Implications of the Melamchi water supply project for the Kathmandu Valley groundwater system

Bhesh Raj Thapa[a,b,*], Hiroshi Ishidaira[a], Maksym Gusyev[c],
Vishnu Prasad Pandey[b], Parmeshwar Udmale[d], Masaki Hayashi[e] and
Narendra Man Shakya[f]

[a]*Interdisciplinary Research Center for River Basin Environment (ICRE), University of Yamanashi, Takeda 4-3-11, Kofu,
Yamanashi 400-8511, Japan*
Corresponding author. E-mail: bthapa.ioe@gmail.com
[b]*International Water Management Institute (IWMI) – Nepal Office, Durbar Tole, Pulchowk-3, Lalitpur, Nepal*
[c]*International Centre for Water Hazard and Risk Management (ICHARM), Public Works Research Institute (PWRI), Tsukuba,
Japan*
[d]*Department of Civil and Earth Resources Engineering, Kyoto University, Kyoto 615-8540, Japan*
[e]*Department of Geoscience, University of Calgary, 2500 University Dr. NW Calgary, Alberta, T2N 1N4, Canada*
[f]*Department of Civil Engineering, Institute of Engineering, Tribhuvan University, Pulchowk, Lalitpur, Nepal*

Abstract

To meet the demand deficit in Kathmandu Valley, the Government of Nepal has planned to supply an additional 510 million liters per day (mld) of water by implementing the Melamchi Water Supply Project (MWSP) in the near future. In this study, we aim to assess the spatial distribution of groundwater availability and pumping under five scenarios for before and after the implementation of the MWSP using a numerical groundwater flow model. The data on water demand, supply infrastructure, changes in hydraulic head, groundwater pumping rates, and aquifer characteristics were analyzed. Results showed that groundwater pumping from individual wells ranges from 0.0018 to 2.8 mld and the average hydraulic head declined from 2.57 m below ground level (bgl) (0.23 m/year) to 21.58 m bgl (1.96 m/year). Model simulations showed that changes in average hydraulic head ranged from +2.83 m to +5.48 m at various stages of the MWSP implementation, and −2.97 m for increased pumping rates with no implementation of the MWSP. Regulation in pumping such as monetary instruments (groundwater pricing) on the use of groundwater along with appropriate metering and monitoring of pumping amounts depending on the availability of new and existing public water supply could be interventions in the near future.

Keywords: Groundwater management; Groundwater modeling; Kathmandu Valley; Melamchi

Introduction

Kathmandu Valley's (KV) water resources management has been dependent on groundwater supply to meet increasing water demands due to the rapid population growth, deterioration of water-related infrastructure, improper land-use planning, and the rapid increase of built-up areas. Currently, the centralized potable water supply provided by the public agency, Kathmandu Upatyaka Khanepani Limited (KUKL), can only meet 19% (dry season) and 31% (wet season) of the valley's water demand, estimated at 370 million liters per day (mld) (KUKL, 2015) in 2015. The deficit between water demand and supply may increase up to 322 mld by 2021 (Udmale *et al*., 2016). The deficit is currently filled by other sources such as rainwater harvesting, stone spouts, springs, and pumping from privately owned wells (Thapa *et al*., 2016a, 2016b, 2018). Groundwater is considered to be a safe and reliable source of water, resulting in a steady increase in groundwater pumping from the valley's aquifers (Pandey *et al*., 2010). For example, the KUKL (previously Nepal Water Supply Corporation) increased groundwater pumping from 2.3 mld in 1979 to 29.2 mld in 1999 (Pandey *et al*., 2012) and the total estimated pumping including private withdrawals was 59.1 mld in 1998 (Metcalf & Eddy, 2000). In 2009, the estimated groundwater withdrawals reached 70.9 mld (Dhakal, 2010), resulting in a rapid decline of groundwater levels across the valley from 2.57 m to 21.58 m between 2003 and 2014 (KVWSMB, 2012; Shrestha, 2012; Gautam & Prajapati, 2014) below ground surface. Rapid urbanization may have exacerbated the decline by increasing impermeable surfaces in the valley's groundwater recharge areas (Cresswell *et al*., 2001) and have increased the vulnerability of the aquifer system to pollution due to inadequate treatment of wastewater from urban areas (Pandey *et al*., 2010; Shrestha *et al*., 2016; Gautam *et al*., 2017). Therefore, the current practices of groundwater use are unsustainable and could lead to irreversible groundwater quality deterioration and land subsidence in the valley (Shrestha *et al*., 2017). Several studies have reported nitrate and *Escherichia coli* contamination in shallow groundwater as well as a high level of arsenic and iron in deep groundwater, making the valley's groundwater unsuitable for drinking without pretreatment (Warner *et al*., 2008; Chapagain *et al*., 2010; Pathak *et al*., 2011; Tanaka *et al*., 2012; Tamrakar & Shakya, 2013; Shrestha *et al*., 2015).

Currently, there is a regulatory provision for acquiring licenses by paying an annual fee of 20,000 Nepalese rupees (NRs) (about 200 US dollars) for abstracting groundwater for non-domestic purpose from the deep wells. Each licensed client must install a bulk water meter to keep a monthly record of groundwater use and to renew the license on an annual basis. The groundwater abstraction can be completely shut down in the case of an operation without a license. The Kathmandu Valley Water Supply Management Board (KVWSMB) has demarcated three districts to issue groundwater abstraction licenses with a defined withdrawal limit: 2–15 liter per second (lps) in the northern district (safe zone); 2–7 lps in the central district (semi-critical zone); and 2–3 lps in the southern district (critical zone) (KVWSMB, 2014). Despite regular monitoring by the KVWSMB, these regulations are not fully enforced, causing licenses to often not be renewed and thus creating groundwater use records and fees to become not easily accessible. In addition, the number of shallow domestic wells are unknown due to the current provision of exempting licenses for groundwater withdrawals from dug wells up to 50 m below ground level (bgl) and tube wells with a diameter up to 10 cm (KVWSMB, 2014). As a result, the current governance of the valley's aquifer system has failed to curb groundwater demands or even be able to quantify existing groundwater withdrawal amounts in the valley.

To achieve sustainable water resources management, the Government of Nepal has planned to increase the valley's water supply by implementing an inter-basin water transfer program known as the Melamchi Water Supply Project (MWSP). The MWSP focuses on developing a bulk distribution system through improvement of the distribution network located mostly in the central groundwater district (CGD) and will be operated by the KUKL to supply water to the valley's existing users as well as to future users in new service areas in the Kathmandu Valley. The MWSP implementation will provide an additional 510 mld of water supply from the Melamchi River as an off-the-valley source in two phases: 170 mld by September 2016 (delayed by two years due to unforeseen circumstances including the 2015 Gorkha earthquake, shortage of fuel, and other project management issues) and 340 mld by 2023 (personal communication with procurement officer of the MWSP). Despite this planned surface water supply, the existing groundwater use in the valley is unlikely to be completely abandoned after the successful completion of the MWSP. This is due to high investments in groundwater supply infrastructure and the high pricing of KUKL water (NRs. 42.37/m^3). Therefore, there is a need to investigate the impacts of various groundwater pumping scenarios on the valley's aquifer system under pre- and post-MWSP conditions to evaluate appropriate water resource management actions.

This study is the first attempt to utilize a numerical modeling approach to investigate implications of the MWSP. Numerical groundwater flow models can provide quantitative answers to various questions regarding water resource management including impacts of changes in land use and land cover on water availability and of increased pumping on surface water features (Haitjema *et al.*, 2010; Gusyev *et al.*, 2012, 2013a, 2013b). A steady-state finite-difference groundwater flow model of the Kathmandu Valley watershed was set up using Visual MODFLOW (VMOD) Flex (Schlumberger Water Services, 2014). MODFLOW is a commonly used tool for groundwater resource assessment (McDonald & Harbaugh, 1988; Gusyev *et al.*, 2013a, 2013b; Anderson *et al.*, 2015). The results of model simulation are analyzed using geographical information system tools to estimate the change of simulated hydraulic heads between the baseline and various scenarios to: (1) assess the spatial distribution of groundwater pumping; (2) evaluate the behavior of hydraulic heads under different scenarios for pre- and post-MWSP conditions; and (3) suggest practical policy interventions for the sustainable utilization of groundwater resources in the valley based on the aquifer response. Despite the limitations of this study, these results help identify data needs in the watershed to improve the groundwater model and can serve as a baseline for future studies and sustainable management of the valley's groundwater.

Study area

The Kathmandu Valley watershed is located between 27°32′13″ and 27°49′10″N latitudes and 85°11′31″ and 85°31′38″E longitudes, and is surrounded by mountains. Elevations range between 1,212 and 2,772 m above mean sea level (amsl) (Figure 1). The watershed has a bowl-shape area of 664 km^2 and is drained by the Bagmati River and its tributaries (Bishnumati, Hanumante, Dhobi, Godabari, Balkhu, Kodku, Nakhhu, and Manohara). The outlet of the Bagmati River is located at the southern end of the watershed. The boundary of productive aquifer systems is outlined by the three KVWSMB groundwater districts with the new KUKL water supply service area located mostly in the central district (Figure 1). The population in the valley has increased from 1.1 million in 1991 to 1.6 million in 2001 to 2.5 million in 2011 (CBS, 2003, 2014a), which increased the water demand
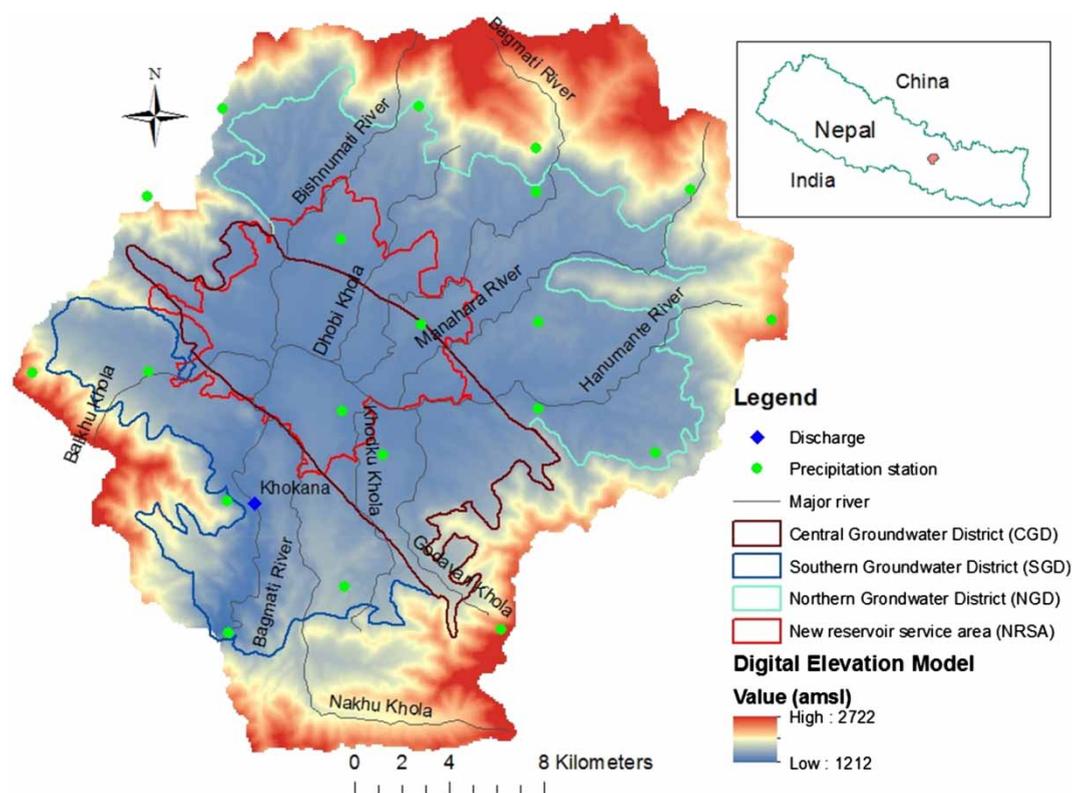
Fig. 1. The study area of the Kathmandu Valley watershed with precipitation and discharge gauging stations, groundwater observation wells, and the three groundwater districts and the boundary of the new reservoir service area for the Melamchi Water Supply Project.

from 155 to 370 mld (Thapa *et al*., 2016a, 2016b, 2018). Agricultural lands in the valley have decreased from 62% to 42% between 1984 and 2000 (ICIMOD, 2007).

The KVWSMB groundwater districts are surrounded by low-permeability fractured rock formations and the outer periphery (hilly area) of the valley is covered by mixed forest. In the valley, the peri-urban area is partly agricultural and partly built up, while the central part of the valley is covered by built-up urban areas (Thapa *et al*., 2016a, 2016b, 2018). The northern groundwater district (NGD) is situated on top of coarse unconsolidated deposits, which have high permeability and the highest potential for groundwater abstraction (Figure 1). The southern groundwater district (SGD) sits on top of a thick (200 m) confining unit of clay (JICA, 1990) with a deep confined aquifer composed of Pliocene sand and gravel with interbedded lignite, peat, and clay beneath the aquitard layer (Yoshida & Igarashi, 1984; Shrestha *et al*., 2016). The CGD has a dual aquifer system separated by an aquitard of interbedded black clay and lignite up to 200 m thick (Yoshida & Igarashi, 1984). The shallow unconfined aquifer of the CGD is composed of up to 50 m thick Quaternary sand, with some discontinuities, interbedded silt and clay, and is underlain by thick (up to 200 m) black clay accompanied by some lignite and peat with low permeability (Shrestha, 2012). The deep confined aquifer is considered the main source of groundwater for the KUKL, private companies, and industries.

Materials and methods

Data collection

The data on population and its projection as well as on service area demarcation were extracted from published and unpublished reports by the KUKL and the MWSP. These data were used to estimate water deficit situations in the KUKL service area from estimated water demand and supply (Figure 2). The 2011 population census data were collected from the Central Bureau of Statistics (CBS, 2012). The record of population growth rates was obtained for each Village Development Committee (VDC) and Municipalities between 2001 and 2011 and projected rates from CBS for the year 2011 to 2031 (CBS, 2014b). Groundwater recharge rates were estimated for each hydrologic response unit, which is the smallest spatial unit having a unique combination of soil type, land cover and use, and slope within a sub-basin, using the physically based hydrological model Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998; Thapa *et al.*, 2017). The SWAT model was developed for the valley's watershed using precipitation, temperature, relative humidity, and solar radiation from year 2000 to
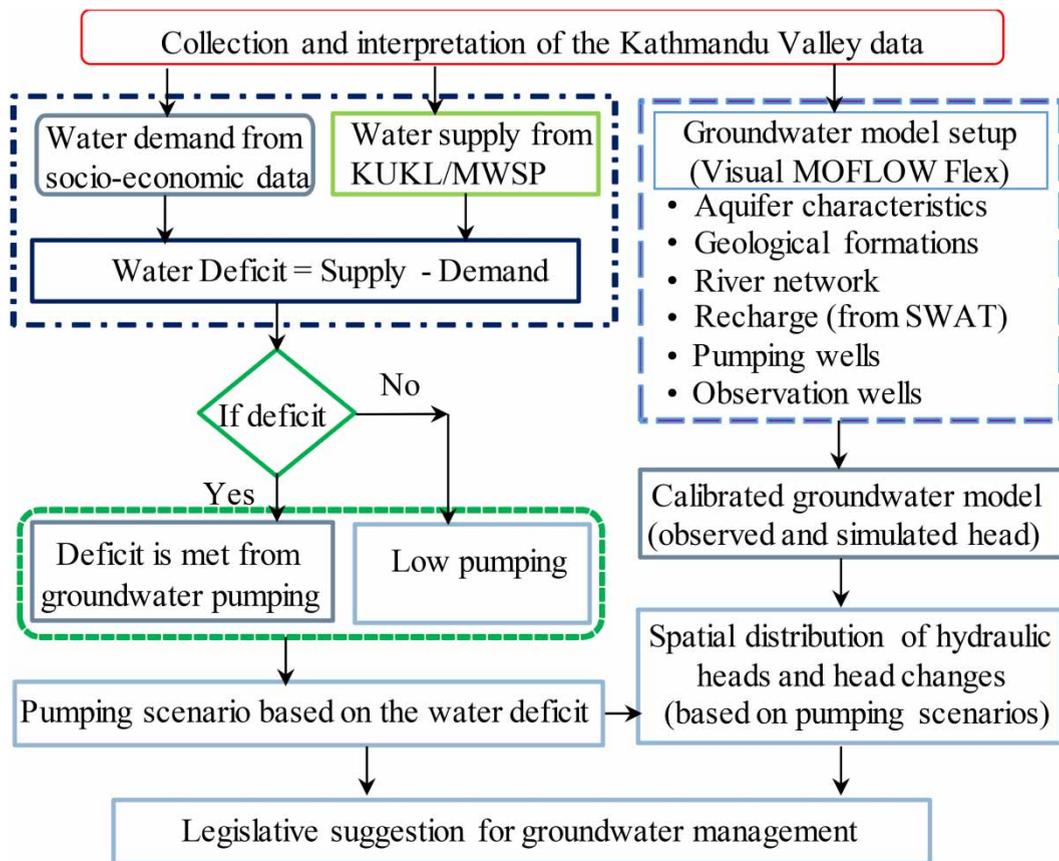

Fig. 2. Methodological framework of this study (KUKL is the Kathmandu Upatyka Khanepani Limited, MWSP is the Melamchi Water Supply Project).

year 2010 as input, and was calibrated using runoff data measured at Khokana gauging station (see location in Figure 1) (Thapa *et al.*, 2017). A surficial geology map was obtained from the Department of Mine and Geology (DMG/BGR/DOI, 1998). The latitude, longitude, and elevation for the three hydrostratigraphic units, also known as the shallow aquifer, the aquitard, and the deep aquifer, were obtained from Pandey & Kazama (2011). Information on pumping and observation wells was obtained from the Groundwater Resources Development Board (GWRDB).

The water deficit was estimated by Thapa *et al.* (2016a, 2016b, 2018) for the entire service area using a constant demand of 135 liters per capita per day (lpcd) and future demand for projected population was estimated using collected population data of each sub-area (at ward level) within the service area (CBS, 2012) with predicted rates (CBS, 2014a). The estimated water deficit was considered for the ground-water abstraction scenarios.

Pumping scenarios

Five different groundwater pumping scenarios were formulated based on the water deficit situation for the KUKL service areas considering three MWSP timelines as well as best and worst case scenarios. As per the estimated completion of the MWSP, water deficit situations were calculated for 2018 (after the completion of the first phase), 2023 (after the completion of the second phase), and 2030 (post-MWSP as well as the target year of achieving sustainable development goals (SDGs)). These scenarios generated for different time periods were implemented in a steady-state groundwater flow model, which was calibrated to groundwater heads and considered as a baseline in this study. Transient response of the valley groundwater system to a major change in pumping rates is an important factor, but it was not considered in the present analysis assuming an almost instantaneous equilibrium. The effects of pumping scenarios were investigated for the valley's reservoir service areas (RSAs) using the calibrated groundwater model with simulated hydraulic head distributions under the five scenarios. Simulation results were analyzed for each groundwater district to propose regulatory interventions for the sustainable management of groundwater resources in the valley. A brief narrative of the baseline and five scenarios is given below and summarized in Table 1.

Current rate of pumping (baseline). In 2016 (current situation), the KUKL provides water for the whole valley (old RSA) with rates ranging from 27 to 66 lpcd, which is generally less than the medium-term human requirement (WHO, 2005). The existing water deficit of domestic and industrial water use is matched by groundwater abstractions from privately owned wells. This scenario is the

Table 1. Groundwater pumping scenarios selected based on the potable water supply, demand, and deficits in the new and existing reservoirs' service areas.

Reservoir service area/Pumping scenario	Baseline scenario (current situation)	After 1st phase of MWSP, (S1)	After 2nd phase of MWSP, (S2)	Future (SDGs target), (S3)	Optimistic scenario, (S4)	Pessimistic scenario, (S5)
New	Estimated pumping rate of 2016 (A)	50% of (A)	10% of (A)	10% of (A)	10% of (A)	150% of (A)
Existing			125% of (A)	150% of (A)		

baseline case for pumping wells with current rates and these rates are used to generate other scenarios by using different percentages of pumping.

Pumping decreased by 50% of current rate (S1).   The KUKL services more water than in 2016 after the first phase of the MWSP completed in 2018. The new RSA receives water at rates ranging from 70 to 130 lpcd, while the existing RSA receives 56 to 157 lpcd. In this scenario, we assume a 50% reduction in pumping for both new and existing RSAs as the future water demand is partly fulfilled.

Pumping at 10% of the baseline rate in the new RSA and 125% in the existing RSA (S2).   The new RSA receives a sufficient amount of water after the second phase of MWSP is completed in 2023, but the situation in the existing RSA becomes worse than the baseline. Hence, this scenario considers pumping in the new RSA at 10% of the baseline rates and 125% of the baseline in the existing RSA. The 10% rate is considered 'minimal' pumping that may exist even after getting sufficient water from the KUKL utility. In the valley, it may be not possible to fully stop pumping because people may still rely on groundwater for some domestic purposes.

Pumping at 10% of the baseline rate in the new RSA and 150% in the existing RSA (S3).   For the SDG's target year 2030, the new RSA has sufficient water supply with 10% pumping as in the previous scenario, but the situation in the existing RSA is much worse than in the year 2023. Hence, this scenario considers an increased pumping by 150% in the existing RSA.

Pumping at 10% of the baseline (or, optimistic scenario) (S4).   This scenario considers the minimal pumping state in the entire valley. Assuming proper water redistribution in the KUKL service areas, all water demand is satisfied and there is no water deficit in the valley. Since the KUKL service areas already have physical infrastructure for groundwater pumping in place, there is a possibility of using groundwater for gardening and other non-domestic purpose due to poor water quality. This is considered to be an optimistic scenario and 10% of current pumping is assumed in both RSAs in this scenario.

Pumping 150% of baseline, (or, pessimistic scenario) (S5).   This scenario considers a delay in the MWSP implementation and the water deficit is estimated to increase by 1.5 times of the current deficit. Hence, this is a pessimistic scenario and it considers an increased groundwater abstraction by 150% of the baseline scenario.

Model setup

A finite-difference groundwater flow model of the Kathmandu Valley watershed was set up in the VMOD Flex with a uniform grid size of 120 m (Figure 3). The VMOD model has three layers implemented with data obtained from Pandey & Kazama, (2011) to represent the shallow and deep aquifers separated by the aquitard. The spatially distributed geological formations were reclassified into six VMOD property zones in Layer 1 (one zone having the same hydraulic and storage property values) as shown in Figure 3(a) and implemented in each of three layers resulting in 18 zones, as shown in Figure 3(b) and 3(c). Note that zone 1 has inactive cells which represent a no-flow boundary of the model domain and is not considered in the model calculation (see the outside boundary of the modeled
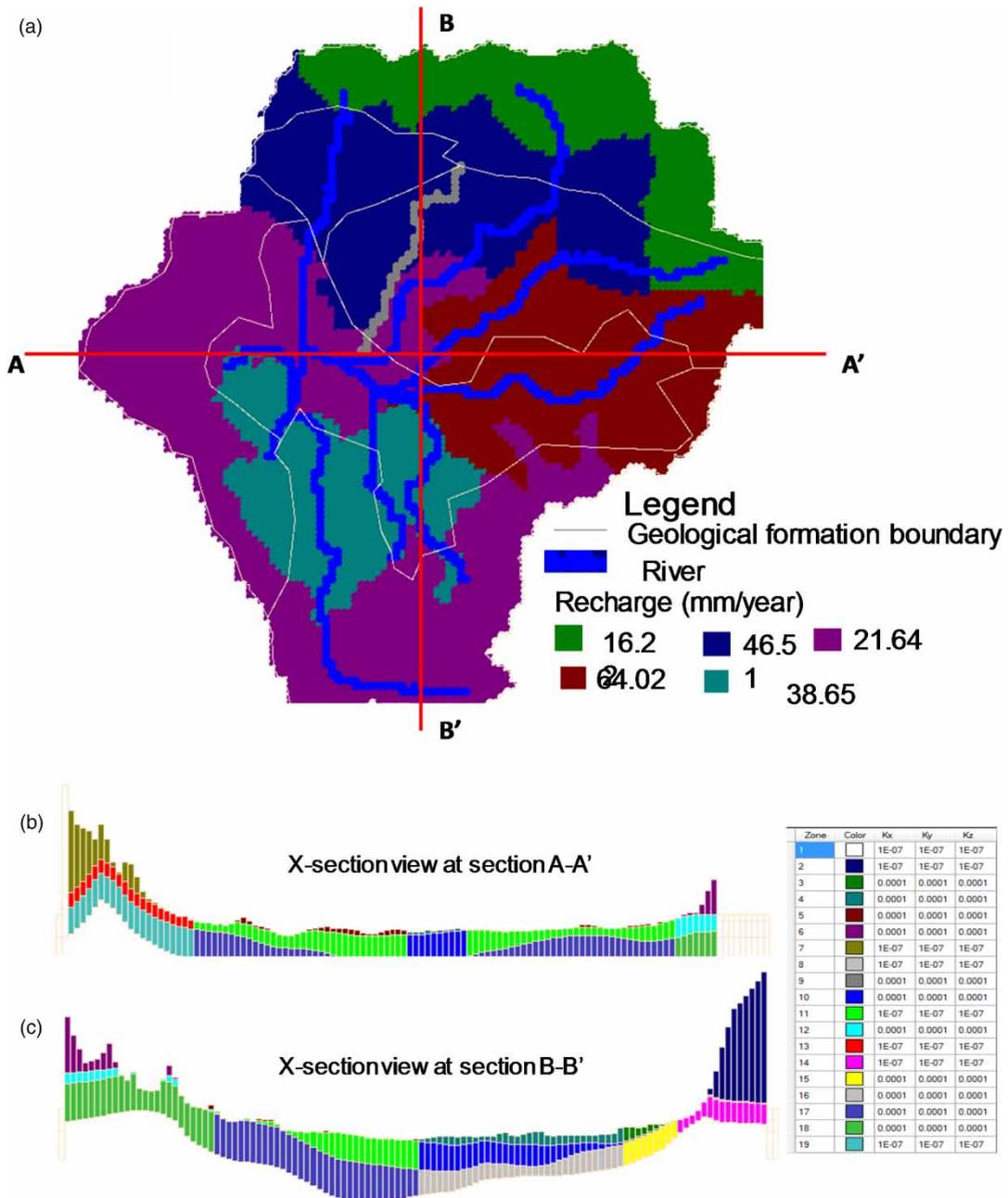
Fig. 3. Groundwater flow model setup in the Visual MODLOW Flex for Kathmandu Valley: (a) top view of aquifer recharge zones with river and drain networks and boundary of reclassified geologic formations utilized for property zones. Cross sections with hydraulic conductivity zone values are shown in (b) A–A′ and (c) B–B′.

valley's watershed and the cross sections in Figure 3). The VMOD zone budget was calculated for these 18 aquifer property zones in the VMOD model of the valley. Hydraulic conductivity values were

assigned for each zone based on the available information on aquifer material properties and modified during the model calibration.

In Figure 3, five groundwater recharge zones and the surface water network were assigned in Layer 1 of the model. Nine perennial rivers were implemented with river package as surface water boundary conditions and one intermittent surface water feature was implemented as a drain. Shape files of the surface water network were imported and assigned as segments using river water and bed bottom elevations at the start and end of each segment, and river bed conductivity of 0.1 m d^{-1}. From the GWRDB, 19 groundwater observation wells with observed data from January 2003 were used for the model calibration and 379 pumping wells with available information (latitude, longitude, screen depth, and abstraction rates) were implemented in the VMOD model using the well package (Figure 4). The changes in water head over time were not considered, which is one limitation of this study. MODFLOW 2005 numerical engine was used and the rewetting option was active, allowing model cells to become dry or wet during the iterative solution of the steady-state flow equation. The model calibration was conducted manually by trial-and-error method to obtain an acceptable difference between observed and simulated heads. During the manual calibration, hydraulic conductivity values of one zone were
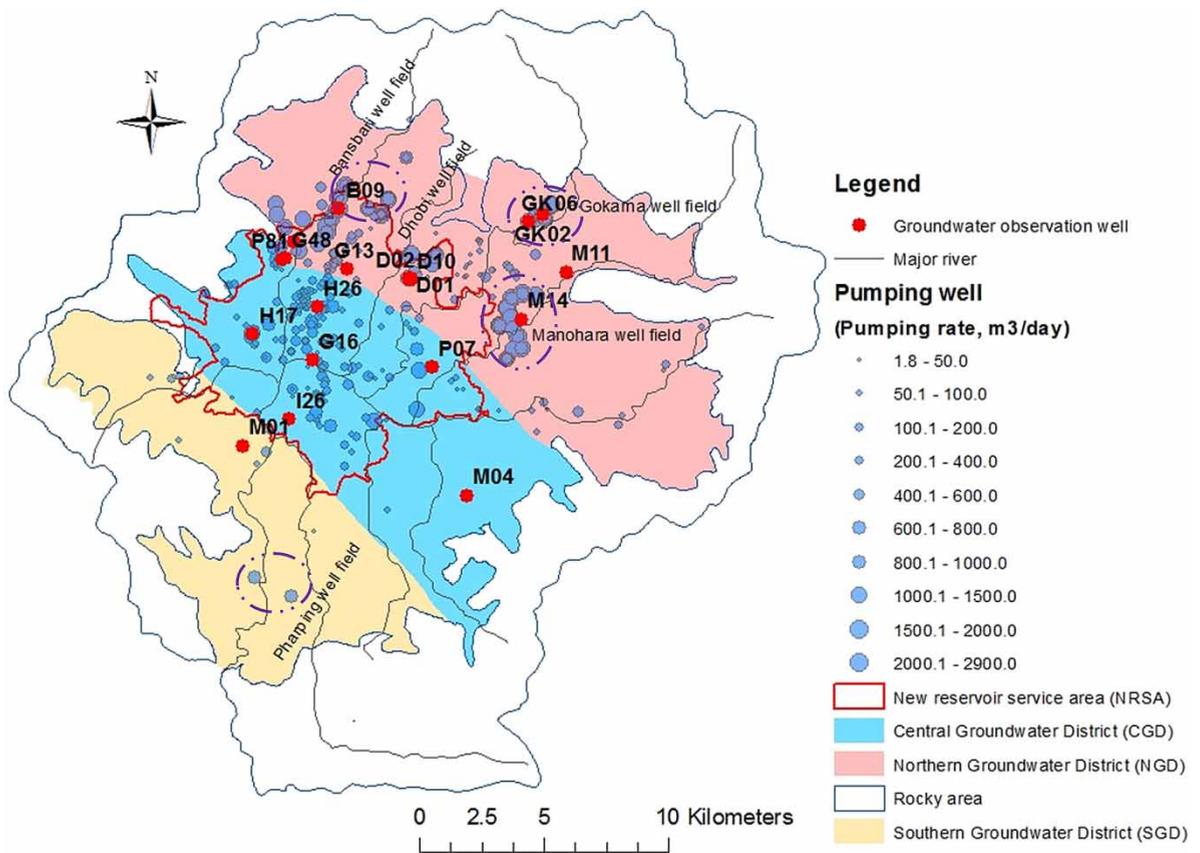

Fig. 4. Spatial distribution of pumping wells with abstraction rates at northern, central, and southern groundwater districts of the Kathmandu Valley.

adjusted to match observed heads of those wells in the zone. Water balance was evaluated using the VMOD zone budget to confirm realistic river water losses and gains of the model simulation. The same procedure was conducted iteratively for all 18 zones.

Results and discussion

Groundwater pumping

In 2012, the GWRDB (McDonald & Harbaugh, 1988) reported that most of the existing 759 deep tube wells had been abandoned, and only some were still in use by various users, such as hotels, embassies, government offices, and carpet and brick companies. It is a limitation of this research that only 379 pumping wells listed in the GWRDB inventory and their pumping rates in 2009 were considered while there could be many more new wells, some of which may have been already abandoned. The majority of the 379 pumping wells are located in the central part of the valley, where the KUKL is planning to supply water from off-the-valley source via the MWSP, with 154 wells in the NGD, 212 wells in the CGD, and 13 wells in the SGD. The estimated groundwater abstraction from the valley was 143 mld, consisting of 102, 38, and 3 mld from the central, northern, and southern groundwater districts, respectively. Abstraction rates from individual wells ranged from 0.00018 to 2.8 mld, with an average of 0.65 mld for the NGD, 0.00028–1.1 mld with an average of 0.18 mld for the CGD, and 0.00042–0.86 mld with an average of 0.24 mld for the SGD (Figure 4). Higher pumping rates were mainly from the KUKL production wells and three wellfields in Manohara, Bansbari, and Dhobi. The average rate of hydraulic head decline in the valley was 0.69 m/year for the 11 year (2003–2014) period with 1.12 m/year in the NGD, 0.72 m/year in the CGD, and 0.23 m/year in the SGD. For the NGD, the observed decline of hydraulic head is 12.35 m and is 21.58 m at well B13 and 3.12 m at well M12 in the 11 year (2003–2014) period. The groundwater head of CGD wells declined by 5.05 m at well H17, 6.33 m at well P81, 11.6 m at well I26, and 8.76 m at well M04, and the district average was 7.93 m. The SGD has only one observation well, which is M01 and has a reported 2.57 m decline of its groundwater head for the 11 year (2003–2014) period.

Model calibration with baseline scenario

Figure 5 shows the correlation between observed hydraulic heads in January 2003 and the heads generated by the steady-state simulation using 2009 pumping rates. The calibrated groundwater model had a correlation coefficient of 0.70 with observed data, which is a reasonable model performance considering the limitation of available data and the large uncertainty in subsurface information. Despite a reasonable overall model fit, the errors are not randomly distributed across the valley; the simulated hydraulic heads for the wells in low-elevation areas have large positive biases and those in high-elevation areas have negative biases (see locations of the observation wells in Figure 4). The minimum head difference of 3.7 m was observed at well M12 and maximum head difference of 21.47 m at well P07, which is screened in Layer 2, while another well G16 screened in Layer 2 shows a better fit. Two wells, D10 and D02, located in close proximity to each other in the NGD, demonstrate an underestimation of simulated heads in Layer 1. Observation wells H26 and G13, screened in Layer 3, showed an overestimation of groundwater heads and may be due to the oversimplification of the hydrogeology on the western side
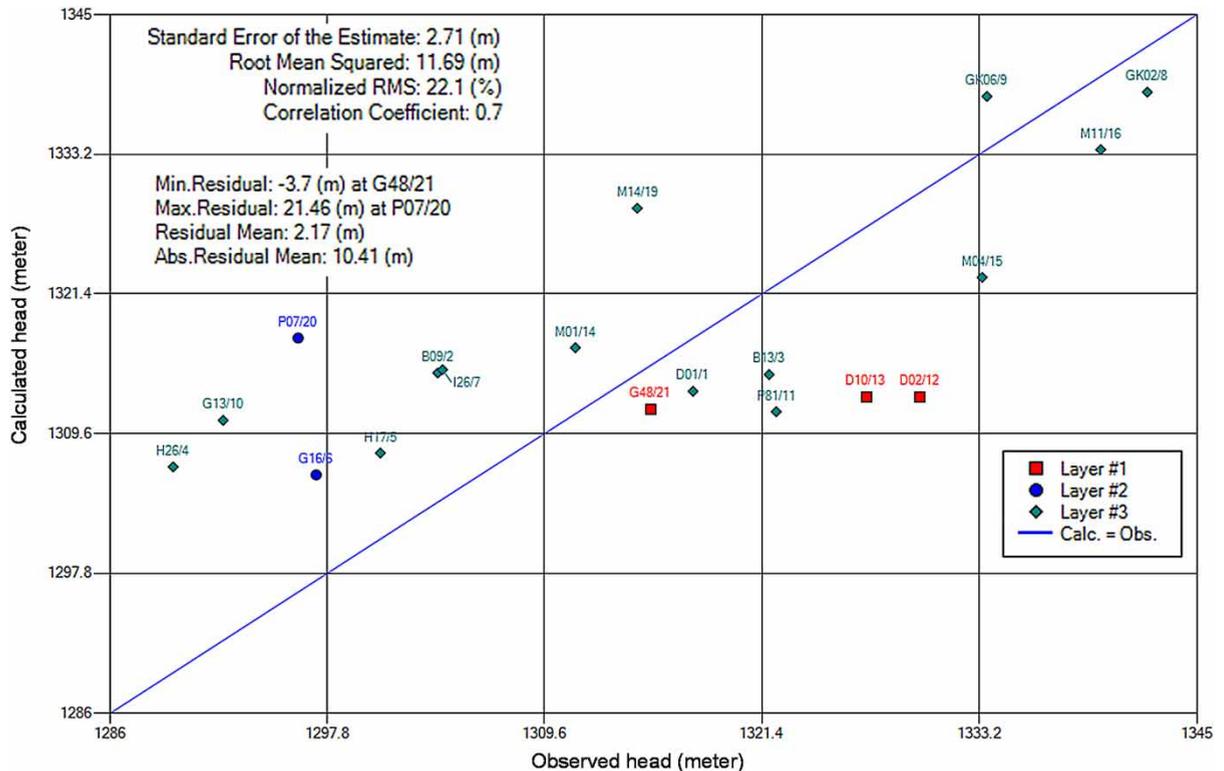
Fig. 5. Calibration of hydraulic heads for January 2003 using unpublished observed values from GWRDB (Groundwater Resources Development Board).

of the valley. These groups of observation wells with large simulated differences should be the focus of future studies to improve the model performance locally as well as across the valley. Figure 6 shows the spatial distribution of simulated hydraulic heads in the shallow (Layer 1) and deep (Layer 3) aquifers. A cone depression is observed in both Layers 1 and 3 in the CGD, but they are slightly offset due to the different rate of pumping in each layer. For scenario analysis, results are considered as satisfactory, but the groundwater flow model could be further improved with additional data in future studies.

Analysis of scenario simulations

Figure 7 shows changes in simulated hydraulic heads between the baseline and the five scenarios summarized in Table 1 in Layer 3 (Figure 7(a)). The results of the first scenario show an average increase of hydraulic heads by 3.37 m across the three groundwater districts and by 3.20 m, 2.77 m, and 4.49 m in NGD, CGD, and SGD, respectively (Figure 7(b)). The reduction of pumping is considered after the implementation of the first phase of the MWSP and indicates a greater increase in the northwestern part than in the central part of the valley.

In the second scenario (Figure 7(c)) after the implementation of the second phase of the MWSP, the new RSA receives a sufficient amount of water and hence there is a possibility to reduce pumping,
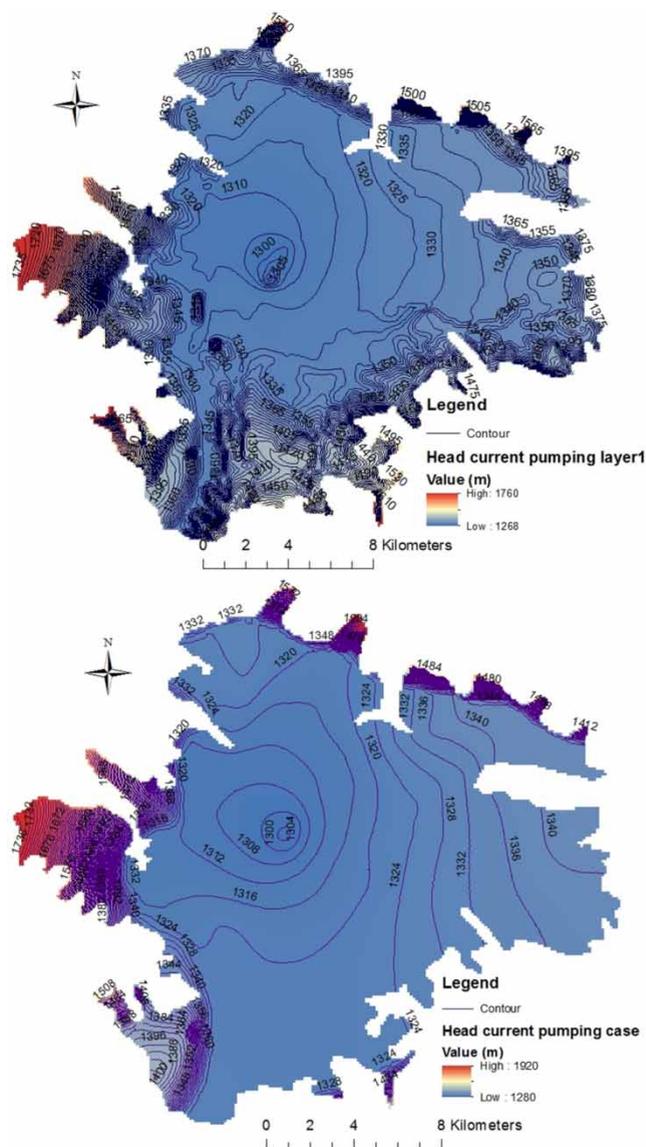
Fig. 6. Spatial distribution of simulated hydraulic heads in the shallow (top) and deep (bottom) aquifers in the three ground-water districts within the Kathmandu Valley using the calibrated model. Head values are in meters above mean sea level.

perhaps to the minimal pumping condition. In contrast, the water deficit becomes worse in the existing RSA, leading to an increase of pumping by 25%. As a result, there is an increase (up to 11 m) in hydraulic heads inside the new RSA, mainly in the central-western part of the valley. The increase of pumping by 25% in the existing RSA increases the head (up to 7 m) in the north-western part of the valley at nearby Bansbari well field, but it results in a decrease of heads in the north-eastern part of the valley (Figure 7(c)). The average increase of hydraulic heads is 2.24 m, 3.59 m, 4.25 m in the NGD, CGD, and SGD, respectively. The average increase of head is 3.15 m for the entire valley due to a major
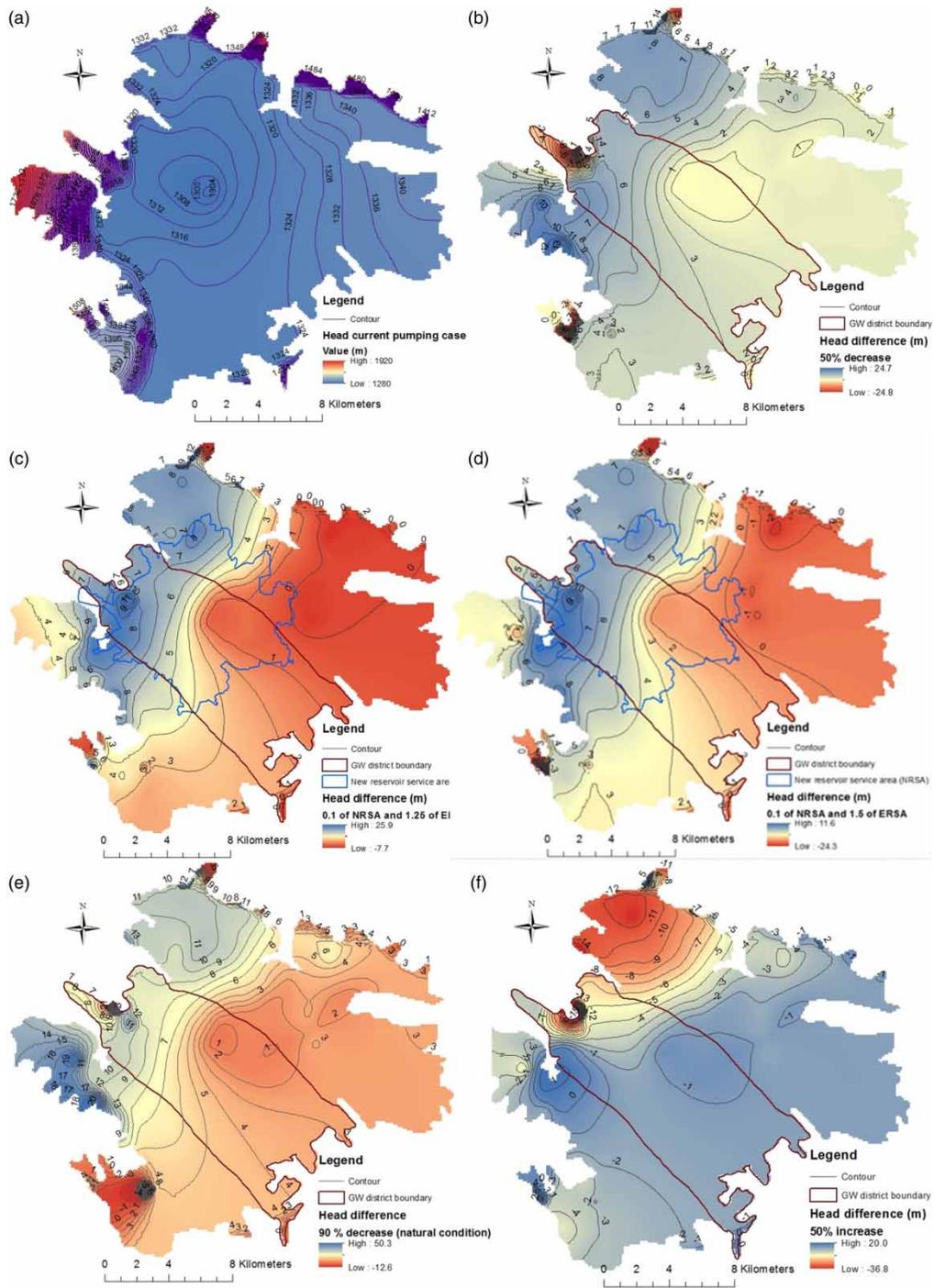
Fig. 7. Simulated heads in the baseline scenario (a) and head changes between the baseline and (b) 50% reduction, (c) minimal (10%) in the new RSA and 25% increase in the existing RSA, (d) minimal (10%) in the new RCA and 50% increase in the existing RSA, (e) optimistic, and (f) pessimistic scenarios.

decrease in pumping inside the new RSA, where most of the pumping wells occur, and the water deficit is substantially reduced inside the new RSA in this scenario.

In the third scenario, in the existing RSA, the situation would deteriorate due to the unmet total demand and increased pumping by 50% in the existing RSA. In this scenario, hydraulic heads decrease in the north-eastern part of the valley and increase in the central and north-western parts (Figure 7(d)). The average change of hydraulic heads is 1.62 m, 3.47 m, and 4.2 m in the NGD, CGD, and SGD, respectively. The average change of heads for the valley is 2.83 m. These results indicate that there is a substantial impact on the groundwater system after the completion of the MWSP, especially if proper regulatory mechanisms are able to curb pumping from the deep aquifer by substituting it with the piped water supply to meet any water deficit.

In the optimistic scenario, the MWSP is completed in the stipulated time and the water supply is redistributed across all sub-districts of both new and existing RSAs, fully satisfying all water demands. The minimal pumping in the entire valley leads to increases in hydraulic heads by 5.48 m, on average, and 5.06 m for the NGD, 4.83 m for the CGD, and 7.11 m in SGD (Figure 7(e)). The highest increase in SGD is due to a major reduction in pumping in two wells in the southern part (Pharping well).

For the pessimistic scenario, there will be a severe water deficit with a possible increase in pumping by 150% of the current rate in the entire valley if the MWSP is not completed on time. The average decrease of hydraulic heads is −2.97 m for the KV and is −4.0 m, −2.19 m, and −2.19 m in the NGD, CGD, and SGD, respectively (Figure 7(f)).

Limitation of the current study

Despite the availability of advanced modeling technology with available local data, the current model setup is only the first attempt to represent the complex aquifer system of the Kathmandu Valley. The first limitation of this study is the lack of updated groundwater abstraction information from active pumping wells because the pumping rate data were available only for 379 out of 759 existing wells and estimated from an old record from 2009. Using a more current and comprehensive data set would improve our estimates of the decline of hydraulic heads and identification of the areas of potential concern. A sparse observation well network and the lack of river discharge data were the second major limitations of this study. To calibrate the groundwater flow model, the 2003 hydraulic head data were used as the most complete data set, while river discharge data were unavailable to calibrate surface–groundwater interactions on the majority of perennial streams. Two river gauging stations allowed a match of river losses to groundwater between simulated and observed discharges on river reaches, but this is insufficient for the rest of the watershed, especially in groundwater recharge areas. In this study, we simplified the surface geological information into six subgroups assigned to all three depth layers. The mountainous area in the active model domain based on perennial rivers was assumed to be a low-permeability zone. Utilizing isotope tracers such as tritium in wells and river water during the base flow period will help to quantify groundwater contributions from the low permeable areas to the perennial streams and the aquifer system, respectively (Gusyev et al., 2016). Having more detailed geological and hydrogeological information should resolve problematic areas in future models by using more vertical layers with finer spatial grids. In addition, we assumed a steady-state situation in the aquifer system which was necessary for evaluating change in groundwater heads in management scenarios. However, the decline of groundwater heads at different rates is seen in all available observation wells

and a transient model will be useful for determining the temporal responses of the groundwater flow system for pumping in future studies.

Summary and recommendation

This study presents an investigation of water resources management scenarios in the Kathmandu Valley using a groundwater flow model developed with limited available data. Groundwater models are useful tools that can make use of available data and guide new data collection in critical areas for improving simulation results, while answering practical questions regarding water management. In model simulations representing various stages of implementation of the MWSP, estimates of groundwater abstraction rates played a critical role in the analysis of the impacts of the MWSP. The model was used to simulate the spatial distribution of hydraulic heads for the different scenarios and the results were used to evaluate the implication of changes in pumping rates and recommend policy options. The first phase of the MWSP will partially fulfill water demand of both new and existing RSAs, while after the second phase of the MWSP, the water demand of the new RSA is fully met but the existing RSA still faces a water deficit. Despite getting sufficient utility water, there is still a possibility to abstract groundwater using available infrastructure. The spatially averaged changes in hydraulic head ranged from $+2.83$ m to $+5.48$ m in various stages of the MWSP implementation and -2.97 m for increased pumping rates with no implementation of the MWSP.

These findings demonstrate a potential improvement in groundwater management with the implementation of the MWSP and proper regulation. There may be inequality in access of potable water, which could lead to conflicts among the groundwater users and regulators. In this situation, subsidizing water pricing based on the water deficit situation in the RSAs may be one solution. Detailed assessments of implementation of subsidizing water pricing needs to be considered in future studies. Based on these results, it is recommended that, after the first phase of the MWSP, the KVWSMB motivates groundwater users to voluntarily reduce their pumping rates by up to 50% for the sustainable management of groundwater. However, after the second phase of the MWSP, appropriate regulation on groundwater pumping needs to be based on the accessibility of piped water supply and enforced with appropriate regulatory and monetary mechanisms. Such regulatory mechanisms could be monetary incentives to install meters to monitor pumping rates. For example, the KVWSMB may aim to impose a higher price for groundwater pumping licenses in the new RSA, medium prices in the existing RSA, and nominal charges in the areas having neither new nor existing public water supply based on the price and availability of water. Although the installation of bulk meters is expensive for consumers and regular groundwater use monitoring is not an easy task for the KVWSMB, these data are required for policy formulation, zoning of groundwater potential, groundwater vulnerability mapping, and regulating groundwater withdrawals.

Currently, several rules, regulations, and strategies exist for regulating water supply and sanitation in the valley; however, the situation has not improved over the past decades. The historical trend of observed hydraulic heads demonstrates a steady decline of 0.69 m/year due to increasing groundwater abstraction in the valley. Combining the current depletion of the aquifer system with increasing water demand in the future will result in the overexploitation of groundwater resources. Hence, various policy instruments are necessary for the effective implementation of spatially differentiating pricing policy. The implications of various policy regulations to recommend differing pricing policy on the

valley's groundwater system need to be identified in future studies with a coupled economy and groundwater model.

The MWSP is the key project to combat the present water deficit, but investigations into the impact of the MWSP on the groundwater system have been lacking. In this regard, the current study is the first attempt to evaluate the implications of the MWSP on the valley's groundwater system linking with the potable water deficit calculated from water demand and supply. Therefore, this study provides answers to water management questions, such as 'What may be the impacts of possible change in pumping in different stages of MWSP implementation?' In addition to the MWSP implementation, there will be a need to evaluate impacts of climate and land-use changes in the valley's groundwater system. These changes could affect the permeability of the urban landscape and increase wastewater discharge into rivers. Therefore, the spatial dynamics of these changes should be incorporated in future research.

Acknowledgments

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