs interpretation. The DEM is prepared from SRTM data (90 $\times$ 90 m resolution). Groundwater occurrences, movement and fluctuations have been described with the help of maps. Water level fluctuation method was employed for groundwater recharge estimation. Analyses of Pump tests were carried out to assess aquifer parameters using Jacob's straight line approach. Electrical resistivity tomography (ERT) survey consisting of 72 electrodes was carried out using SYSCAL Pro. Hydrogeological cross sections were drawn with the help of lithologs data. The elevation contours of top and bottom elevations of individual stratum were determined and sliced along defined sections using Surfer 8.0. Water level monitoring data from 12 observation wells has been statistically analyzed for water level rise trend.

Hydrogeological investigations

Physiography and drainage

Physiographically, ArRiyadh forms a plateau tilted to the East and South-East. It lies between two Questas: Tuwayaq in the west and Hit in the east. The elevations in the study area ranges from 645 m above mean sea level (m amsl) in SW to 575 m amsl in NE, i.e., the slope is towards the eastern part. The Eastern districts of ArRiyadh occupy portions of Wadi As-Sulaiy drainage. A dendritic pattern has developed draining towards the Eastern alluvium. The natural drainage of the eastern ArRiyadh region is towards SSE. The natural drainage system is severely affected by developmental activities throughout the region.

Geological setup

Geologically, the study area is underlain by massive Jubailah limestone. The rock is predominantly an aphanitic limestone, locally interbedded with Calcarenite and calcarenitic limestone. The Jubailah limestone is overlain by Arab formation. The Arab formation is characterized by a diverse lithology ranging from aphanitic to coarse calcarenitic limestone and Calcarenite. The basal part of Arab formation is highly fractured. At places, the Arab aquitard, a low permeable unit separates the two (ADA 1990). The Arab formation is overlain by Sulaiy formation. The junction of Arab/Sulaiy is marked by accumulation of residual soil derived from the intense weathering of overlying rock and steep hills of resistant limestone breccia of the basal Sulaiy formation. The Sulaiy formation is distinguished by a suit of chalky white to creamy yellow fine-grained limestone and often found to be highly to completely weathered at the surface. The Kharj formation, lying unconformably above Sulaiy formation, comprises a variable assemblage of horizontally bedded lacustrine limestones with associated bedded gypsum and gravel. In eastern ArRiyadh, the alluvial material is deposited mainly by Wadi As-Sulaiy, consisting partially of saturated carbonate silty sands, interbedded with gravels, often cemented with a coarse-grained matrix of low hydraulic conductivity values. It covers a large area of the eastern

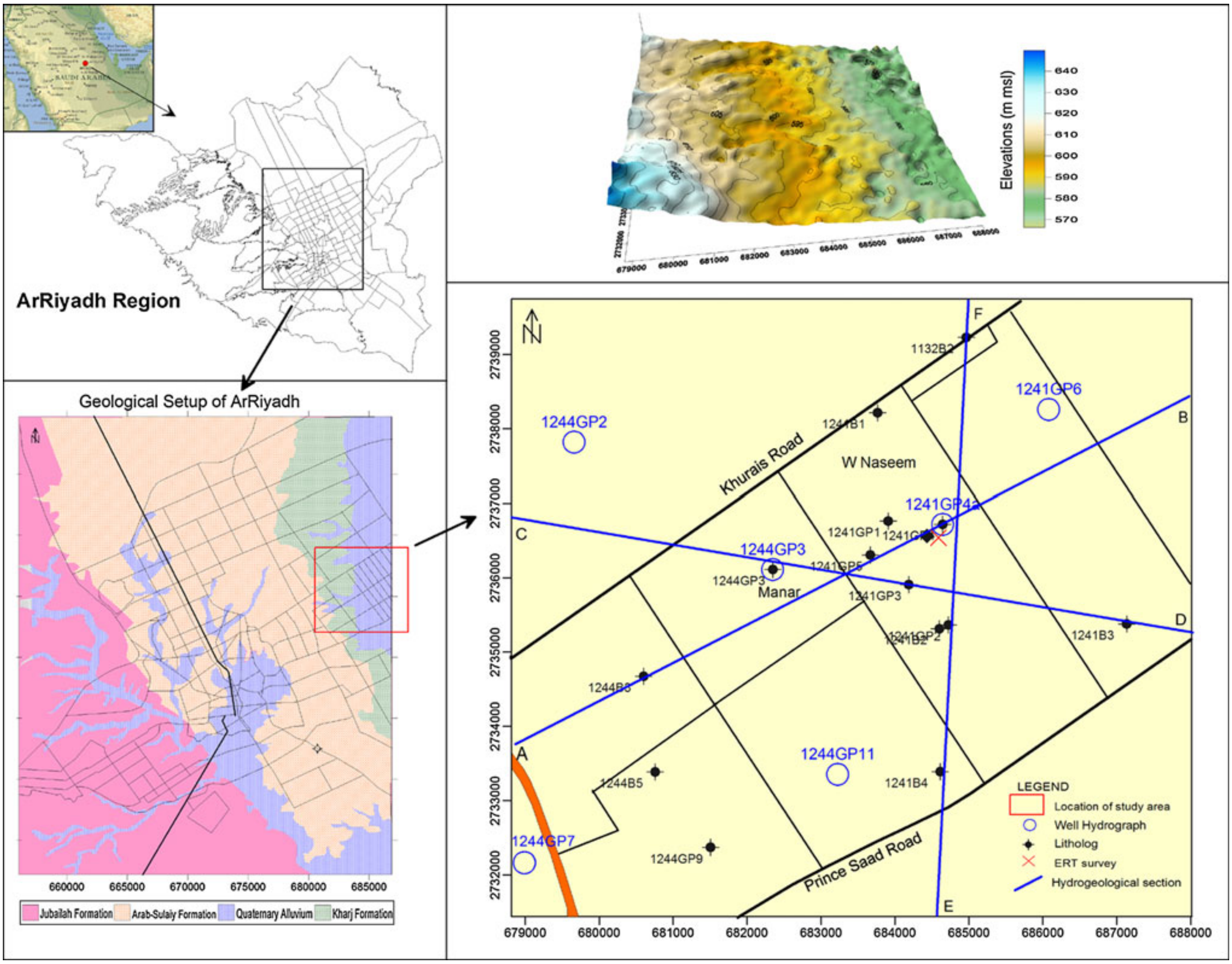


Fig. 1 Base map of the study area

parts of the city and its thickness ranges from 5 to 50 m (ADA 1990).

Groundwater occurrences and movements

Water level data of January 2009 was used to prepare depth to water level map. The depth to water level ranges from 4.6 to 14.5 m bgl. The depth to water level map shows shallow water level conditions (i.e. <4.5 mbgl) in the middle of the study area, thus, forming a mound type feature (Fig. 2).

Water table altitude, a controlling factor for groundwater flow, was estimated from detailed topographic data by subtracting the estimated depth to water. The water table altitude varies from 645 m amsl in the SW part to 575 m amsl in the NE. The groundwater contours in the eastern alluvium follow the topography of the study area (Fig. 3). The general groundwater flow direction is towards NE up to the middle part and turns further east towards the end. The groundwater forms a mound towards the SW corner of the study area. The average hydraulic gradient in the west part is 16 m/km; however, in the eastern part the average hydraulic gradient is 5 m/km. The water table in the western part is within the limestone terrain. The closely spaced contours may indicate low permeability values in the SE part, if uniform recharge to groundwater is assumed throughout the study area.

Pump test results

Several Pump tests were conducted within ArRiyadh city by ADA. The aquifer system comprises mainly four hydrogeological units, starting from the bottom to top: Jubailah aquiclude, ArRiyadh aquifer, Arab-Sulaiy aquitard and discontinuous alluvial aquifer. The Jubailah limestone is massive with very low permeability values range from 10^{-4} to 10^{-3} m/day. Fractured Sulaiy formation beneath Wadi Sulaiy valley is found to be significant

Fig. 2 Depth to water level map (m bgl)

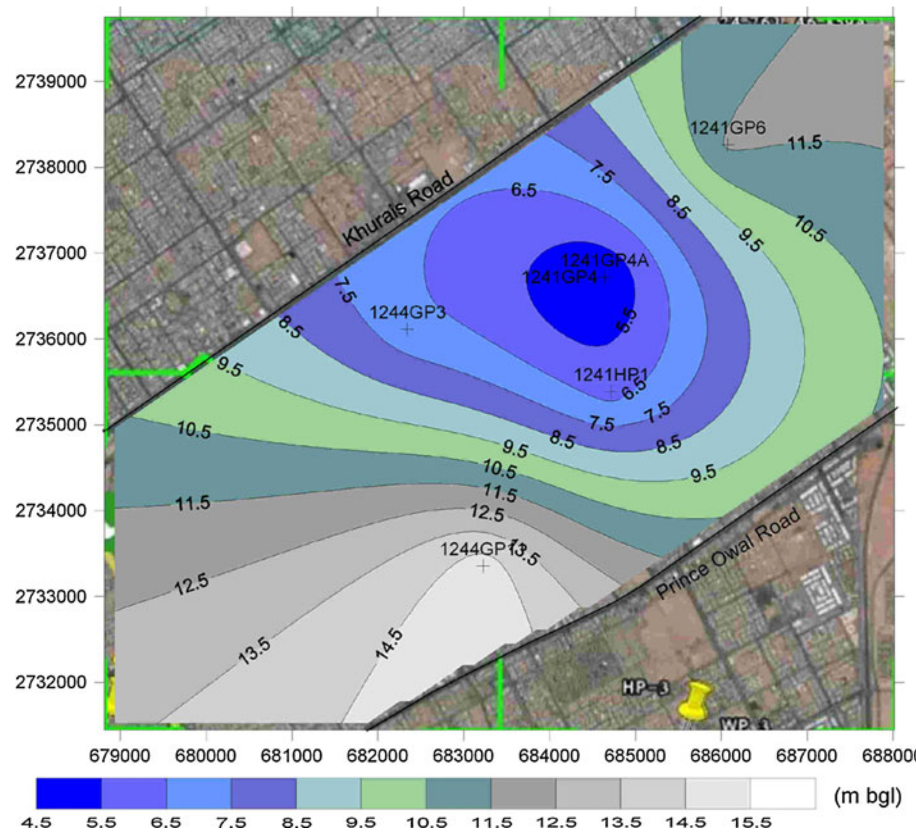
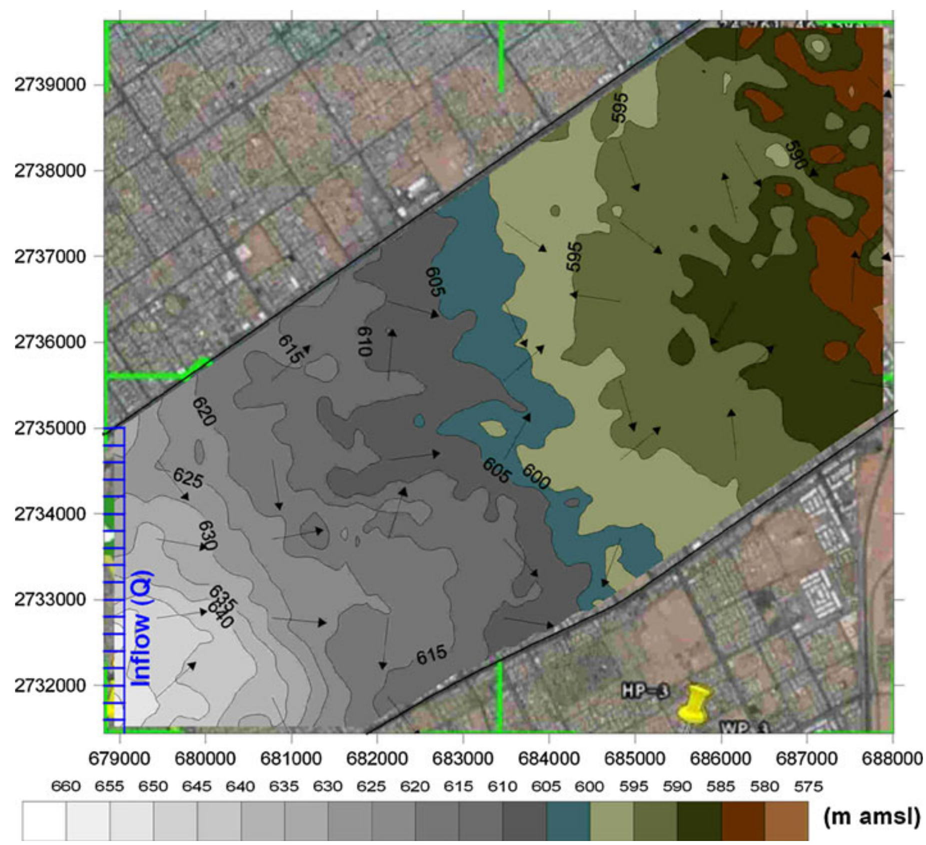


Fig. 3 Water table contour map (m amsl)



groundwater resource exploited by 56 boreholes drilled to an average depth of 113 m and with an average pump capacity of 780 m^3/day (ADA 1990). The hydraulic conductivity values of eastern alluvium range from 0.005 to 0.05 m/day (ADA 2002). Table 1 shows the generalized stratigraphy with average conductivity of the hydrogeological units within ArRiyadh (ADA 1998).

For present study, two Pump tests were carried out in the central part of the study area, i.e., Naseem West. The first Pump test was conducted on pump well 1 (PW-1) and observation were made on wells P-1 and P-2. The static water level in PW-1, P-1 and P-2 was 4.09, 3.92 and 5.03 m, respectively. The first Pump test was conducted at a rate of 1,785.6 m^3/day for a period of 8,640 min. During pumping, P-1 shows gradual drawdown, but P-2 shows no response to pumping at least initially and lasts with very little drawdown at the end. The drawdown at P-1, P-2 after 120 and 960 min are 0.29, 0.04 and 0.37, 0.10 m, respectively (Fig. 4). The noticeable difference in drawdown values of two observation wells, in all likelihood, is attributed to a difference in aquifer parameters of two permeable horizons. However, it also accounted for the fact that shallow depth in the pump well (W-1) is not fully screened as it was initially designed to pump from the lower layer. The pumping test analysis was done using linear regression method where the time-drawdown is governed by Jacob's straight line method (Cooper and Jacob 1946). The transmissivity (T) and storage coefficient (S) values at P-1 are 3,364.84 m^2/d and 0.5×10^{-3} and for P-2, 6,813.5 m^2/d and 0.055, respectively.

The second Pump test was conducted on pump well 2 (PW-2). The PW-2 was designed as fully tapping the shallow horizon with screened depth ranging from 2 to 24 m. This test is made to analyze aquifer parameter of the top alluvial layer. The pump well was operated at a rate of 432 m^3/day for 10,000 min. The drawdown observations were made at P-1 and P-2. The drawdown values are notated with negative sign to differentiate these from events of water level rise which is shown by positive values. Drawdown at observation well P-1 shows minimal effect of pumping. The P-2 shows a gradual drop in water level with pumping and perfectly follows the similar drawdown pattern as that of the pumping well (W-1). Linear regression method of Jacob equation (Cooper and Jacob 1946) was employed for pumping test analysis. The transmissivity (T) and storage coefficient (S) values for P-1 are 8,054.21 m^2/d and 0.15 and for P-2, 800.06 m^2/d and 0.017, respectively.

From the second Pump test drawdown graph, it can be inferred that drawdown at P-1 remains unchanged. The drawdown in P-1 and P-2 after 10,000 min of pumping is 0.05 and 0.36 m, respectively. Therefore, from both the Pump tests, it can be inferred that two observation wells, i.e., P-1 and P-2 lack hydrodynamic connectivity because of thick clay lens in between. Thus, it is inferred from the results that the thick clay in the middle of study area hinders vertical flow. The most unusual part of the observation is that the water level in P-1 rises at times during pumping due to recharge from nearby septic tanks. Moreover, while explaining such peculiar situation, possibility of conduit flow cannot be ruled out.

Table 1 Stratigraphy of hydrogeologic units in ArRiyadh region (ADA 1990, 2002)

Age	Geological formation	Hydrogeological unit thickness (m)	K (m/day)	Lithology
Recent	Alluvium	Central alluvium 5–50	0.0–100	Unconsolidated saturated siliceous and carbonate sand and carbonate gravels, often intermixed and interbedded with silts and clays
		Eastern alluvium 5–45	0.005–0.05	Partly saturated carbonate silty sands, interbedded with gravels
Tertiary	Kharj	Cemented gravels 5–30	0.1	Lacustrine limestone with bedded gypsum and gravel, cemented by ferruginous calcite and fractured. Clasts are typically aphanitic limestone and are set in medium to coarse-grained matrix of low hydraulic conductivity
Cretaceous	Upper Arab–Sulaiy	Localized fractured zones 10–50	1–10	Fractured zones generally trending west–east and characterized by open joined aphanitic and calcarenitic limestone. Major fracturing appears to exist beneath Kharj formation
Jurassic		Arab-Sulaiy aquitard 10–50	0.000001–1	Bedded and massive calcarenitic and aphanitic limestone with occasional collapse breccias. Open area of vugs and fractures is low
	Lower Arab	ArRiyadh aquifer 10–100	5–100	Highly fractured aphanitic and brecciated limestone and vuggy calcarenitic beds with high secondary porosity but low intergranular porosity
	Jubailah	Fractured rock 10–50	20–100	Highly fractured aphanitic limestone occurring in and adjacent to wadi valleys
		Massive rock 100	0.0001–0.1	Massive aphanitic limestone of low hydraulic conductivity

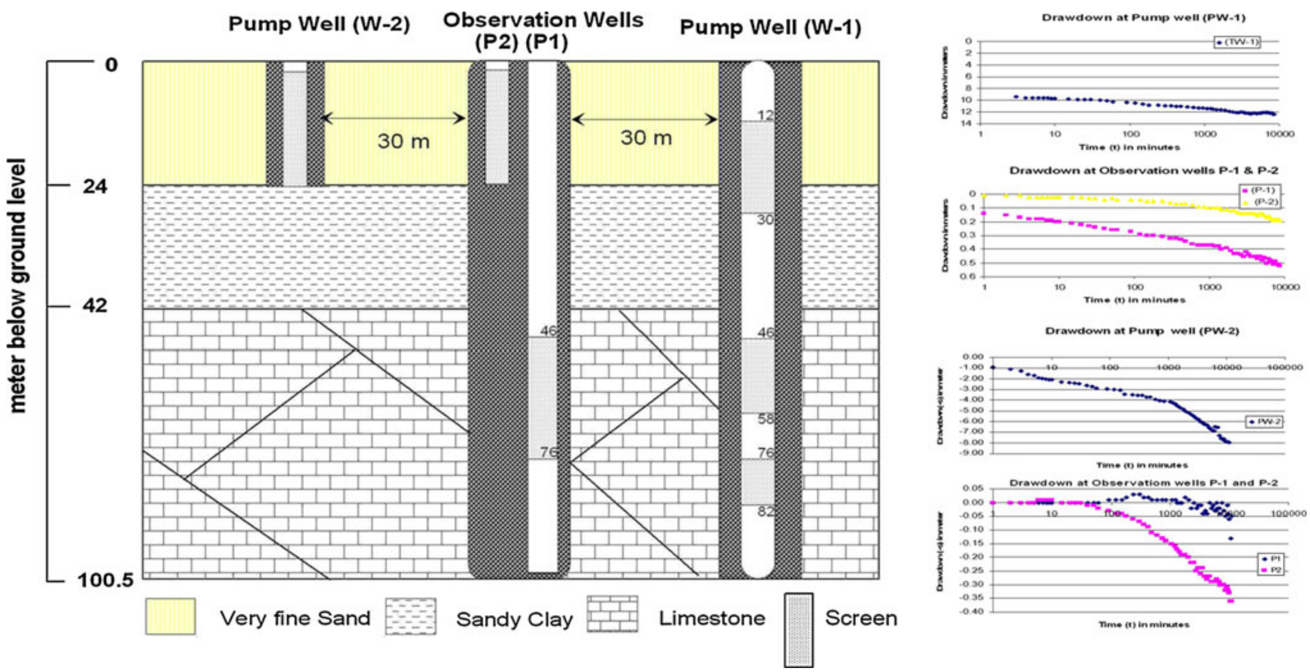


Fig. 4 Schematic site plan for Pump tests and time versus drawdown graph for Pump tests 1 and 2

Electrical resistivity tomography (ERT) survey

Electrical Resistivity methods have a wide application and have been used for monitoring soil-water content (Brunet et al. 2010), groundwater exploration (Yadav and Singh 2007), local groundwater recharge (Descloitres et al. 2008) and delineation of groundwater potential (Zaidi and Osama 2010). An electrical resistivity tomography (ERT) survey was carried out with an objective to find the depth of the water-bearing zones and subsurface stratification. SYSCAL Pro unit with 72 electrodes was used for carrying out the survey.

The ERT survey was carried out using dipole–dipole configuration with minimum electrode spacing of 2 m. The total length of section was 144 m. The depth of penetration for the survey was about 28 m. Dipole–dipole configuration was used because it gives the best horizontal resolution amongst all the sequences available. RES2DINV Software (Loke 2002) was used for inverting the apparent resistivity values along the selected profile. Figure 5 shows the results of the survey carried out using the dipole–dipole configuration with a unit electrode spacing of 2 m. The depth of investigation obtained is about 26.2 m. The total number of data points for making the section is 2,079. The inverse model resistivity section shows low resistivity at depths below 5 m on the right side.

The ERT survey confirms the presence of shallow water level depths in the area surveyed. The thick black dashed line marks the interface between the unsaturated and the water-bearing zone. The water-bearing zone indicated by resistivity values less than 20 Ω m starts at a depth of approximately 5 m from the ground surface and dips slightly to the left. The high resistivity shown on the surface is mainly due to the contact resistance. No structural anomaly was found in the survey results.

Aquifer geometry

Lithological data from 25 bore wells were utilized in delineating the vertical and horizontal aquifer disposition. Three hydrogeological cross sections were drawn, in order to infer the extents and thickness of alluvium, clay and alluvium–limestone interface. It is inferred from hydrogeological sections that the thickness of graded alluviums increases towards the east. The presence of clay within eastern alluvium is also evident. The profile AB runs across the middle in NE–SW direction. The clay layer attain a thickness of 20 m in the middle at PW-1 and suddenly disappears as only 1 m of clay is traced in 500 m far bore well, i.e., 1241 GP-4 (Fig. 6a). This sudden proliferation of clay in a small depression (*Graben*) like feature is rather striking which needs more explanation. Most likely, the flood event debouched clay particles in the depression and died out. The successive flood event brought sand particles which were deposited further east of the depression feature.

The CD section reveals the thickness of alluvium increasing towards the eastern part, however, clay pinches out after bore well 1241-GP3 and disappears in the eastern part of the section (Fig. 6b). In the EF section, clay is present throughout the section. This section is drawn in NS

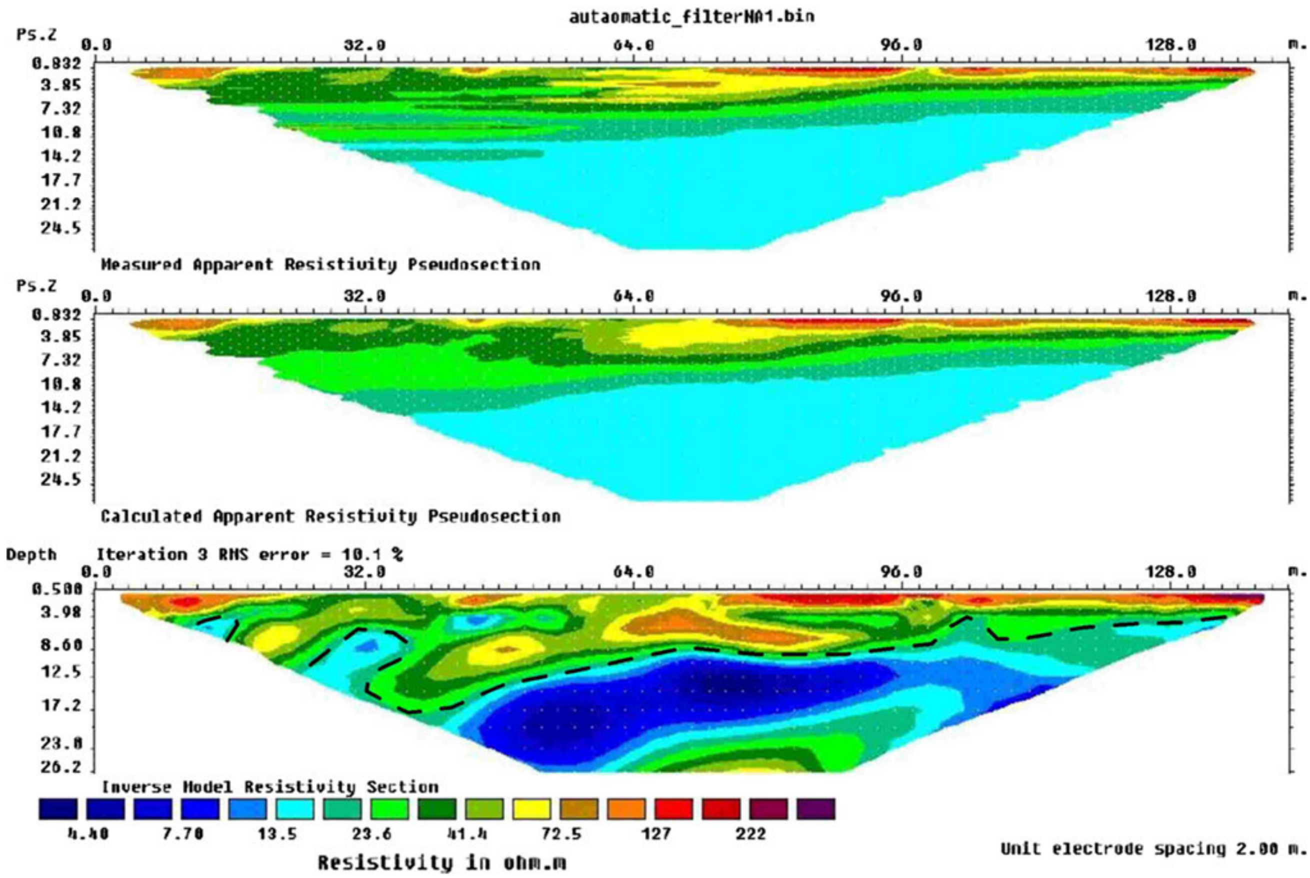


Fig. 5 Resistivity section

direction which shows alluvium at the top and 12 m of intervened clay at bore well 1132-B2. Further south, at 1241 GP-2, clay thins out and exposed at the surface (Fig. 6c).

The thickness of clay encountered in each bore well has been superimposed over the depth to water level map (Fig. 7). The fact which readily emerged out is that the zones of high water levels (<4.5 m bgl) corresponds to the region where clay thickness is 20 m. This thick clay inhibits the vertical groundwater movement and causing water level rise in central part of the study area. Geotechnical boreholes and a limited number of tests have indicated that the clays contain substantial gypsum. On saturation of gypsum, significant swelling can occur.

Also, locally occurring gypsum with gravel within alluvium has high potential for development of perched water tables due to its low permeability and poor drainage characteristics. Thus, underlying Sulaiy formation is semi-confined in nature as it is partly underlain by hard clay.

Water level variation trends (2003–2009)

Historical water level data from 12 permanent observation wells were collected from ArRiyadh Development Authority (ADA). Temporal water level variation trends have been established with the help of water level data. Perusals of hydrographs indicate that water level within the eastern ArRiyadh and the adjacent areas is continuously rising. At large, the water level trends seem unaffected by climatic factors, i.e., rainfall or rain storm, as water level rises steadily without any cyclic or event-related correlation (Fig. 8). This phenomenon is unlikely in rain-fed regions where water level fluctuations are strongly correlated with rainfall events. However, the increasing water levels are attributed to induced artificial recharge (ADA 1990, 2002). Water level rise in different districts of Eastern ArRiyadh is shown in Table 2. It is evident that Naseem (W) region witnessed highest rate of water level rise with 0.55 m/year followed by Manar with a rate of 0.52 m/year.

Groundwater recharge estimation

Leakages from water networks, cesspools/leaching pits/subsurface domestic water tanks, excess irrigation, water front landscaping and seepage from septic tanks have contributed to a rise in the groundwater table. The quantification of each parameter is very difficult and beyond the

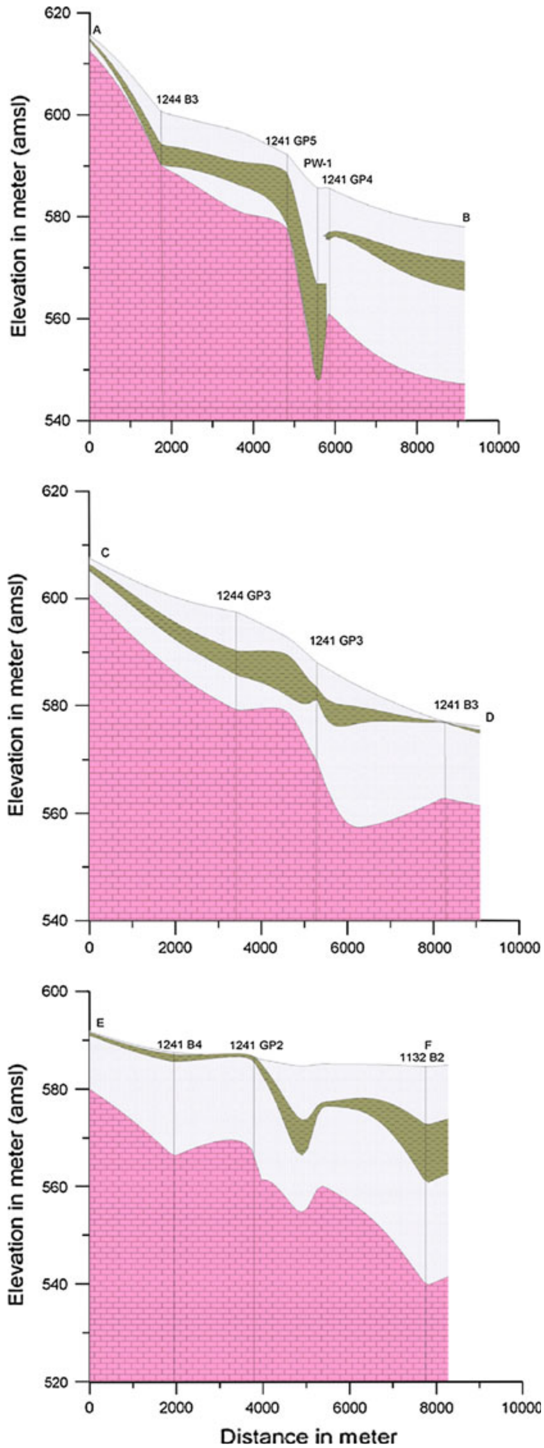


Fig. 6 Hydrogeological cross section along **a** profile AB **b** CD and **c** EF

scope of this paper. However, an integrated approach for the recharge estimation has been employed, utilizing average annual rise in water levels. Among the physical methods, the water table fluctuation technique (WTF) links the change in groundwater storage with resulting water level fluctuation through the storage parameter (specific yield in unconfined aquifer). The WTF fluctuation method was first used to estimate groundwater recharge and has since been used in numerous studies for the same purpose (Leduc et al. 1997; Moon et al. 2004) or groundwater storage changes estimation (Ruud et al. 2004). However, accuracy in specific yield estimation and records of water level fluctuation is crucial for realistic estimates of groundwater recharge.

The change in groundwater storage (ΔS) can link to specific yield(S_y) and resulting water level fluctuation (Δh) as follows:

$$\Delta S = S_y \times \Delta h$$

$$\Delta S = 0.13 \times 0.61$$

The average fluctuation for study area from January 2008 to January 2009 is 0.61 m. The average specific yield is taken as 0.13. Thus, change is groundwater storage becomes 0.0793 m. In the absence of major groundwater outflow component or groundwater abstraction scheme, the change in groundwater storage can be taken as net groundwater recharge. The gross groundwater recharge (R_G) in the selected area turns out to be 3.33 × 10^6 m^3 which is equivalent to a recharge value of 79.28 mm/year.

Estimation of boundary inflows (B_{in})

The water table contour map indicates inflow to the study area from the western part. The subsurface inflow from the boundary has been calculated as follows:

$$B_{in} = Q = T \sum_{i=1}^{n} \frac{dh_i}{dl} \times dw$$

where, T is the transmissivity, dh/dl is the hydraulic gradient for a grid i and dw is the width of a grid. Applying the above formula for the estimation of boundary flow across a grid pattern, shown in Fig. 3, the amount of B_{in} comes out as 0.47 × 10^6 m^3.

Deducing boundary inflow (B_{in}) from gross recharge (R_G) brings about the net recharge (R_N) which is 2.86 × 10^6 m^3/year and equivalent to 68.1 mm/year.

Discussion and conclusions

Lithologs data from 25 bore wells have been utilized in delineating the vertical and horizontal aquifer disposition. The hydrogeological cross sections show eastern alluvium as the top layer. The thickness of alluvium increases towards the NE and E. The presence of discontinuous clay within or at the bottom of the eastern alluvium is inferred. In the central part, it acquires a fairly good area and attains a thickness of 20 m at PW-1. This probably is the reason for high water level rise in the middle part. A critical

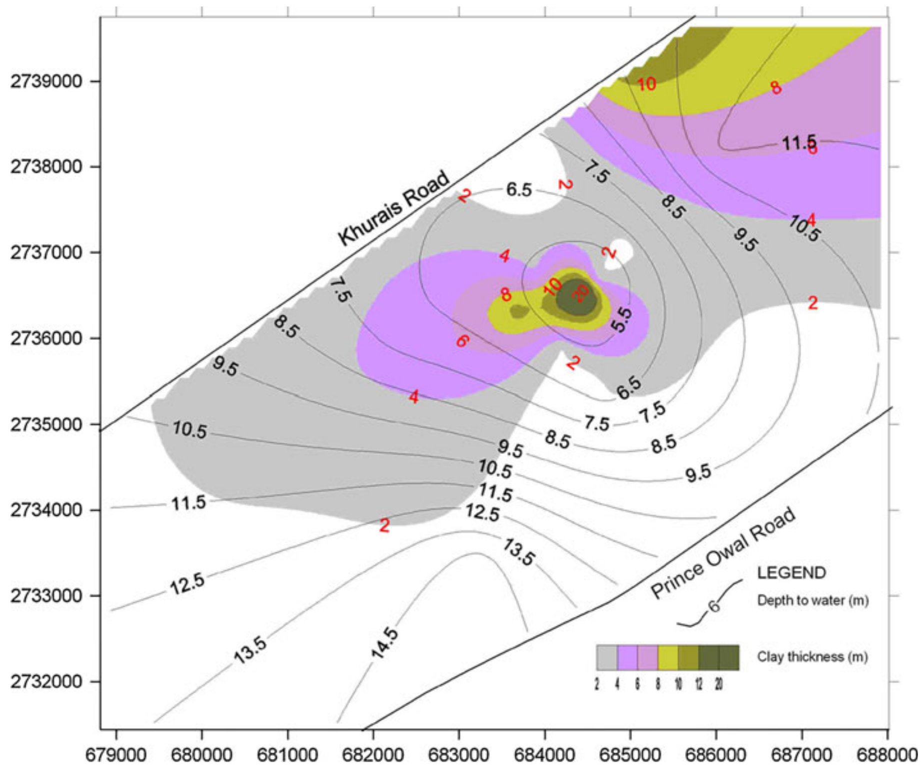


Fig. 7 Thickness of clay and depth to water level

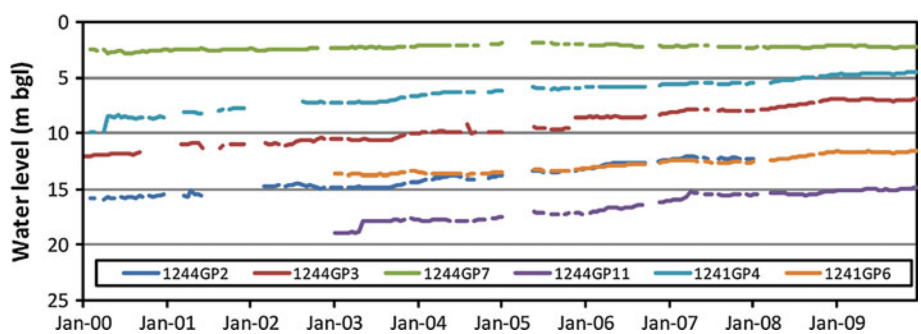


Fig. 8 Long-term water level fluctuation trend

Table 2 Water level fluctuation in Eastern ArRiyadh region

Observation well			Water level (m bgl)		Water level rise (m/year)
Location	Well ID	Depth (m)	January 2000	December 2009	2000–2009
Roudah	1244GP2	20	15.66	11.85	0.38
Manar	1244GP3	24	12.10	6.91	0.52
Rabwah	1244GP7	10	2.43	2.16	0.03
Salam	1244GP11	35	20.00	14.83	0.52
Naseem (W)	1241GP4	24	9.90	4.45	0.55
Naseem (E)	1241GP6	30	16.20	11.60	0.46

groundwater mound of 4.5 m bgl has formed in the central part of the study area. From 2000 to 2009, water level has risen with an average rate of 0.41 m/year. Naseem (W) and Manar witnessed comparatively higher rising rate than other eastern districts.

Pump test inferences lead to a conclusion that the eastern alluviums and underlying Sulaiy formation are not hydrodynamically interconnected, at least locally, because of the thick clay in between. The ERT survey also confirms the presence of perched water table in the central part of

area studied. Interface between the unsaturated and the water-bearing zone has been marked. The water-bearing zone indicated by resistivity values <20 Ω m starts at a depth of approximately 5 m from the ground surface and dips slightly to the left. The findings seem consistent with the depth to water level map of the study area. The high resistivity shown on the surface is mainly due to the contact resistance. No structural anomaly was found in the survey results. Conducting the survey along a couple of different survey lines would be helpful in confirming the findings of the present study.

Keeping in view the high construction cost and extremely low conducive shallow depths, dewatering through gravity drainage network is not being suggested. The findings of the study provide better understanding of shallow groundwater dynamics and may help in execution of any corrective program to curb water level rise problem. The drainage system of the locality needs to be improved to reduce groundwater recharge. Efforts should be made to stop utility network leakages, surface disposal and ponding of waste water. An efficient drainage network is urgently required in the west Naseem region.

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