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Melamchi water supply project: potential to replenish Kathmandu's groundwater status for dry season access

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Abstract

Kathmandu Upatyaka Khanepani Limited (KUKL) currently uses 35 surface and 57 groundwater sources to supply water for Nepal's capital, Kathmandu. It is necessary to understand if the Melamchi Water Supply Project (MWSP) can assist lean period water supply by indirectly increasing groundwater storage, through diverting excess water supply to groundwater recharge zones. The current study analyzed long-term groundwater depletion to assess available groundwater storage, followed by assessment of groundwater balance for the Kathmandu Valley. Results show that total groundwater extraction for Kathmandu was 69.44 million cubic meters (MCM) and drawdown of the groundwater surface was 15–20 m since the construction of wells in 1984/85, indicating substantial overexploitation. Results indicate that the ongoing unmet demand of 170 MCM/year can be easily satisfied if groundwater storage is recharged effectively, as underground water storage potential is 246 MCM/year due to a groundwater depletion rate of 2–10 m. From results, it is evident that that the timely implementation of the MWSP can help ease ongoing water stress and aid in reversing the damage caused to groundwater storage. In the long run, MWSP can supply water and recharge groundwater during monsoon periods, thus improving the quality of life and socio-economic status in Kathmandu.

Keywords: Groundwater; Kathmandu; Melamchi Water Supply Project; Nepal; Water supply

Introduction

Nepal is one of the fastest urbanizing countries of South Asia, with Kathmandu, the capital city, having the highest urbanization rate in the nation (Jha & Shrestha, 2010). As a result, the city faces water management issues in supplying for the water demands of the growing city (Lacombe *et al.*, 2019). Kathmandu houses the largest population (approximately 1.5 million) and economy of Nepal

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with 50% of urban population and 30% of the national gross domestic product (HMG & IUCN, 1995; HMG & MoPE, 1999; ADB, 2010). The population of Kathmandu is growing at 4.5% per annum, and with migration and economic impacts, the growth rate is projected to increase further in the coming decades (MoPE *et al*., 2001; Central Bureau of Statistics, 2011). With the population increase, there is considerable increase in stress on the Government of Nepal to provide domestic water supply (HMG & IUCN, 1995; HMG & MoPE, 1999; Metcalf & Eddy, 1999, 2000, 2002; HMG, 2004; Udmale *et al*., 2016). In particular, drinking water quality and quantity is one of the biggest concerns in the Kathmandu Valley (Cresswell *et al*., 2001; Chapagain, 2014). Even though Kathmandu is rapidly urbanizing, long-term water supply schemes to sustain such growth are limited, even before any population explosion (Binnie & Partners, 1973a, 1973b, 1989). The drinking water supply sector for the valley has been subjected to many reforms since 1891 (Chapagain, 2014). One key institutional reform was in the separation from the Nepal Water Supply Corporation (NWSC) and formation of the Kathmandu drinking water supply sector through the Kathmandu Valley Water Supply Management Board (KVWSMB). This also led to many policy reforms, in particular the introduction of Public Private Partnership (PPP), through which the Kathmandu Upatyaka Khanepani Limited (KUKL) was formed (ADB, 2000; Kathmandu Valley Water Supply Management Board, 2006; Chapagain, 2014).

The KUKL uses 35 surface water and 57 groundwater sources to supply water for Kathmandu (Jha *et al*., 1997; GWRDB, 2012). According to KUKL the water demand in 2013 in the Kathmandu Valley is 360 million liters per day (MLD) but only 95–154 MLD of water is available, while 50% of it is obtained from the groundwater resources (KUKL, 2012). Stanley *et al.* (1994) estimated that sustainable groundwater withdrawal from the valley's aquifers is 26.3 MLD, while JICA (JICA, 1990a, 1990b, 1990c), suggested that groundwater can be drawn only at around 15 MLD. A well-inventory study by the Ground Water Resource Development Board in 2012 indicated the presence of 759 deep tube wells in Kathmandu. Total groundwater extraction by private and community tube wells is 31.15 million cubic meters (MCM) (GWRDB, 2012). The annual groundwater extraction by NWSC and KUKL wells in Kathmandu is 38.29 MCM (KVWSM, 2010). This shows the annual extraction of groundwater from the deep tube wells in Kathmandu is 69.44 MCM. Both analyses indicate a higher groundwater withdrawl rate than sustainable levels.

As a result of insufficient supply of surface water for both drinking and non-drinking uses, approximately 50% of the water supply in Kathmandu is from groundwater systems that comprise both shallow and deep aquifers (Jha *et al*., 1997; Khatiwada *et al*., 2002). Tube wells, dug wells, and stone spouts are the major mechanisms of groundwater use (ICON *et al*., 2002). As a result, the groundwater of Kathmandu Valley is under immense pressure from heavy use for domestic and industrial purposes (Cresswell *et al*., 2001). Under such conditions, and with limited water supply, Cresswell *et al.* (2001) indicated more than a decade ago that with the ongoing groundwater extraction rate, which is 20 times that of the recharge rate (15 mm per year), groundwater reserves will be empty in 100 years. Without sufficient institutional and policy reforms, the groundwater extraction rates are projected to increase across the valley. When this is combined with the population increase, the groundwater reserves will be emptied far earlier than the 100 year timeline.

Due to the unsustainable population growth and associated increase in water use, the citizens of Kathmandu Valley experience severe water stress for domestic use (Chapagain, 2014). Less than 50% of the water need is satisfied, thereby increasing stress on other water resources, especially groundwater to sustain livelihood and to invest for industrial purposes. However, as the groundwater resources are finite, the ongoing water stresses have led to unsustainable groundwater use. Under these circumstances, it is necessary to quantify the current groundwater trend in the region with an aim to understand if groundwater recharge activities can increase groundwater resources (e.g. Agoramoorthy *et al.*, 2016; Chinnasamy, 2016a; Chinnasamy & Agoramoorthy, 2016; Chinnasamy *et al.*, 2018a, 2018b; Jadeja *et al.*, 2018). In addition, there is a need to understand if the Melamchi Water Supply Project (MWSP) scheme will indirectly benefit groundwater resources if some of the excess water, especially during wet seasons, can be tactically used to recharge existing water harvesting structures (e.g. temple ponds, city ponds, wells, headwaters of ancient spouts, etc.).

Objectives

The major objective of this study is to assess the groundwater depletion trends for the Kathmandu Valley, using Ground Water Resources Development Board (GWRDB) records, with the aim of quantifying the increase in groundwater storage due to excess water supply from MWSP in groundwater recharge zones. The other objectives include assessment, from literature review, the potential of groundwater recharge zones and aquifer characteristics. With this information the authors aim to understand the enhanced groundwater recharge rates in the Kathmandu Valley due to the MWSP water supply, under the assumption that there may be an excess of water during wet seasons and leakage in water supply systems.

This paper, for the first time, will use observed groundwater data to monitor the current groundwater depletion in the Kathmandu Valley. The paper will also analyze the aquifer properties for the Kathmandu Valley aiming to estimate recharge rates. With the MWSP, it is estimated that the groundwater contribution for Kathmandu’s water supply will be lower. However, due to the delay in the project and ever increasing population growth, groundwater resources have seen a decline beyond sustainable rates.

A combination of observed groundwater data, water supply/use data and groundwater recharge potential from MWSP (by using MWSP excess water to recharge existing ponds and lakes in the valley) will be analyzed to investigate sustainable methods for use of groundwater and surface water for Kathmandu. The results generated will illustrate the use of MWSP water during wet seasons and groundwater during dry seasons, thereby providing physical evidence to support the conjunctive use of groundwater and MWSP surface water for the Kathmandu Valley.

Methods

Study site

Kathmandu Valley, an oval-shaped tectonic basin, is one of the largest intermontane basins developed within the Lesser Himalaya of Central Nepal (Figure 1). The valley is 30 km long East to West and 25 km North to South with an area around 650 km^2. The Kathmandu Valley includes three districts, namely Kathmandu, Lalitpur and Bhaktapur, and is located between latitude 27,032′34″ and 27,049′11″ North, and longitude 85,011′10″ East and 85,031′10″ West. The valley is surrounded by the Mahabharat mountain range with four hills acting as forts of the valley: Phulchowki in the South East, Chandragiri/Champa Devi in the South West, Shivapuri in the North West, and Nagarkot in the North East. The Valley encloses the entire area of Bhaktapur district, 85% of Kathmandu district and 50% of Lalitpur district. The valley floor is typically plane with small hillocks, many river terraces and floodplains ranging in elevations between 1,300 and 1,400 m. The highest altitudes are 2,166 m

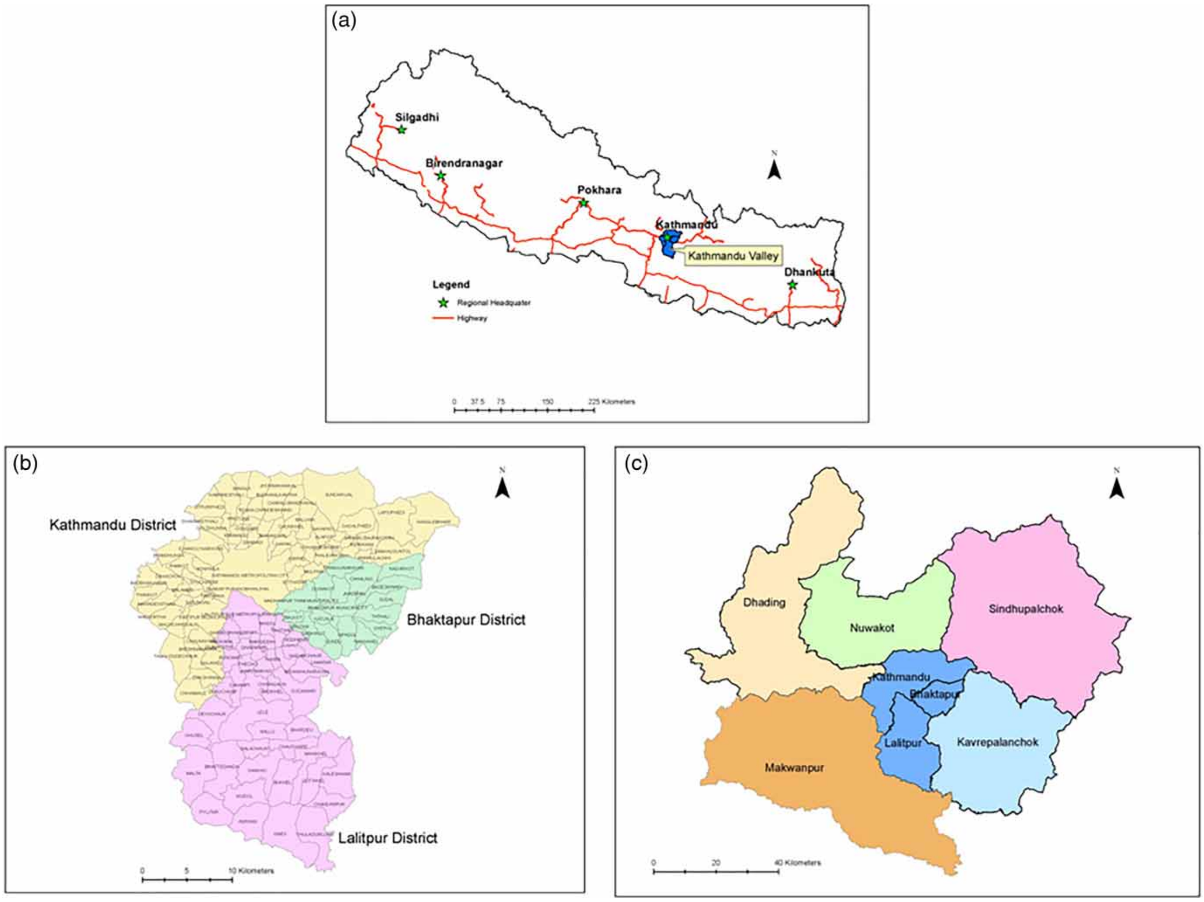

Fig. 1. Maps showing (a) location of Kathmandu Valley in Nepal (blue), (b) major districts in Kathmandu and (c) location of municipalities, and Village Development Committees (VDCs) in Kathmandu Valley. Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wp.2019.080.

(in Bhaktapur), 2,732 m (in Kathmandu), and 2,831 m (in Lalitpur). Some of the higher mountain peaks surrounding the Kathmandu Valley are Phulchowki (2,800 m), Chandragiri (2,365 m), Nagarjun (2,100 m), Shivapuri (2,453 m) and Nagarkot (2,100 m) (GWRDB, 2012).

The Kathmandu climate is characterized as subtropical and cool temperate with four seasons: spring from March to May; summer from June to August; autumn from September to November; and winter from December to February. The rainy season is present during the monsoon period from June through September with about 80% of the annual rainfall (the average total precipitation in the Kathmandu Valley is 1,159.65 MCM per year) occurring during the rainy season. The rainfall varies with altitude with the higher elevations having higher rainfall than lower regions, for example only 1,300 mm per year rainfall occurs in the valley floor while 3,000 mm per year rainfall occurs in the mountain rim surrounding the valley. Average temperature for the region in summer season is around 30 °C and minimum temperature in winter season is about 0 °C (GWRDB, 2012).

The core of the Kathmandu Valley is densely populated with both urban and rural residents. The valley's population was estimated to be 3.5 million people in 2015, with the Kathmandu district having the largest share, followed by Lalitpur and Bhaktapur districts. Due to the continuing migration of rural population into the Kathmandu Valley, the expansion of rural areas into adjacent urban areas is likely to continue without regulation (GWRDB, 2012). KVWSWSI (2010) and Shrestha & Shukla (2010) predict that the population of the Kathmandu Valley will be 4.5 million and 5.8 million in 2020 and 2025, respectively.

Kathmandu Valley water supply and water stress

Kathmandu Valley's population is ever increasing due to migration of villagers for better employment. The KUKL is responsible for water supply in the region. The KUKL has been supplying water to the Kathmandu Valley from 35 surface water sources around the Kathmandu Valley peripheries, 57 deep tube wells (DTWs) and 11 dug wells. KUKL has 43 reservoirs and 20 treatment plants with a total treatment capacity of 117 MLD. The total water demand in year 2012 was 350 MLD. The production capacity of the KUKL system is 144 MLD in the wet season and 84 MLD in the dry season. The trend of water demand and supply scenarios in Kathmandu Valley is shown in Figure 2 and Table 1 (KUKL, 2012).

In addition to the KUKL water supply, most of the people depend on ancient water supply sources and groundwater resources (GWRDB, 2012). The valley has many traditional and ancient stone water spouts: around 237 in Kathmandu, 77 in Lalitpur, and 53 in Bhaktapur (Becker-Ritterspach, 1995; Amatya, 2006). These stone spouts were installed within rectilinear pits built into the ground and supplied through 'Raj Kulos' (state water canals) in a decentralized approach. In recent years, urbanization and the associated decline in water level across the valley have led to the drying up of the majority of these spouts.

Groundwater resources for water supply in the Kathmandu Valley

There has been immense stress on the groundwater resources of the Kathmandu region (Metcalf & Eddy, 1999, 2002; Shrestha *et al*., 2013). The GWRDB recently conducted a study to assess the

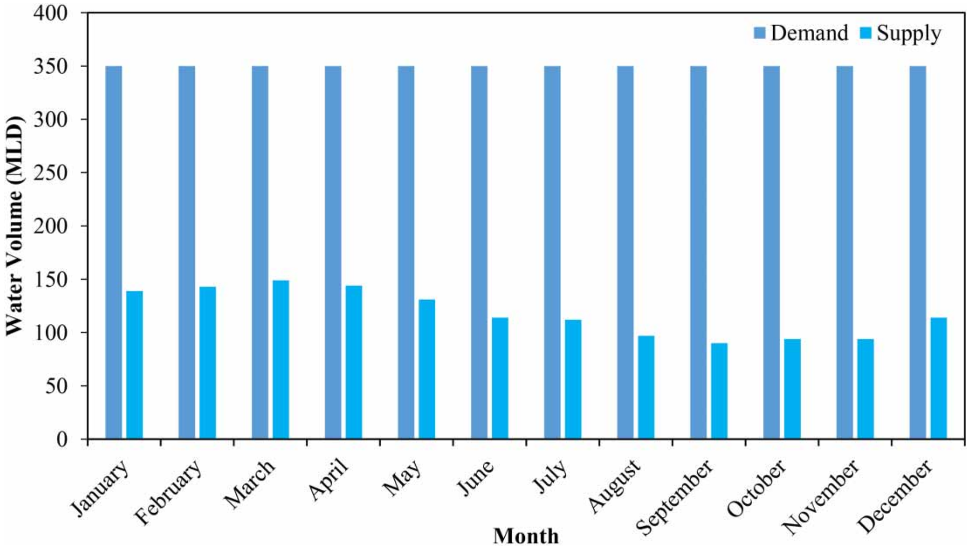

Fig. 2. Domestic water demand and KUKL water supply in the Kathmandu Valley (*Source*: KUKL, 2012).

Table 1. Water supply and demand in Kathmandu Valley (*Source*: KUKL, 2012).

Volume (MLD) /year	2010	2011	2012	2013
Water demand	320	350	350	360
Water supply	180	180	182	182
Unmet water demand	139	170	168	178

groundwater balance components and the water demand and supply scenario in the Kathmandu Valley (GWRDB, 2012). As per the report, approximately 20% of the water applied to irrigation is returned to the aquifers in the region. One important result from the study was that there is considerable leakage in the city's water supply, which indirectly recharges the local aquifers. The report estimates that despite the annual demand of 350 MLD water, NWSC/KUKL could only supply 182 MLD (KUKL, 2012). Of this total water supply, it is assumed that 54% of the water is supplied by using water from surface water sources, while the remaining 46% was supplied using water from deep tube wells (typical of depth from 50 to 200 meters). The report also indicated that 35–40% of the supplied water (49 MLD) is being lost due to leakage in the distribution system (KUKL, 2012). It is assumed that part of this water goes as baseflow, while the rest goes to recharge the groundwater aquifer of the valley.

Groundwater data

The groundwater monitoring by GWRDB was started from the year 2000 in the Kathmandu Valley, specifically covering the Melamchi water supply region. The monitoring wells were selected on the basis of available well inventory survey carried out by Melamchi Water Supply Development Board (MWSDB). In the beginning 50 wells were selected for the groundwater-level monitoring program. Out of the 50 selected GW level monitoring wells (both production and abandoned), the monthly monitoring works were performed in 32 wells in August 2000. The remaining 18 wells could not be used for monitoring purpose due to lack of monitoring provision therein. The present monitoring works are being carried out by the GWRDB. The 32 monitoring tube wells are located in the three groundwater districts are Northern, Central and Southern district (as discussed in Figure 3 below). The distributions of the wells are listed as follows: (a) Northern Ground Water District: BB-1, DK-1, DK-2, DK-3b, DK-8, BB-6a, GK-5, GK-4, MH-6a, M-5, M-8, M-11, M-12, M-13 and M-14 and DK-3b; (b) Central Ground Water District: Bal-1a, G-17, G-16, G-13, H-26, H-17, I-26, P-15, M-6, M-7, and BH-LK; (c) Southern Ground Water District: PH-1, P-15, P-7, G-2a, G-48, M-1 and M-4.

Data from the aforementioned districts were used to assess the current trend in groundwater extraction and to explore possibilities of using MSWP water for groundwater recharge activities. It is noted that due to difficulties in acquiring the data, and large data gaps, only four wells (M-1, M-4, M-11 and M-14) were analyzed to assess the long-term trends (from 2001 to 2014) for the Kathmandu Valley.

Groundwater aquifer characteristics review

Over the past years, there have been various studies regarding the geologic system of the Kathmandu Valley, with particular emphasis on the groundwater aquifer characteristics. In this section, an attempt is being made to summarize key findings from various studies in the region. Regarding the overall

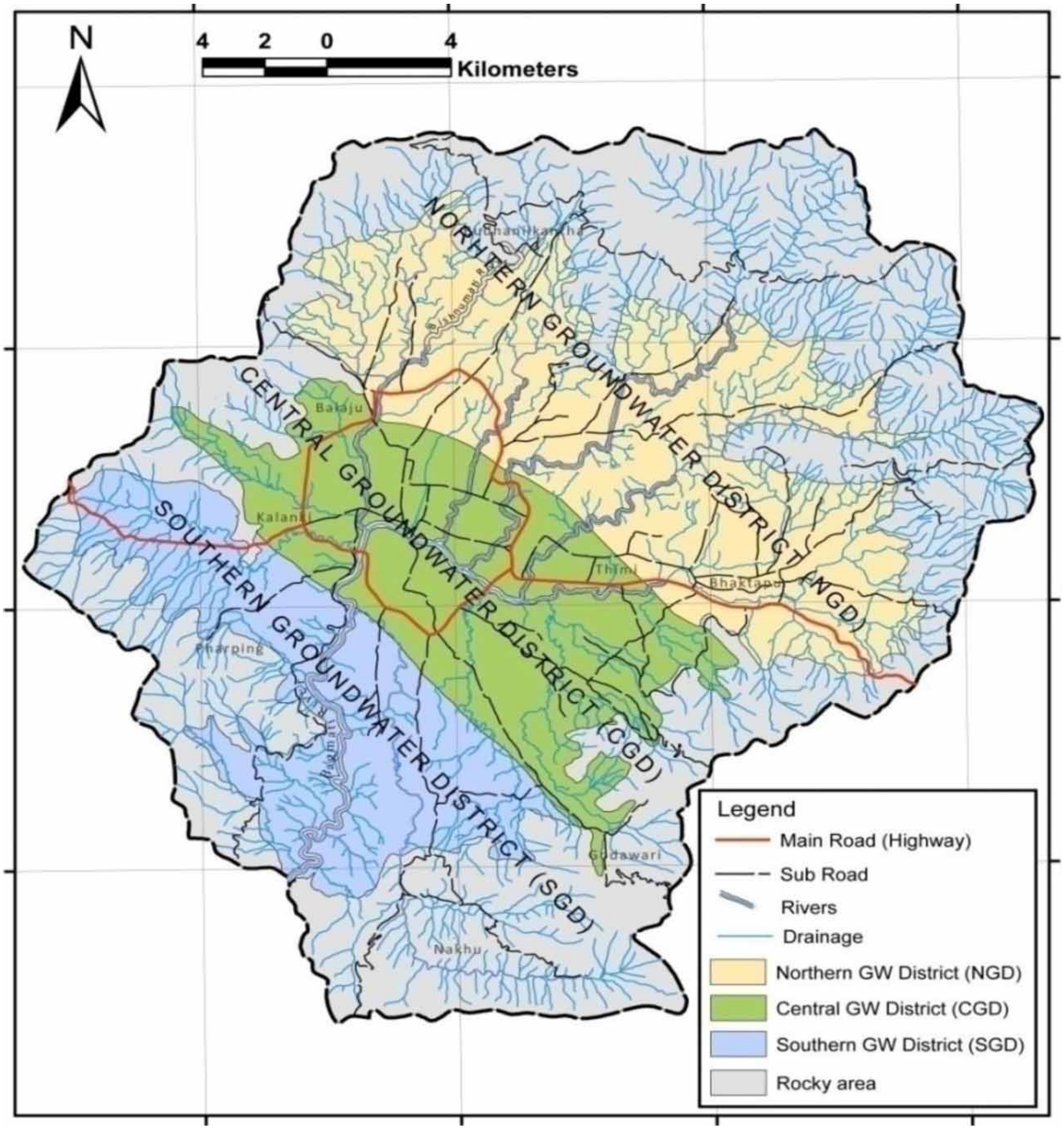

Fig. 3. Groundwater divisions (known as groundwater districts) of Kathmandu Valley based on JICA (1990a, 1990b, 1990c).

stratigraphy for the Kathmandu Valley, it is estimated that fluvio-lacustrine geological deposits are present above the bedrock up to a thickness of 600 m. Above this, the Kathmandu Valley floor has three prominent features: (1) a thick clay layer on the surface, (2) a deep confined aquifer which is (3) confined by basement rocks at the bottom. It is noted that in many regions, the thick clay layer separates the confined aquifer from the unconfined aquifer, thus acting as an aquitard. The clay bed is noted to attain a maximum thickness of 200 m in the south, while less thick on the northern side (DoI, 1998; Kharel *et al.*, 1998). In another study, Gautam & Rao (1991) classified Kathmandu Valley into four groundwater zones: (1) unconfined aquifer zone, (2) and (3) two confined aquifer zones, and (4) no groundwater zone. JICA (1990a) also classified the groundwater divisions into three distinct groundwater districts as shown in Figure 3.

On the other hand, estimating the specific aquifer properties of the Kathmandu Valley has been challenging and therefore, different methods were used by various studies. As a result, research works in the past have brought up various estimations on groundwater recharge volume. For example, Binnie & Partners (1989) estimated a groundwater recharge of 30–40 MLD, while JICA (1990a) calculated 27 MLD, based on simulation model. In another study, Gautam & Rao (1991) estimated 12.63 MLD of groundwater recharge. Kansakar (1996) calculated the groundwater balance of −12.6 MCM (deficit) by estimating rechargeable groundwater resources (dynamic groundwater reserve) of 5.5 MCM and abstraction for drinking purposes and industrial uses of 13.87 MCM and 4.23 MCM, respectively. Stanley *et al*. (1994) estimated the total sustainable withdrawal of groundwater from the valley's aquifers to be 26.3 MLD. Another example for variations would include the estimation of the natural recharge of groundwater in the valley: ranging from 30,000 to 40,000 m^3 per day (Binnie & Partners, 1989), to 15,000 m^3 per day (JICA, 1990a), and about 13,000 m^3 per day (Gautam & Rao, 1991).

It is to be noted that all the aforementioned research needs to be updated, as the dominant land-use pattern has changed drastically owing to the increase in urbanization activities. Also, the recharge characteristics would have changed owing to the ongoing climate change patterns (GWRDB, 2012).

Melamchi Water Supply Project

The MWSP is an inter-basin and inter-sectoral water transfer project designed to meet the long-term (over 30–40 years) water demand of three major cities of Kathmandu Valley (Kathmandu, Patan and Bhaktapur), located in the Bagmati basin, by diverting water from the Melamchi River located upstream of the adjoining Indrāvati basin, which is part of the Koshi River. The major transmission line of the MWSP project is shown in Figure 4 (in red), while a map of existing water supply systems is shown in Figure 5. In Figure 5, the individual color indicates the coverage of the distribution network which is fed either by surface or groundwater supplies. The water from Melamchi will be collected to the Sundarijal/Manhakal chaur system and distributed to the other systems across the valley (MWSDB, 1998).

The project, under the infrastructure development component, includes physical intake and river diversion structures, a 26 km long tunnel, 25 km access road to the tunnel sites, 22 km of approach road, 15 km of main access road to the project intake site, a water treatment plant with a capacity of 170 MLD in Kathmandu, bulk distribution systems (transmission pipe lines and reservoirs in the Kathmandu Valley), improvement of the city water distribution network and its wastewater system, including the construction of wastewater treatment plants (MWSDB, 1998).

Estimation of economic benefits

Water supply rates from the region during wet and dry season will be estimated. In addition, the price to purchase groundwater will be estimated. Since the aim of this study is to assess the increase in recharge along already existing infrastructure, there is no direct costs to the system, other than channeling excess water from the main MWSP channel to the recharge infrastructures via portable pipes or

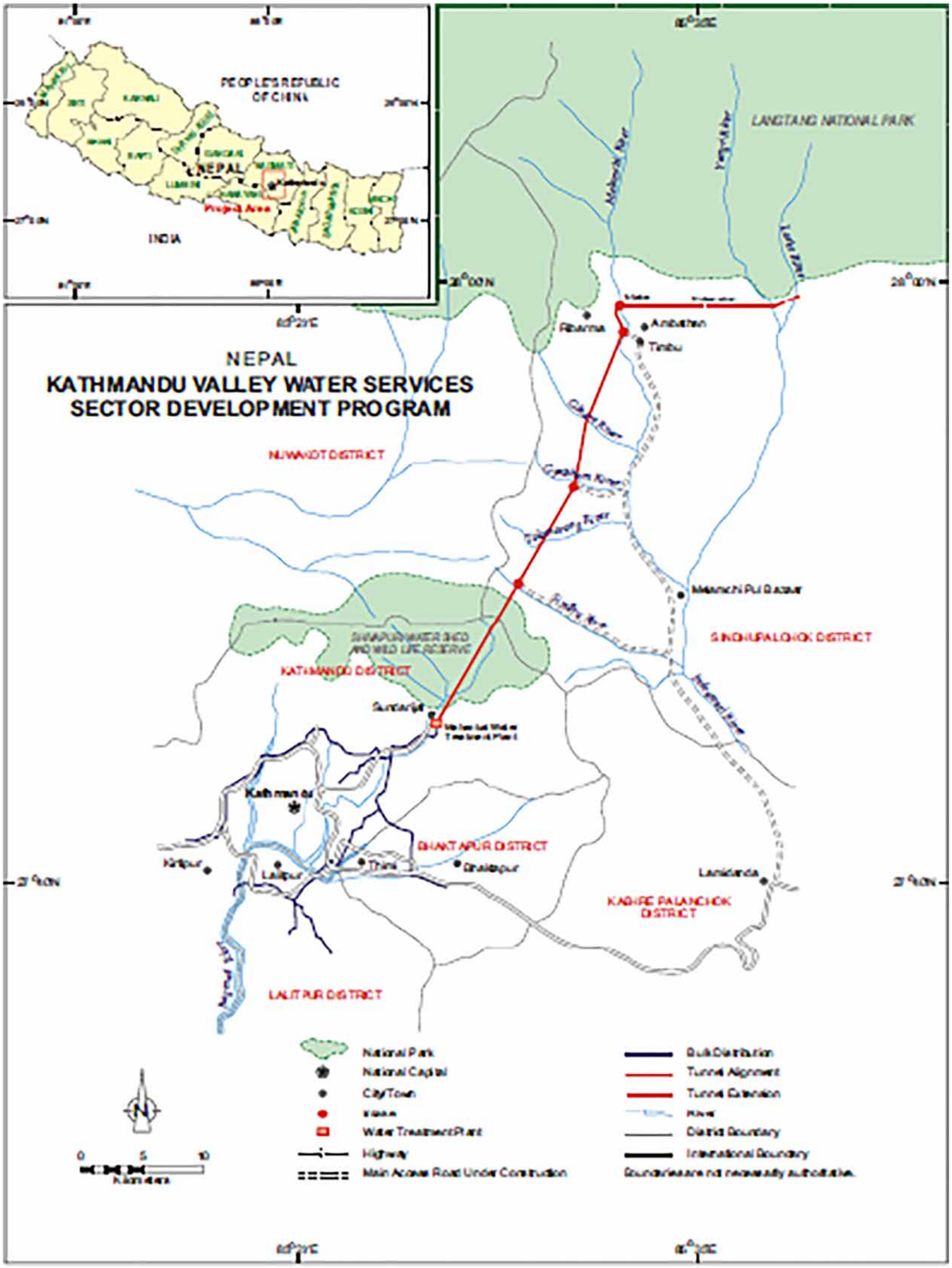

Fig. 4. Kathmandu Valley in Nepal, with the proposed Melamchi water supply scheme (*Source*: MWSDB, 1998). Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wp.2019.080.

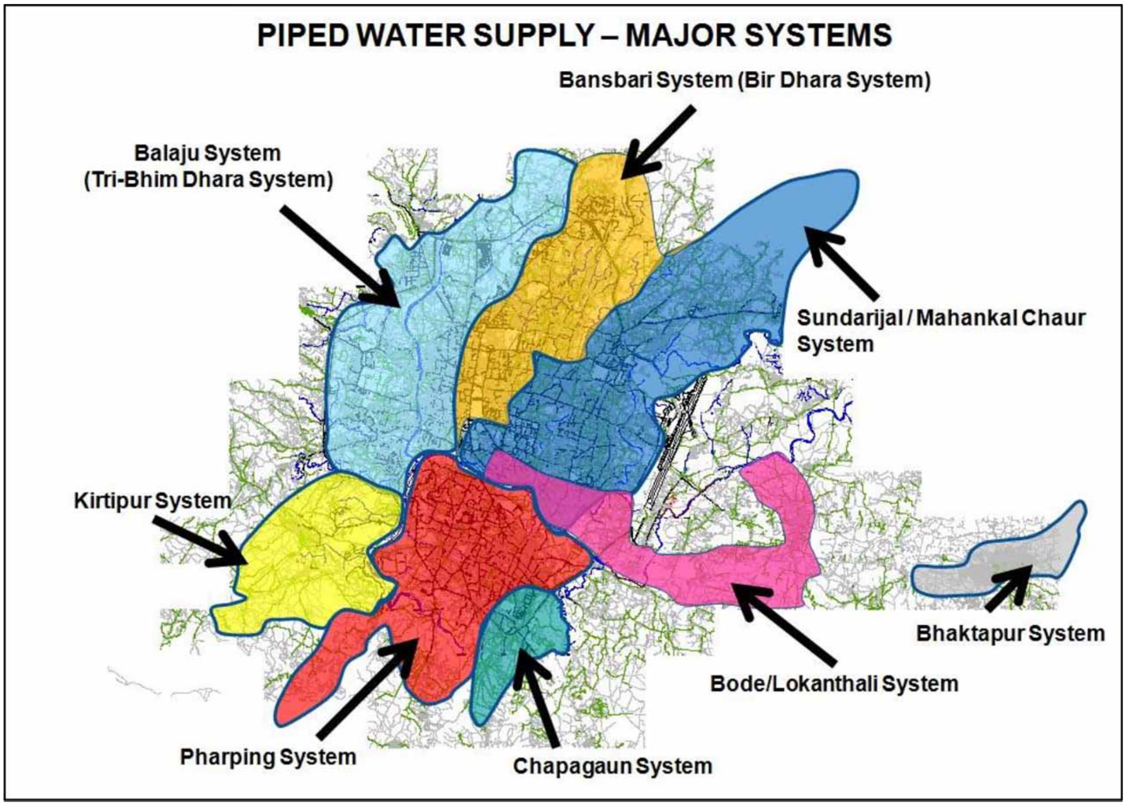

Fig. 5. Existing piped-water major supply systems which will be supplemented under the MWSP scheme for the Kathmandu Valley (*Source*: MWSDB, 1998). Please refer to the online version of this paper to see this figure in color: http://dx.doi.org/10.2166/wp.2019.080.

earthen canals. Such activities can be assumed to be carried out by local organizations (e.g. District or VDC offices) as the benefits are more localized than at large scale.

In order to assess the economic benefits in using MWSP water to recharge groundwater resources, it is necessary to understand the current tariffs for water, both in the government sector and private sector. The existing cost (NRs = Nepal Rupees) of KUKL water supply and private water supply is shown in Table 2.

On the private market, the cost of a 6,000 liters tanker supply of water is generally NRs. 1,200 (NRs 0.2 /liter), while a 12,000 liters tanker costs NRs. 2,000 (NRs 0.17 /liter). Therefore, on average, NRs 0.183 per liter on average.

Results

Groundwater balance in the Kathmandu Valley

As discussed in the earlier sections, groundwater is one of the major water resources to ease the increasing water supply stress for the Kathmandu Valley, which is undergoing rapid urbanization.

Table 2. Water tariffs under the KUKL system and private system for the Kathmandu Valley.

KUKL water supply tariff[a]

Pipe size (Inch)	Maximum limit of use (Liter)	Connection with meter installation: Tariff (NRs)	Connection with meter installation: Additional cost per 1,000 liter beyond maximum limit of use (NRs)	Connection without meter (NRs)
1/2″	10,000	100	32	785
3/4″	27,000	1,910	71	4,595
1″	56,000	3,960	71	9,540
1.5″	155,000	10,950	71	26,280
2″	320,000	22,600	71	54,255
3″	881,000	62,240	71	149,415
4″	1,810,000	17,865	71	306,880

Private water supply tariff[b]

Liters	Tariff (NRs)
6,000	1,200
12,000	2,000

[a]*Source*: http://www.kathmanduwater.org/notice/Tariff%20RateFinal-2070%20Srawon.pdf.

[b]*Source*: Field survey.

NRs = Nepal Rupees (1 USD = 107.2 NRs).

The current study aimed to understand the groundwater balance for the Kathmandu Valley, and hence summarized results from the GWRDB (2012) report. The groundwater balance for the Kathmandu Valley is computed as follows (GWRDB, 2012):

$$\Delta GW = \text{Groundwater Inflow} - \text{Groundwater Outflow} \tag{1}$$

$$\Delta GW = (P + Ir + Sr) - (ET + GD + I + GL + Q) \tag{2}$$

$$GD = (De + Sh + St) \tag{3}$$

where ΔGW is the change in groundwater storage, P, Ir and Sr are groundwater recharge due to rainfall (precipitation), irrigation return flows and supply return flows, respectively, ET is evapotranspiration losses, I is the irrigation water demand, GL is the groundwater loss to the aquifer and Q is the baseflow, GD is the total groundwater draft, which is the sum of draft from deep aquifer (De), shallow aquifer (Sh) and stone spouts (St). All volumes are in MCM.

Computation of the major groundwater balance components according to GWRDB (2012) is discussed in the following sections.

Groundwater recharge and groundwater basin area. According to the reports by the Japan International Cooperation Agency (JICA, 1990a, 1990b, 1990c), the Kathmandu Valley watershed is divided into three parts: Northern, Central and Southern (Figure 3). Out of the total area of the northern part (157 km^2), 59 km^2 is the area available for groundwater recharge. The total area of the central part is 114 km^2, however only 6 km^2 is suitable for groundwater recharge, and of the total area of 55 km^2 in the southern part, groundwater recharge area is 21 km^2. Hence total recharge area of the Kathmandu

Valley is around 86 km^2 (Dixit & Upadhya (2005). In another study by Pandey *et al.* (2010), the aquifer area for the Kathmandu Valley was quantified using GIS layers, giving a net area of 241 km^2. GWRDB (2012) estimates that the groundwater basin of the Kathmandu Valley covers 327 km^2, which is approximately 50% of the total watershed area (650 km^2). For this current study, the latest groundwater basin area estimation by GWRDB (2012) was used (i.e. 327 km^2).

Groundwater recharge from precipitation (P). GWRDB (2012) used precipitation data from the Department of Hydrology and Meteorology (DHM) and estimated that the 34-year average annual rainfall for the Kathmandu Valley is 1,784 mm. With a valley area of 650 km^2, the amount of groundwater recharge from rainfall was estimated to be 1,159.6 MCM per year.

Groundwater recharge from irrigation return flows (Ir). The Department of Irrigation (DoI) estimates that the total irrigated command area in the Kathmandu Valley is 9,120 ha (DoI, 2007). Based on the agricultural activity in the Kathmandu Valley, the GWRDB (2012) estimated that 23.61 MCM per annum was consumed by the crops out of which the return flows due to irrigation water was computed to be 20% (i.e. 4.7 MCM per annum).

Groundwater recharge from transmission losses (Sr). The GWRDB (2012) estimated that 35–40% of the total water supply of KUKL (66.43 MCM) is lost to the groundwater aquifer (26.6 MCM) due to transmission losses, especially due to leakage in the transmission pipes.

Total groundwater draft (GD)

Groundwater extraction from deep aquifer (*De*): GWRDB (2012), from their well inventory study in Kathmandu Valley, indicate that there are 759 deep tube wells in the region, with a total groundwater extraction by private (hotels, industries, companies and housing companies) and community tube wells (organizations, offices, etc.) in the order of 31.15 MCM. In addition, using the water budget report by the Kathmandu Valley Water Supply Management Board (KVWSM, 2010), the annual groundwater extraction by NWSC and KUKL wells in Kathmandu Valley (used for water supply in the region) was estimated to be 38.29 MCM. This shows that the annual extraction of deep aquifer groundwater from the Kathmandu Valley was 69.4 MCM in 2012 (Table 3).

Groundwater extraction from shallow aquifer (*Se*): A huge gap between demand and municipal water supply still prevails in the region, which has given rise to the private water sector. These private players satisfied most of the water demand for the Kathmandu Valley by sourcing water mainly from the groundwater sources such as tube wells and natural spring sources found in and around the Kathmandu Valley region. Water is transported from these sources by vehicles ranging from 2,000 liters (using pickup trucks) to 12,000 liters (using water tankers). Since there are good profit margins in this business, there has been a sharp increase in the number of private water suppliers and private tube wells tapping in to the local aquifers. In a recent study on the water market in the valley, Shrestha & Shukla (2010) indicate that on average 25.5 and 8.5 MLD of water were sold in the market during dry and wet seasons, respectively, during the year 2009. It was also noted that the shallow aquifer was used for extraction of this water. In order to close the groundwater balance, GWRDB (2012) had to estimate the volume of water supplied by the private sector. However, since there is a paucity of data on private water supply, GWRDB (2012) assumed that 50% of the supply gap was supplied by the private sector. For

Table 3. Water balance computation for Kathmandu Valley (*Source*: GWRDB, 2012).

Sl. No.	Water balance component	Water volume (MCM)
Input to the system		
1	Precipitation (*P*)	1,159.6
2	Irrigation return flow (*Ir*)	4.7
3	Water supply return flow (*Sr*)	26.6
Output from the system		
1	Evapotranspiration (*ET*)	521.3
2	Groundwater Draft (*GD*)	
	a. Deep Aquifer (*De*)	69.4
	b. Shallow Aquifer (*Se*)	58.8
	c. Stone Spout (*St*)	2.1
3	Irrigation Water (*I*)	23.6
4	Loss to Deep Aquifer (*GL*)	5.7
5	Baseflow (*Q*)	529.4
Groundwater storage change		−19.4

the year 2012, the supply gap was 61.32 MCM and hence GWRDB (2012) assumed that 50% of this deficit was met by groundwater from shallow aquifer, totaling 30.66 MCM of water extraction from shallow aquifers. In addition to this, KUKL also used shallow wells to supply 28.44 MCM of water, thus bringing the total water extracted in the shallow aquifer to 58.8 MCM (Table 3).

Groundwater extraction from stone spouts (*St*): It is noted that stone spouts, traditional water supply schemes, still supply the water needs of the valley citizens in regions where KUKL water supply is limited. GWRDB (2012) reports that 103, 43 and 78 stone spouts are located in Kathmandu, Lalitpur and Bhaktapur, respectively, thus totaling 224 stone spouts for the Kathmandu Valley. In Kathmandu most of the stone spouts have dried up, while 37 spouts are perennial in Lalitpur and only 27 are currently operational in Bhaktapur. From the district reports on spout discharge (ICON *et al*., 2002), GWRDB (2012) estimated that the average discharge from these stone spouts is 2.1 MCM annually.

Groundwater loss to deep aquifer (*GL*): Studies in the past have utilised various calculations on the volume of groundwater loss to deep aquifer in the Kathmandu Valley. It is noted that recent scientific studies on this topic have been limited. For the purpose of this study the critical recharge is calculated on the basis of latest report published by JICA in 1993 (JICA, 1993). According to this report, the annual groundwater loss to deep aquifer recharge is 5.7 MCM per year.

Baseflow discharge and evapotranspiration (*Q* and *ET*): GWRDB (2012), using discharge data from DHM (Khokana Station installed by DHM, station Index No. 550.05), estimated the average annual baseflow discharge of the Baghmati River to be 529.44 MCM per annum. Using evapotranspiration (*ET*) data from DHM, the annual average *ET* was estimated to be 521.3 MCM.

Using the results from the aforementioned subsections, the groundwater balance was estimated by GWRDB (2012) as shown in Table 3, with an annual deficit of 19.4 MCM.

From the aforementioned results, the GWRDB (2012) indicates a net water deficit of 19.4 MCM for the 2012 year in the Kathmandu Valley. These results were in agreement with previous studies, for example, Kansakar in 1996 estimated a deficit of 12.6 MCM, while HYM Consult (1997) estimated a deficit of 22.71 MCM in year 1993. The aforementioned results all collectively show that the aquifer in the Kathmandu Valley has been constantly under stress due to over-extraction activities. Such activities may not be sustainable in the long term, and could cause high socio-economic stress (Chinnasamy & Agoramoorthy 2015, Chinnasamy & Prathapar 2016).

Long-term groundwater level trend

The previous section indicated that there is over-extraction of groundwater in the basin. The current study analyzed long-term groundwater level trends to assess the groundwater depletion in the regions that supply water for Kathmandu. Long-term groundwater level data from years 2001 to 2013 in four wells were used for this purpose. For the purpose of orientation, within the Kathmandu Valley, the observation well M1 (Figure 6(a)) is located in Kirtipur at the south, the observation well M4 (Figure 6(b)) is located in Lubhu at the south east, the observation well M11 (Figure 6(c)) is located in Danchhi and the observation well M14 (Figure 6(d)) is located in Mulpani at the north. It is noted that the Mulpani region lies in the recharge area of deep aquifer of the valley. In addition, it is noted that for most cases the water level data for the years 2005–2007 and 2009 were not available.

Long-term groundwater trend results indicate that all wells have a net decline in groundwater levels (Figure 6(a)–6(d)). The observation well in Lubhu (Lalitpur) recorded the greatest decline of 1.27 m per year. The observation wells at Mulpani and Kirtipur recorded groundwater decline of 0.46 and 0.34 m per year, respectively. The observation well in Danchhi recorded the least decline with a rate of 0.06 m per year.

It is also noted that, records from the well fields of the NWSC in the deep aquifer have shown a drawdown of the surface by 15–20 m since the construction of the wells in 1984/85 indicating substantial over-exploitation. Both static and pumping water level have been depleted in most parts of the Kathmandu Valley. This trend is verified by the water level hydrographs from GWRDB monitoring wells across the valley. Data from 2001 to 2014, which indicate a decline in water level by 2 m in Kirtipur, 10 m in Lubhu, 3 m in Mulpani and 10 m in Koteshwor.

The overall analysis shows that the decline in water level is not occurring in some isolated part of the valley but in the whole of the Kathmandu Valley. In addition, it is reported that there are about 103, 43 and 78 numbers of stone spouts in Kathmandu, Lalitpur and Bhaktapur, respectively. In Kathmandu most of the stone spouts are dried up. Out of 78 stone spouts in Bhaktapur, only 27 are operational. The drying of these spouts and the lowering of water levels in the observation wells indicate that the decline of water level is taking place in both shallow and deep aquifers.

Groundwater storage volume assessment

As performed in India in a similar geological setting, the water table fluctuation method was used to assess the groundwater storage volume in the basin (CGWB, 2015). According to this method, the groundwater storage volume (GW) due to change (Δ) in groundwater level (GL) is assessed as follows (Equation (4)):

$$GW = \Delta GL * S_y * A \tag{4}$$

where GW is in cubic meters (m^3), ΔGL is in meters (m), S_y is the specific yield – a hydrologic parameter of the aquifer (unitless) and A is the area of the aquifer in meters squared (m^2). Pandey *et al.* (2010)

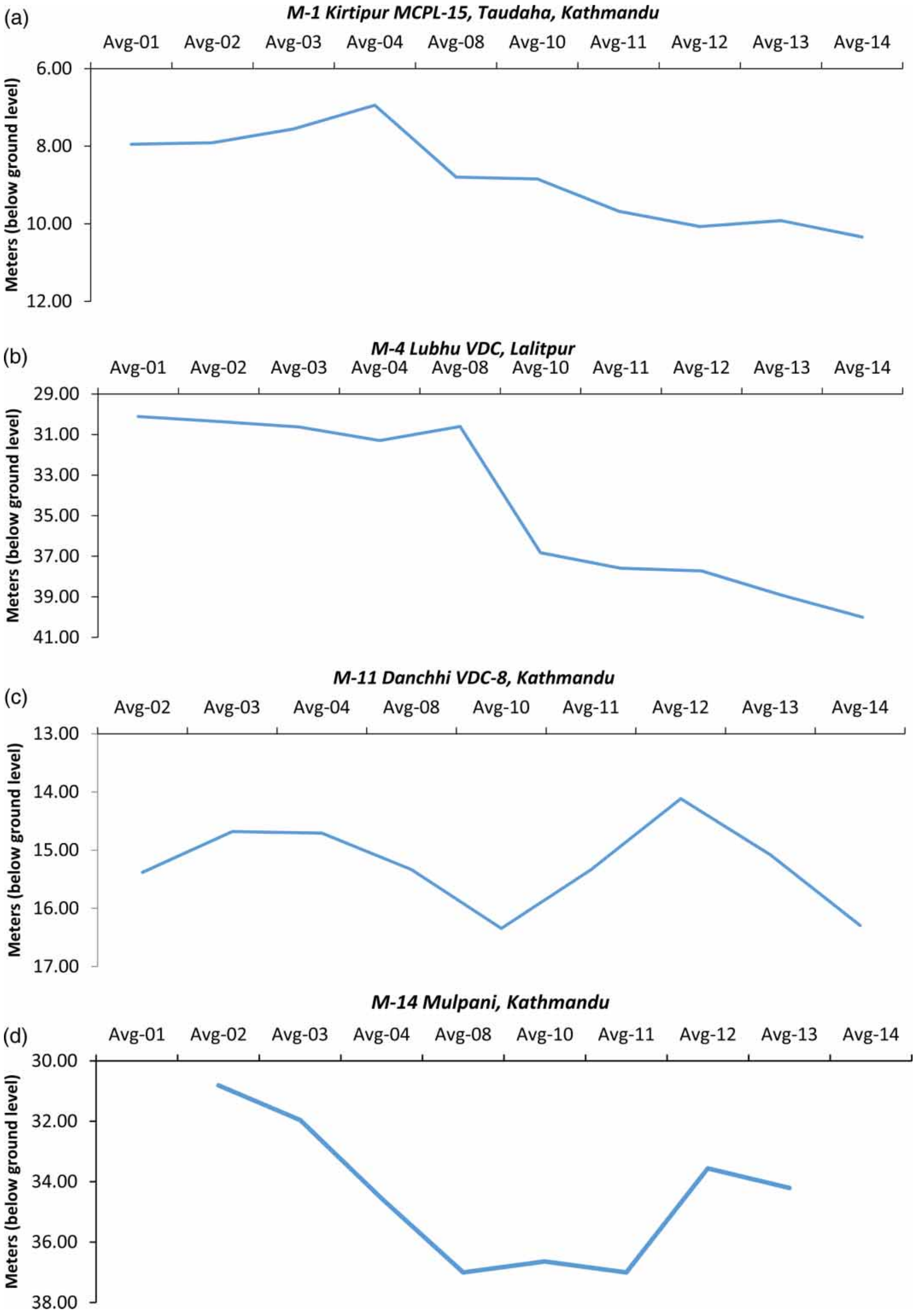

Fig. 6. Long-term groundwater trends for selected observation wells in the Kathmandu Valley: (a) Kirtipur, (b) Lubhu, (c) Danchhi and (d) Mulpani.

reported that the specific yield of the shallow aquifers for the Kathmandu Valley was 0.2, while GWRDB (2012) estimated the area of the aquifer to be 327 km^2 with an average ΔGL of 3.76 m over the study period from 2001 to 2014 (using the four observed wells). Using these values in Equation (4), it was estimated that the current depletion in the groundwater aquifers of the Kathmandu Valley can store an average of 246 MCM. Since the unmet demand in the valley is 168 MLD (Table 1), this groundwater storage volume can easily aid in easing the water stress for the Kathmandu Valley. In addition, groundwater storage can be recharged during the wet season wherein excess water can be diverted to recharge structures, while water can be pumped from this source during the dry season. It is noted that all the recharge water need not come from the MWSP scheme alone as there is enough excess water that leaves this basin during the wet season (Chinnasamy *et al.*, 2015; Chinnasamy, 2016b). It can be noted that the 246 MCM volume was based on the groundwater depletion over the study period (2001–2014) and hence the annual unmet demand of 61 MCM (equivalent of 168 MLD) can be eased even at annual timescales if the groundwater resources are recharge sustainably.

Economic benefits

The current MWSP scheme is reported to supply an additional 170 MLD for the Kathmandu Valley. However, this supply volume is still less than the unmet demand in the region when the aforementioned groundwater storage is not taken into account (Table 1). In the event that excess water is being diverted to the groundwater recharge structures in the Kathmandu Valley, it is assumed that all water harvesting structures will be filled up with water during excess flow regimes. This is because the Kathmandu Valley basin is not a water deficit basin, especially during wet seasons, but a basin suffering from unmet water demands due to lack of water management initiatives (Chinnasamy *et al.*, 2015). There is tremendous flow in the basin during wet seasons, while the dry seasons have low flow. Therefore, while all the water demands are met in the basin during wet seasons, there are huge unmet demands during the dry seasons. According to Chinnasamy *et al.* (2015), the Koshi basin, which contains the Kathmandu Valley, generates 8,262 MCM of surface runoff water annually with 7,368 MCM during the wet season (90% of total annual flow). The study also noted that the current unmet demand was only 660 MCM, and hence storing/diverting excess water would be an economically profitable method to ease water stress.

If proper management plans are laid, wherein the MWSP supply scheme also channels excess water to the recharge zones of the basin, the current groundwater storage depletion can be filled. Under this trend, a total volume of 246 MCM of water can be stored in the groundwater reserves in the valley during the wet season. This water can then be pumped and supplied to the public at a fraction of the cost that tankers charge during dry season. As per the previous sections, during the dry season, on average, water is sold by private agencies at 0.17 NRs per liter, and 0.009 NRs by the government agencies (Table 2). Even securing this water is very tough due to long wait lines, and fuel shortages for supply vehicles. Therefore, assuming that 246 MCM can be stored in the groundwater reserves and that the government agencies ration this water under their current tariff, groundwater storage can save up to 2.2 billion NRs for the valley during the dry season, and also regulate the supply of water throughout the dry season. In addition to the costs, the time that women spend collecting water can be greatly reduced, thus improving their quality of life, and the excess water can be used for better sanitation facilities. With proper management plans and institutional policy amendments, the excess water can be used to recharge the groundwater storage stores in the Kathmandu Valley.

Discussion

Earlier studies indicated that the groundwater extraction came into existence in the Kathmandu Valley from 1970s, with initial extraction less than 0.04 MCM per year. The impact of this extraction was minimal on the groundwater status, but by the 1980s the extraction was 3.51 and 12.3 MCM per year during 1982 and 1987, respectively. This extraction caused visible impacts on the groundwater levels with a slight decline in groundwater levels. From the 1990s haphazard pumping caused significant impact on groundwater levels. The pumping rates were 18.7 and 21.26 MCM in 1993 and 1999, respectively (Kharel *et al.*, 1998; Metcalf & Eddy, 2000; Pandey *et al.*, 2010).

Comparing the groundwater levels between 2013 and 1984, a drastic decline in groundwater level in the deep aquifers was inferred, some aquifer depletion rates ranging from 1 to 4 m per year. It was also inferred that most of the regions impacted by high groundwater level decline were in or near regions with high groundwater abstraction rates, especially the northern–northeastern parts of the Kathmandu Valley. In other studies, failure of deep wells, dug wells and dhunge dharas (traditional stone water spouts) due to the over-extraction have been reported across the valley. Systems dependent on shallow aquifers, namely dug wells, dhunge dharas and ponds were failing mostly due to inadequate water for recharge. It is noted that wells in the older parts of the town, e.g. Patan sub-metropolis, have survived as the rate of increase in urbanization activities is less (Shrestha, 2009; GWRDB, 2012). Another common report is the drying up of newly drilled bore and deep wells, which gave water for a short period from stagnant storage, but eventually failed due to falling groundwater levels.

It is noted by many studies that the increasing water demand for the Kathmandu Valley population cannot be solely satisfied by current or proposed water supply schemes by the federal agencies and from municipal corporations (Cresswell *et al.*, 2001; Dixit & Upadhya, 2005; Pattanayak *et al.*, 2005; Shrestha, 2012). The inadequate and inefficient supply systems of municipal corporations have led the population at large to supplement their water supply by tapping into traditional water sources, i.e., stone spouts (Shrestha, 2009; Shrestha *et al.*, 2013). Unfortunately many stone spouts are now converted into temporary waste dumps that require proper rehabilitation.

Future directions

First and foremost, as noted in the review sections, there are many inconsistencies in assessing the properties of the aquifers and data on water demand and supply. Therefore, future studies should aim to collect and archive quality data that can be used to accurately estimate water demand and supply in the region. Such initiatives should be undertaken by federal agencies that have a large stake in water supply and management in the valley.

Chapagain (2014) notes that the unplanned and unregulated urbanization in the Kathmandu Valley has been the primary reason for inadequate water supply in the region. As a result, Chapagain (2014) urges the federal agencies to consider water supply schemes while undertaking urbanization plans. However there exist many challenges in increasing groundwater recharge by using present water recharge structures, mostly related to anthropogenic activities (Dixit & Upadhya, 2005). Results from this study will aid in sensitizing ongoing groundwater issues in the Kathmandu Valley to the government officials and general public. With such knowledge, the strategic distribution of Melamchi water can aid in easing water stress and also aid indirectly by increasing groundwater reserves which will ease dry season water stress.

With the MWSP it is assumed that better channeling of water will occur due to improved infrastructure in water transmission lines. Therefore, there is a school of thought that with the MWSP water supply scheme, the water leakage during transmission will be lower than the current rate of 35–40%, and as a result the amount of water indirectly recharged to the aquifer would be less under the MWSP scheme. While the new MWSP infrastructure would indeed cut transmission losses, the possibility for channelizing excess water from MWSP and seasonal rainfall would be high. As a result, there will be more water to directly induce more recharge to the aquifers. Future studies should therefore attempt to quantify any change in groundwater recharge due to the MWSP scheme. Groundwater simulation models, e.g. MODFLOW, can be used to use these estimated changes in groundwater recharge to assess the distribution of groundwater volume across the basin (Chinnasamy, 2012; Chinnasamy & Hubbart, 2014a, 2014b).

Udmale *et al.* (2016) estimated the water deficit (demand – supply) in a recent study and found that even with the completion of the MWSP, there would be a deficit of 102 MLD for the Kathmandu Valley. In addition, they note that if the MWSP is completed in time, along with other water harvesting methods, especially treatment and distribution infrastructure, the water deficit can be eliminated by 2025.

Future studies should concentrate more on the fact that the MWSP alone cannot solve the water crisis for Kathmandu Valley (Laia *et al.*, 2013), but a more proactive hydraulic and water accounting models, such as Water Evaluation and Planning (WEAP) (Chinnasamy *et al.*, 2015) can be used to assess optimum conditions to release water to recharge structures within the MWSP plan, thereby not affecting downstream water users. In addition, scientifically validated decision support tools (DSTs) should be developed specifically for the region to augment sustainable and conjunctive use of surface and groundwater resources for the domestic supply of the ever-growing Kathmandu Valley. Furthermore, various scenarios should be analyzed using the developed DSTs, to increase the efficiency of water conservation and management efforts. Conjunctive use of surface and groundwater resources, increasing groundwater recharge rates by using MWSP and introduction of rainwater harvesting structures are key to having no water deficit by 2023.

Conclusion

Preliminary results from the current study indicate that the groundwater of the valley is being consumed at unsustainable rates, thus leading to widespread groundwater depletion. Due to this depletion, it was estimated that a groundwater storage of 246 MCM has been created. If this storage is recharged by excess runoff in the wet season, the stored water can easily satisfy the ongoing domestic water deficit of 178 MCM per annum. The timely implementation of the MWSP can aid in easing the ongoing water stress and can aid in reversing the damage caused to groundwater storage due to the delay of the project if appropriate infrastructure are planned that can harvest excess surface runoff during the monsoon months. Therefore, in the long run, MWSP water can supply water and recharge groundwater during the monsoon period, and groundwater resources can ease supply stress during the dry seasons, thus improving quality of life and socio-economic status in Kathmandu. Such a conjunctive use scenario will aid in improving the livelihood for the citizens of Kathmandu Valley.

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