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ORIGINAL ARTICLE

Hydrogeologic characteristics of groundwater aquifers in Kathmandu Valley, Nepal

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Abstract This paper reviews, compiles and comprehensively analyzes spatial variations in hydrogeologic characteristics of shallow and deep groundwater aquifers in Kathmandu Valley. To estimate transmissivity (*T*) (and then hydraulic conductivity) as a function of specific capacity (SC), an empirical relationship between *T* and SC is developed for shallow and deep aquifer. The results show that *T* and SC are log linearly related by an equation $T = 0.8857(\mathrm{SC})^{1.1624}$ [$R^2 = 0.79$] in shallow and $T = 1.1402(\mathrm{SC})^{1.0068}$ [$R^2 = 0.85$] in deep aquifer. The estimated T ranges from 163 to 1,056 m^2/day in shallow aquifer and 22.5 to 737 m^2/day in deep aquifer. Finally, mapping of spatial distribution in hydrogeologic characteristics (thickness, *T*, hydraulic conductivity and storage coefficient) in shallow and deep aquifers are accomplished using ArcGIS9.2 and such maps would be useful in delineating potential areas for groundwater development and simulating groundwater flow in the aquifer system.

Keywords GIS · Groundwater management · Hydrogeology · Kathmandu Valley · Specific capacity · Transmissivity

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Introduction

Groundwater is a major source of water supply in Kathmandu Valley located in central Nepal. Nepal Water Supply Corporation (NWSC), called as Kathmandu Upatyaka Khanepani Limited (KUKL) since 13 February 2008, has a major share (62.2%) in total groundwater extraction (Metcalf and Eddy 2000). The 36% of the NWSC's dry season supply is dependent solely on groundwater (Pandey et al. 2010). Large volume water consumers like hotels, industries, government organizations/institutes, hospitals and business complexes are using their own groundwater wells as a reliable source of water supply.

Groundwater extraction is continuously increasing over the decades since the commencement of mechanized extraction during early 1970s. However, the momentum in extraction was gained mainly after the NWSC introduced groundwater as an important part of their water supply system during mid-1980s. Figure 1 summarizes the stages of groundwater development over the last 30 years and clearly shows a widening gap between actual extraction and recharge since mid-1980s, thus, suggesting the need for management intervention in groundwater extraction. Despite such alarming situation, significant attentions are yet to be paid to develop and implement groundwater management plans based on the available scientific knowledge of the aquifer system, their hydrogeologic characteristics, and groundwater flow dynamics; to fix the groundwater extraction within manageable limits and to protect further deterioration of the

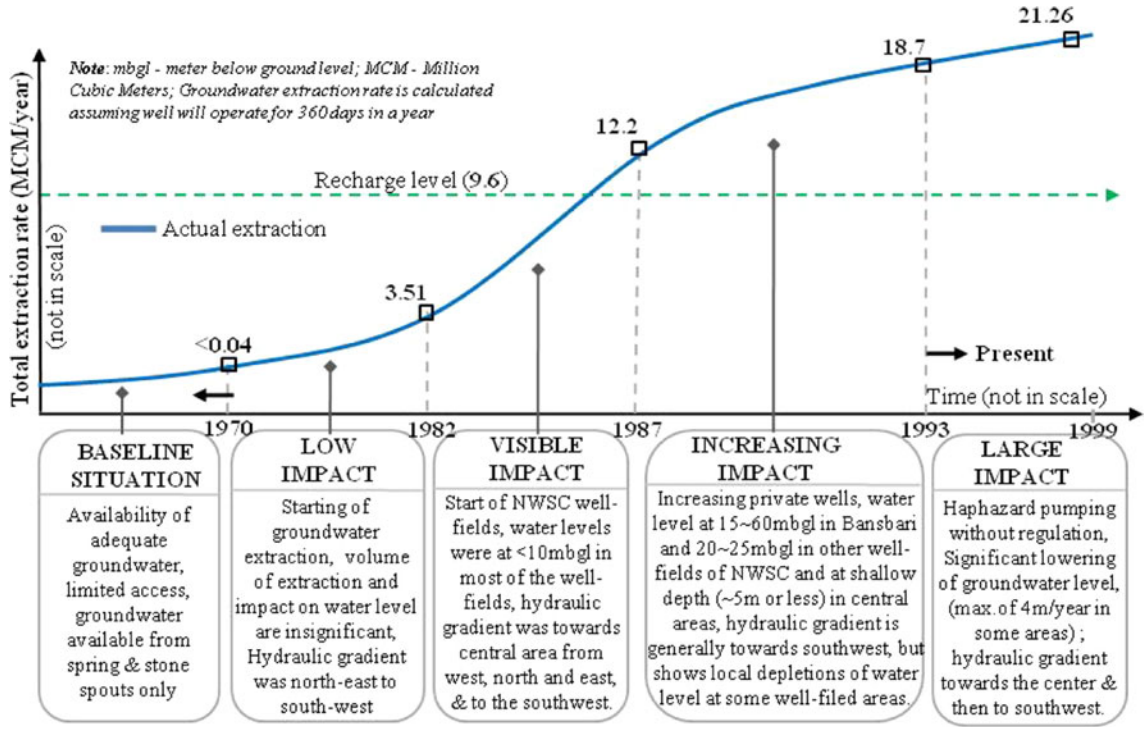

Fig. 1 Stages of groundwater development in Kathmandu Valley and corresponding impacts. [Data sources: time trend of extraction from Metcalf and Eddy (2000); recharge level from Pandey et al. (2010); impact information from Kharel et al. (1998)]

groundwater environment. Therefore, when considering future increase in water demand and sustainable use of groundwater resources, it has become imperative to understand the dynamics of groundwater flow system, and to map hydrogeologic characteristics of the aquifers within a reasonable accuracy to support integrated water resources management plans.

Several studies since early sixties have been carried out to understand the geological formations (e.g. Yoshida and Igarashi 1984; Dongol 1985; Shrestha et al. 1998; Sakai 2001), groundwater quality (e.g. Khadka 1993; Chettri and Smith 1995; Jha et al. 1997; ENPHO 1999; Gurung et al. 2007; Chapagain et al. 2009) and hydrogeology (e.g. Binnie and Partners 1973; JICA 1990; Metcalf and Eddy 2000; KC 2003) of the aquifers in Kathmandu Valley. The hydrogeologic studies were carried out for a number of wells by several organizations during execution of various projects, but to date, no significant attempts are made to strengthen the hydrogeologic knowledge of the aquifers by collectively analyzing highly scattered hydrogeologic information separately for two major hydrogeologic units (shallow and deep aquifers) in Kathmandu Valley. Few of earlier studies have reported that northern part of the groundwater basin has high percentage of aquifer units (e.g. KC 2003; Metcalf and Eddy 2000; Pandey et al. 2010). However, they have neither shed lights on actual depths of the aquifer layers and spatial extent within the entire basin nor have estimated volume of aquifers and their spatial distribution. This study aims to review, compile and comprehensively analyze spatial variations in hydrogeologic characteristics of shallow and deep aquifers in the Kathmandu Valley, to establish an empirical relationship between transmissivity (*T*) and specific capacity (SC), to estimate hydraulic conductivity and to map spatial distribution in hydrogeologic characteristics using Geographic Information System (GIS) technique. Such mapping would be useful in delineating potential areas for groundwater development and simulating groundwater flow in the aquifer system; which have direct implications to groundwater management.

Physiography and geology of the study area

Physiography and climate

The Kathmandu Valley's groundwater basin is elevated at 1,340 m above the mean sea level and covers 327 km^2 of 665 km^2 surface watershed area in central Nepal (Fig. 2a). The groundwater basin is home for 1.53 million people (population density is 4,690 person/km^2), 84.3% of them live in the urban areas (Pandey et al. 2010). The valley is characterized by warm and temperate climate in semi-tropics and receives 80% of 1,755 mm annual rainfall during monsoon season (June–September) (Acres International 2004). The huge amount of rainfall and strong seasonality

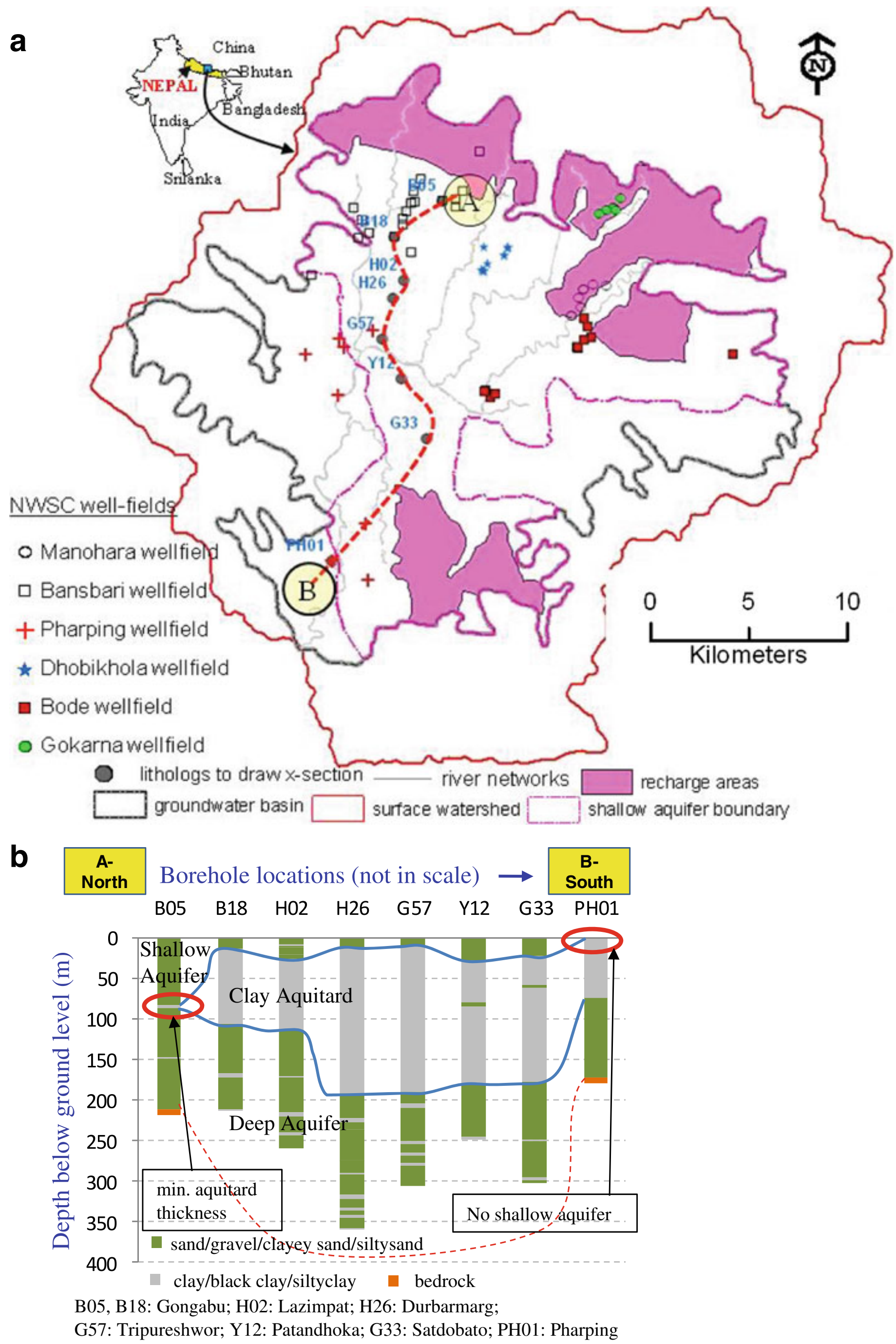

Fig. 2 **a** Study area: Kathmandu Valley groundwater basin in central Nepal (data sources: surface and groundwater basin boundary and recharge areas from JICA (1990); river networks from department of survey in Nepal). **b** North–south cross-section along *A*–*B* (source: lithology from Metcalf and Eddy (2000); JICA (1990); Department of Mines and Geology of Nepal, NISAKU drilling company, National drilling company, Sagarmatha drilling company, groundwater research and development project/ Department of Irrigation, Nepal). *Blue line* separates shallow and deep aquifer, clay aquitard and deep aquifer and *dotted red line* separates deep aquifer with bed rock)

could be used as an opportunity to store rainwater during rainy season (June–September) in the valley's aquifers. A detailed understanding of hydrogeologic characteristics, groundwater storage capacity and groundwater flow dynamics may suggest the prospects in this regards.

Geology and hydrogeologic units

The Kathmandu Valley is composed of two series of geological successions. Precambrian to Devonian rock forms the basement and hills surrounding the valley; and they are overlain by quaternary sediments and recent alluvium (Kharel et al. 1998). The thickness of the sediment deposit (lacustrine and fluvial origin) is up to 500–600 m in the central part of the basin (Kharel et al. 1998). The stratigraphy of the sediment deposits have been classified with different names by a number of authors as shown in Table 1. Sakai (2001) has proposed a new classification of sediment stratigraphy in ascending order as: *Tarebhir*, *Lukundol* and *Itaiti* Formations in the southern part;

Table 1 Correlation of stratigraphy of the Kathmandu basin sediments by different workers (Sakai 2001)

Yoshida and Igarashi (1984) Yoshida and Gautam (1988)			Dongol (1985;1987)	Shrestha et al. (1998)	Sakai et al. (2001)		Sakai (2001) southern part	Sakai (2001) central part
Patan Formation (Fm)			Kalimati clays	Gokarna Fm Tokha Fm Kalimati Fm Chapagaon Fm			Itaiti Fm	Patan Fm
Thimi Fm								Kalimati Fm
Gokarna Fm								
Boregaon terrace deposit			Champi-Itahari gravel		Lukundol Formation	Upper Member		
Chapagaon terrace deposit								
Pyangaon terrace deposit								
Lukundol Fm	Member	VII						
		VI						
		V	Nakhu Khola Mudstone and Keshari-Nayakhandi Lignite	Lukundol Fm Kobagaon Fm		Middle Member	Lukundol Fm	Basal Lignite Member
		IV						
		III						
		II						
		I	Tarebhir basal gravel	Basal boulder bed		Lower Member	Tarebhir Fm	Bagmati Fm

Bagmati, *Kalimati* and *Patan* Formations in the central part; and *Thimi* and *Gokarna* Formations in the northern part of the groundwater basin. From the perspective of hydrogeology, sediment stratigraphy in the valley can be classified in three general hydrogeologic units in descending order as shallow aquifer, aquitard and deep aquifer (Fig. 2b). The shallow aquifer corresponds to *Thimi*, *Patan* and *Gokarna* Formation; aquitard corresponds to *Kalimati* Formation; and deep aquifer corresponds to *Lukundol*, *Bagmati* and *Tarebhir* Formation (Sakai 2001). The thickness of clay layer is more than 200 m in the central part and gradually decreases towards north and southeastern part of the valley. Those areas are major recharge areas (shown in Fig. 2a) for the valley's deep aquifer. In general, most of the recharge areas are confined in high flat plains and alluvial low plains. The aquifer material consists of lake deposits (gravel, sand, silt, clay, peat and lignite) and fluvial deposits (boulder, gravel, sand and silt) (Kharel et al. 1998); and mineral composition of the aquifer material is dominated by quartz, K-feldspar, plagioclase and mica with minor chlorite and calcite (Paudel et al. 2004).

Study approach

This study uses GIS to map spatial distribution in hydrogeologic characteristics (e.g. aquifer thickness, *T* and hydraulic conductivity) of shallow and deep aquifers in the Kathmandu Valley. It starts with the collection of required datasets from various sources (mainly from secondary sources as shown in Table 2), careful review of the collected datasets, selection of reliable datasets, delineating hydrogeologic layers from the borehole data, establishing empirical relationship between *T* and SC for shallow and deep aquifers, estimating hydraulic conductivity (*K*) from *T* and length of screen, and mapping hydrogeologic characteristics of both shallow and deep aquifers using ArcGIS9.2 following the methodology described in Fig. 3.

Table 2 Data and corresponding sources

S no.	Data	Sources
1.	Borehole lithology, screen locations	Department of Mines and Geology, National drilling company, Sagarmatha drilling company, Metcalf and Eddy (2000), Acres International (2004), NISAKU drilling company, JICA (1990), Groundwater Development Project/ Department of Irrigation
2.	Groundwater basin boundary	Digitized from JICA (1990)
3.	Hydrogeology (*T*, *S*, discharge and drawdown)	Metcalf and Eddy (2000), Binnie and Partners (1973), JICA (1990), Acres International (2004), NISAKU drilling company
4.	Elevation points, contours, river networks	Digital data from Department of Survey, Government of Nepal

T transmissivity, *S* storage coefficient

Delineation of thickness and spatial extent of hydrogeologic layers

The thickness and spatial extent of hydrogeologic layers over entire area of the groundwater basin were delineated based on the 112 reclassified borehole data using spatial interpolation techniques in ArcGIS9.2 environment. The lithological information (e.g. sand, gravel, clay, etc.) in each borehole was reclassified as shallow aquifer, aquitard and deep aquifer layers before converting them into a GIS database to be used for the interpolation. Reclassifications were made based on the available knowledge in the published reports (e.g. Metcalf and Eddy 2000) and based on authors' knowledge about the study area.

Elevations of bottom of the geological layers (shallow aquifer, aquitard and deep aquifer) in each borehole were calculated from a Digital Elevation Model of the ground surface and thickness of each layer. Only 30 boreholes

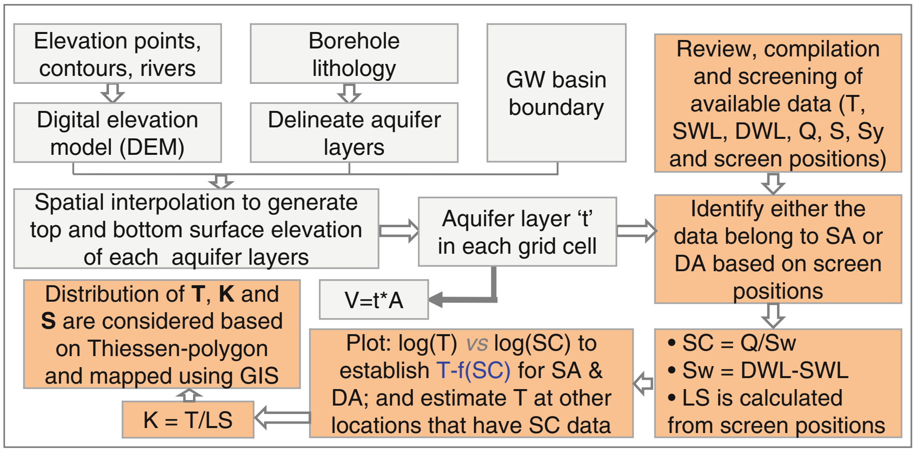

Fig. 3 Methodology flow chart to estimate and map hydrogeologic characteristics. *GW* Groundwater, *T* transmissivity (m^2/day), *SWL* static water level (m), *DWL* dynamic water level (m), *Q* discharge (m^3/s), *S* storage coefficient (−), *Sy* specific yield (−), *SA* shallow aquifer, *DA* deep aquifer, *SC* specific capacity (m^2/day), *Sw* drawdown (m), *LS* length of screen (m), *K* hydraulic conductivity (m/day), *t* thickness of aquifer (m), *V* volume of aquifer (m^3), *A* surface area of a grid cell (20 × 20 m)

were drilled up to the bed rock. The bottom elevations of the deep aquifer for other boreholes were extracted from a *bed rock raster* that was generated by *spline* interpolation of the 30 points. The *spline* method was selected because our data points were unevenly distributed and relatively small in number. The extracted elevations were evaluated by comparing with bottom elevation of the boreholes. In some cases, extracted elevations were above the bottom elevation of the boreholes (i.e. underestimated). Those errors were overcome by assuming that bottom of borehole coincides with that of the deep aquifer in that particular borehole. Finally, elevation raster of bottom of each geological layer were generated using *spline* interpolation and thickness raster of each hydrogeologic layer was generated by subtracting top and bottom layer elevation raster of the respective hydrogeologic layers using "*Raster Calculator*" tool in ArcGIS9.2. The accuracy of the estimate was evaluated by comparing the thickness of aquitard layer beneath the recharge areas, where thicknesses were expected to be minimal.

Empirical relationship between *T* and SC

Transmissivity (*T*) is an important hydrogeologic parameter for developing a local and a regional water plan and developing numerical ground-water flow models to predict the future availability of the water resources; however, they are generally not abundantly available when compared with easy to measure SC. Therefore, it is a common practice to estimate *T* from the SC data (e.g. Razack and Huntley 1991; Huntley et al. 1992; Mace 1997; Mace et al. 2000; Jalludin and Razack 2004; Hamm et al. 2005, etc.). The SC in this study were calculated for 50 wells in deep aquifer and 15 wells in shallow aquifer from the discharge and steady-state drawdown data collected from several sources as shown in Table 2. Separation of wells in shallow and deep aquifers was made based on the aquifer thickness and the screen location information available along with the datasets. Transmissivity data were available for 19 wells in deep aquifer, 12 wells in shallow aquifer and 14 wells extracting in both shallow and deep aquifer. Wells extracting from both shallow and deep aquifers were discarded for the analysis. The SC was not corrected for the well loss.

Estimation of hydraulic conductivity

The hydraulic conductivity refers to the capacity of an aquifer layers to transmit water through the medium. It is calculated as *T* divided by the aquifer thickness at the same well. In this study, aquifer thickness is defined as the total length of screened interval in the well because water wells in the Kathmandu Valley aquifers are generally screened only in the most productive intervals of the aquifer (revealed by several borehole data collected from various sources) and such definition of aquifer thickness has also been adopted by Mace et al. (2000).

Data and sources

Data and information were collected from several sources. The data sources are outlined in Table 2.

Results and discussion

Distribution of thickness of hydrogeologic layers

Thickness of shallow aquifer varies from 0 to 85 m, clay aquitard (that vertically separates shallow and deep

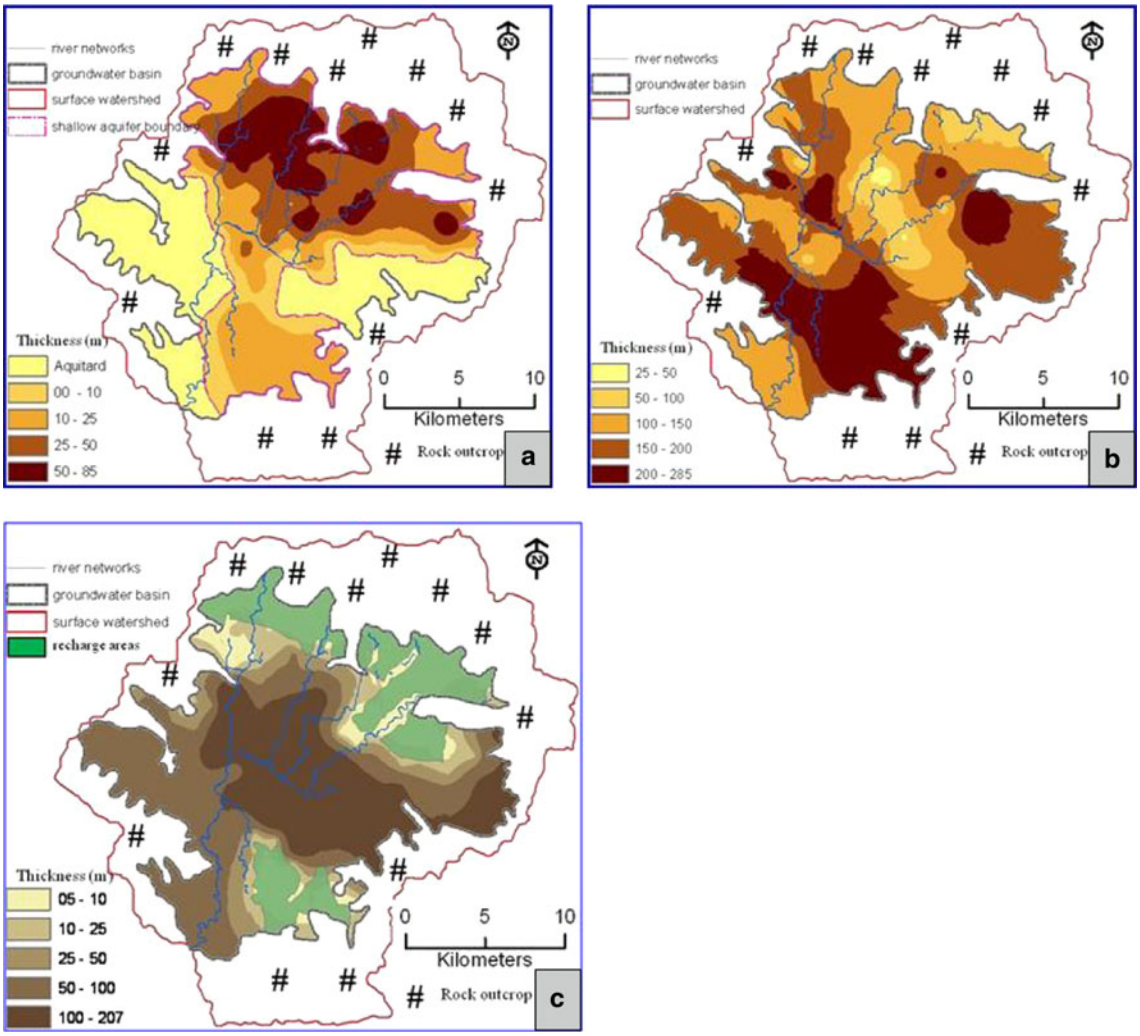

Fig. 4 Thickness distribution: **a** shallow aquifer, **b** deep aquifer and **c** aquitard

aquifer) from <10 m to more than 200 m and that of deep aquifer from 25 to 285 m (Fig. 4). Total thickness of aquifer (shallow plus deep aquifer) varies from 55 to 330 m. There is no shallow aquifer layer in some south-eastern and south-western parts of the groundwater basin; however, perched aquifers which are not considered in this study may exist in those areas. The shallow aquifer is thicker towards the northern part of the groundwater basin while the deep aquifer is thicker towards the southern part. The result about shallow aquifer is consistent with the earlier reports that northern part has a high percentage of aquifer units (Metcalf and Eddy 2000; KC 2003). The clay layer (i.e. aquitard) has minimum thickness (<10 m) towards northern and north-eastern part of the basin. Those areas are consistent with the potential recharge areas suggested by JICA (1990) (recharge areas are shown in Fig. 2a). The shallow aquifer surface extends over 241 km^2 area while aquitard and deep aquifers extend to the entire area of the groundwater basin (i.e. 327 km^2). Total estimated volumes for shallow and deep aquifers are 7,260 and 56,813 MCM, respectively. However, groundwater storage capacity might be much lower than aquifer volume because storage coefficient controls the groundwater storage capacity.

For verifying the results, earlier estimates of spatial distribution in thickness of hydrogeologic layers were not available. However, an indirect approach was considered for the purpose, in which, areas with minimum thickness in aquitard layer were compared with recharge areas of JICA (1990). The recharge areas estimated by JICA (1990) are closely matched to the minimum thickness areas in the aquitard layer estimated in this study (Fig. 4c). This suggests that our estimate is reasonably accurate.

Empirical relation between *T* and SC

The relationship between log (*T*) and log (SC) in shallow and deep aquifers is plotted in Fig. 5. The bi-logarithmic regression line representing the best estimate of *T* has an equation of

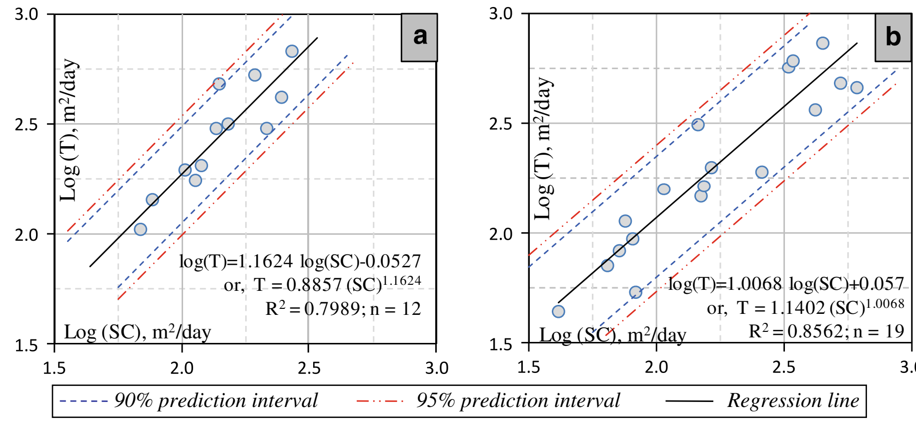

Fig. 5 Plot of transmissivity (T) versus specific capacity (SC): **a** shallow aquifer, **b** deep aquifer

Table 3 Summary of hydrogeologic characteristics of shallow and deep aquifers

S. no.	Parameters (unit)	Shallow aquifer	Deep aquifer
1.	Surface area, A (km^2)	241.0	327.0
2.	Transmissivity, T (m^2/day)	163.2–1,056.6	22.6–737.0
3.	Hydraulic conductivity, K (m/day)	12.5–44.9	0.3–8.8
4.	Permeability, k (m^2)	1.48E−11 – 5.32E−11	3.74E−13 – 1.04E−11
5.	Storage coefficient (S)[a]	0.20	0.00023–0.07000
6.	Aquifer thickness range (m/pixel)	0.0–85.4	25.0–284.4
7.	Aquifer volume range (m^3/pixel)	0.0–34,150.0	10,000.0–113,773.0
8.	Total aquifer volume (MCM)	7,261.27	56,813.70

[a] Storage coefficient in shallow aquifer is called specific yield (S_y); each pixel is 20 m × 20 m; *MCM* million cubic meters

$T = 0.8857(\mathrm{SC})^{1.1624}$ in the shallow aquifer, and $T = 1.1402(\mathrm{SC})^{1.0068}$ in the deep aquifer, where units of T and SC are in m^2/day. The coefficients of determination (R^2) of the linear plot of log–log regression equation are equal to 0.79 and 0.85, respectively, for shallow and deep aquifers.

The prediction uncertainty of the proposed equation was estimated by calculating the prediction interval $P(T)$ as shown in Eq. 1:

$$P(T) = \hat{y} \pm S_{\mathrm{E}} t_{\alpha/2} \sqrt{1 + \frac{1}{n} + \frac{(x - \bar{x}^2)}{\sum_{i=1}^{n} (x_i - \bar{x})^2}} \quad (1)$$

where $\hat{y}$ represents T value for a new observation x (i.e. SC); $t_{\alpha/2}$ represents critical value of t distribution with $n-2$ degree of freedom, α represents significance level, n represents sample size, x_{i} represents ith value of independent variable (i.e. SC); y_i represents ith value of dependent variable (i.e. T); $\bar{x}$ represents arithmetic mean of SC; S_{E} represents standard error of the estimate and calculated using Eq. 2:

$$S_{\mathrm{E}} = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n-2}} \quad (2)$$

The study determined 90 and 95% prediction intervals for the T estimates for a given SC. The 90 and 95% prediction interval spans about 0.44 and 0.54 log cycles for shallow aquifer; and 0.55 and 0.66 log cycles for the deep aquifer. This indicates the range of probable T for a given measured SC is about a half order of magnitude for both shallow and deep aquifer with 90% prediction interval; and is little more than half order of magnitude with 95% prediction interval.

The T at other wells (with only SC data) was estimated using the empirical relation developed in this study. The estimated T range from 163 to 1,056 m^2/day in shallow aquifer and 22.6 to 737 m^2/day in deep aquifer (Table 3, Fig. 6). The estimate in the aquifers is within a range of 18 to 1,174 m^2/day reported in the earlier studies in the study area (JICA 1990; Metcalf and Eddy 2000; Acres International 2004). Relatively wide range of the T suggests some degree of heterogeneity in aquifer structure; which corresponds to significant differences in hydraulic conductivity and thickness of water-bearing sediments. Spatial distribution of the T in shallow and deep aquifer was mapped using ArcGIS9.2 and are shown in Fig. 6. The distribution is based on Thiessen-polygon around the well. The relation between T and SC developed in this study could have future applicability to estimate approximate values of the T at other wells where SC are available. The produced maps for T and hydraulic conductivity could also be used to develop groundwater model of the area.

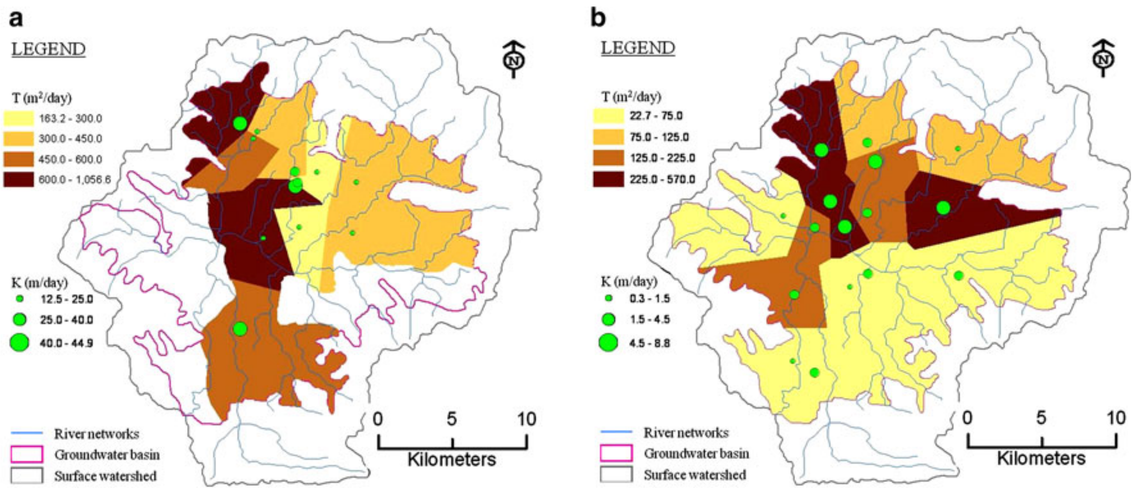

Fig. 6 Transmissivity and hydraulic conductivity distribution: **a** shallow aquifer, **b** deep aquifer

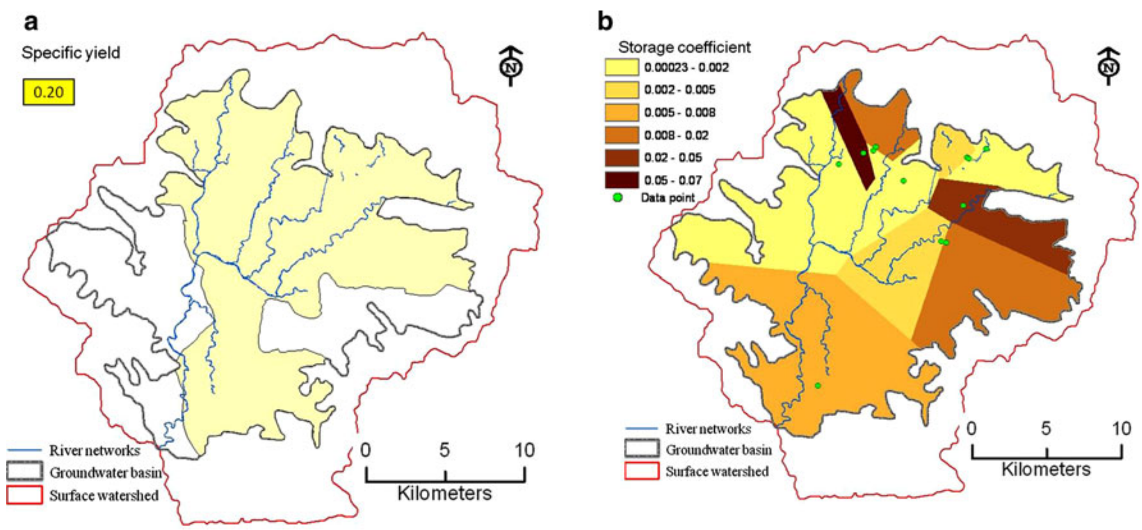

Fig. 7 Storage coefficient distribution: **a** shallow aquifer, **b** deep aquifer

Hydraulic conductivity

The hydraulic conductivity estimates range from 12.5 to 44.9 m/day (mean = 23.7) in shallow and 0.32 to 8.78 m/day (mean = 4.5) in the deep aquifer in the Kathmandu Valley (Table 3, Fig. 6). In addition, the permeability, which is a function of aquifer medium only, range from 1.48E−11 to 5.32E−11 m^2 in the shallow and 3.74E−13 to 1.04E−11 m^2 in the deep aquifer (Table 3). The estimate of hydraulic conductivity in deep aquifer is in good agreement with values reported in Metcalf and Eddy (2000) for deep aquifer (i.e. 0.51–8.16 m/day). These results reflect high degree of heterogeneity in the aquifer structures.

Storage coefficient

Water storage and release ability of deep aquifer is expressed in terms of storage coefficient (S), while that of shallow aquifer is expressed in terms of specific yield (S_y). The S describes the compressibility of the mineral skeleton of the aquifer matrix and the expansion of the water. Values of S are much less than S_y. Storage coefficients in deep aquifer, based on data available in 12 wells, range from 0.00023 to 0.07000 (Fig. 7). Distribution of available data is quite uneven, and large data gap do exist. In the case of shallow aquifer, field measured specific yield data are not available in the study area. However, one of the earlier studies (Acres International 2004) has used 0.20 as an approximate value throughout the study area. In the absence of measured dataset, this value can be considered as an approximate specific yield in shallow aquifer of Kathmandu Valley.

Conclusions

In shallow aquifer thickness ranges from 0 to 85 m, T and SC are log linearly related by an equation $T = 0.8857\,(\mathrm{SC})^{1.1624}$ [$R^2 = 0.79$; 90% prediction interval = 0.44 log cycles] where T and SC are in m^2/day, T estimates range from 163 to 1,056 m^2/day and hydraulic conductivity range from 12.5 to 44.9 m/day (mean = 23.7). While in deep aquifer thickness ranges from 25 to 285 m, T and SC are log linearly related by an equation $T = 1.1402(\mathrm{SC})^{1.0068}$ [$R^2 = 0.85$; 90% prediction interval = 0.55 log cycles] where T and SC are in m^2/day, T estimates range from 22.5 to 737 m^2/day, hydraulic conductivity range from 0.32 to 8.8 m/day (mean = 3.5) and storage coefficient from 0.00023 to 0.07000. The hydrogeologic characteristics discussed in this study would be useful in simulating groundwater flow system and delineate potential areas for groundwater development in the study area.

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