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Evaluation of groundwater environment of Kathmandu Valley

Vishnu Prasad Pandey · Saroj Kumar Chapagain · Futaba Kazama

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Abstract Kathmandu Valley aquifer in central Nepal is continuously under stress since the commencement of mechanized extraction of groundwater resources in early 1970s. Many wells have been drilled in shallow and deep aquifers of the valley; and numerous studies have been made in last four decades to understand the aquifers. However, up-to-date information on well inventory, water extraction, water quality and overall situation of groundwater environment are not yet known in the absence of institutional responsibility in groundwater management. This study attempts to evaluate current state of the groundwater environment considering natural and social system together; to better understand origin of stresses, their state, expected impact and responses made/needed to restore healthy groundwater environment. The analysis reveals increasing population density (3,150–4,680 persons/km^2), urbanization (increase in urban population from 0.61 to 1.29 million) and increasing number of hotels due to tourism (23–62 hotels) during a decade are acting as driving forces to exceed groundwater extraction over recharge (extraction = 21.56 and recharge = 9.6 million-cubic meter-a-year), decrease in groundwater levels (13–33 m during 1980–2000 and 1.38–7.5 m during 2000–2008), decline in well yield (4.97–36.17 l/s during mid-1980s to 1998) and deterioration in water quality. In the absence of immediate management intervention with institutional responsibility for groundwater development, regulation and knowledgebase management (i.e. to facilitate collection, integration and dissemination of knowledge); situation of groundwater environment are expected to deteriorate further. Groundwater modeling approach may help to suggest appropriate management intervention under current and expected future conditions.

Keywords DPSIR · Groundwater environment · Groundwater level · Kathmandu Valley · Recharge

V. P. Pandey (✉) · S. K. Chapagain
Department of Eco-Social System Engineering, Kazama Lab, University of Yamanashi, 4-3-11, Takeda, Kofu, Yamanashi 400-8511, Japan
e-mail: g07dea03@yamanashi.ac.jp; e_vishnupandey@yahoo.com

S. K. Chapagain
e-mail: sarojchapagain@yahoo.com

F. Kazama
Department of Eco-Social System Engineering, University of Yamanashi, 4-3-11, Takeda, Kofu, Yamanashi 400-8511, Japan
e-mail: kfutaba@yamanashi.ac.jp

Introduction

Surface water is inadequate to meet municipal water supply in Kathmandu Valley, in the context of steadily increasing water demand brought by expansion of social system including urbanization. This has led water supply agencies, industries and private sectors to pump groundwater as a safe and reliable alternative since mid-1980s. After then, many wells have been drilled in the valley's aquifers in haphazard manner, taking the advantage of no institutional responsibility to monitor and regulate the groundwater environment. These wells are fulfilling almost 50% of the municipal water demand (Khatiwada et al. 2002) with estimated extraction of 59.06 million liters a day (MLD) (Metcalf & Eddy 2000) or 21.56 million cubic meters a year (MCM/year); which exceeds estimated recharge of 14.6 MCM/year (Binnie & Partners 1988), thus, revealing the case of groundwater mining. Under business as usual scenario, the valley's aquifer reserves are expected to be depleted in less than 100 years (Cresswell et al. 2001). Apart from increasing extraction, degradation in groundwater quality due to anthropogenic activities has reduced usability of groundwater in shallow aquifer, and therefore, pressure is increasing on deep aquifers with relatively good water quality. But, they are not recharged as quickly as shallow aquifers. So, there is urgent need of management intervention to restore healthy groundwater environment and use its resources in a sustainable way. However, there is no systematic and reliable information regarding wells statistics and their parameters (such as location, discharge, hydro-geology, etc.), quality of groundwater throughout the valley, current practice on groundwater use, aquifer storage potential, identification of recharge area and potential for its protection, interaction of society and aquifer resources and other groundwater development issues. This is partly because management of groundwater environment—as an important environment issue—has hardly been in the forefront of scientific and political discussions. As a result, adequate attentions have not been paid by the authorities on monitoring and regulation of groundwater development, and management and use of available knowledge scattered among different stakeholders (e.g. several government and non-government organizations, drilling contractors and individual scholars, etc.). Several studies were 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. 2006), and hydrogeology (e.g. Metcalf & Eddy 2000; Keshab 2003) of the valley's aquifers since early 1960s. But, those were focused particularly on possibilities of groundwater development rather than proper management; and have not shed light on analysis of groundwater environment considering both natural and social system together. In such a context, attempts are made for developing a systematic knowledgebase of the Kathmandu Valley's groundwater environment by separating Drivers, Pressures, State, Impact and Response (DPSIR) and analyzing their extent and interrelationships. The result would be useful for all the stakeholders including policymakers to understand the extent of situation and would serve as a basis in decision making for sustainable management of the valley's groundwater resources.

Materials and methods

Study area

Kathmandu Valley's groundwater basin is elevated at 1,340 m above the mean sea level. It covers 327 km^2 of 664 km^2 surface watershed areas in the central Nepal (Fig. 1). The valley, characterized by a warm and temperate climate in semi-tropics, receives 80% of 1,755 mm annual rainfall during monsoon (June–September) (Acres International 2004). Water resources are derived from surface and groundwater sources. Groundwater is extracted from shallow and deep aquifers separated vertically by a thick clay layer (Fig. 2); which acts as a barrier for direct recharge of the deep aquifers throughout the valley. The clay layer is more than 200 m thick in the central part and gradually decreases towards the edges; and diminishes to zero in some area towards north and southeastern part of the valley (Metcalf & Eddy 2000). Those areas serve as rechargeable areas for the valley's deep aquifer. Along with clay, distribution of shallow and deep aquifer layers is also irregular with discontinuities occurring vertically and horizontally. The aquifer materials consist 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). Transmissivity (*T*) varies between 120 and 1,350 m^2/day per m in the Nepal Water Supply Corporation (NWSC) well-fields (Binnie & Partners 1988). Relatively wide range of *T* suggests some degree of heterogeneity in sedimentary make-up of the aquifers; which corresponds to significant differences in hydraulic conductivity and thickness of water-bearing sediments.

Collectively, the greatest portions of aquifer units occur within northern and northeastern areas of the valley; and are exploited largely by the NWSC through six well-fields (as shown in Fig. 1) and to a lesser extent by private wells. Industries and private sectors are using deep aquifer mainly in central part of the valley.

Methodology

The methodology consists collection of published/unpublished reports, papers, data and information related to the groundwater resources in Kathmandu Valley and analyze them under an established framework (Fig. 3a). An indicator-based approach has been adopted to evaluate groundwater environment of the valley. A set of indicators that reflects the valley's groundwater environment were selected from the literature review. The indicators were structured and analyzed under DPSIR framework developed by Organization for Economic Co-operation and Development (OECD). The DPSIR framework (Fig. 3b) serves as a communication tool between researchers from different disciplines, policy makers and entire stakeholders sharing the aquifer resources. The components in the framework are related by a logic relation: *Drivers* generate pressure,

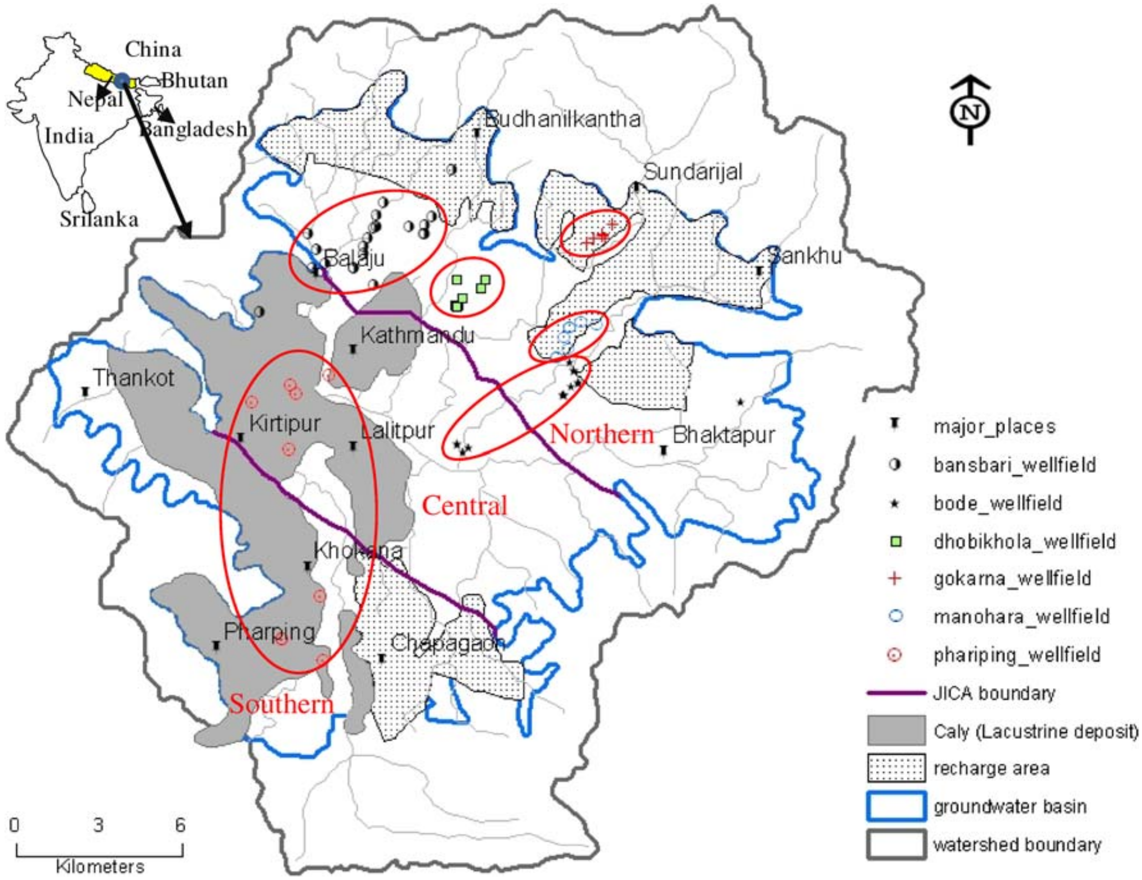


Fig. 1 Surface watersheds, groundwater basin, recharge areas and NWSC well-fields in Kathmandu Valley aquifer (Sources: groundwater basin boundary and recharge area (JICA 1990), clay deposit (Jha et al. 1997))

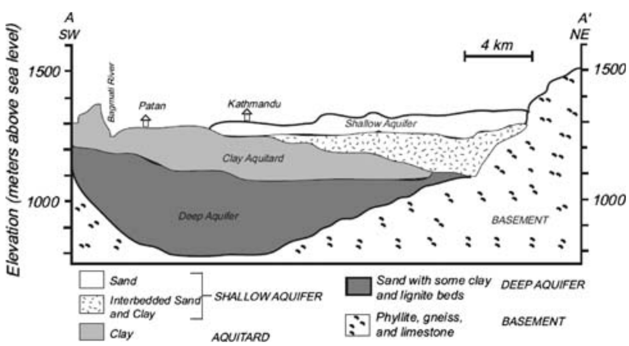


Fig. 2 Kathmandu Valley's aquifers in geological cross-sectional view (Source: Warner et al. 2008)

Pressure influence/modify state, *State* provoke or cause impacts, *Impacts* stimulate or ask for responses, and *Responses* modify or substitute drivers, eliminate/reduce/prevent pressures, restore/influence state and compensate or mitigate impacts.

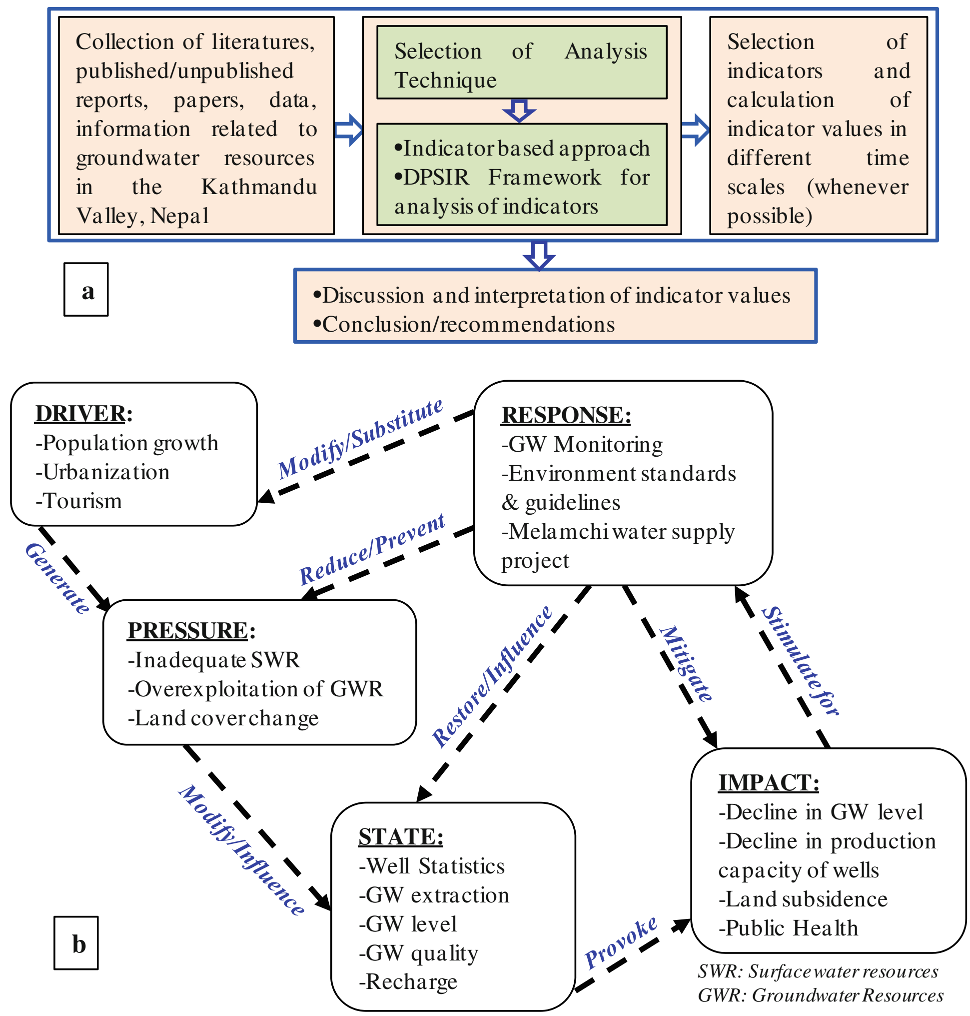
Drivers refer to fundamental processes in a society which drive activities having a direct impact on the groundwater environment. Population growth, of course, is a primary driver which drives water-intensive activities. In addition, urbanization in the valley and tourism are two other drivers generating pressure on the groundwater environment. Tourism is a key component of the valley's economy. Three indicators—population growth, urbanization and tourism—are considered as drivers in this context.

Pressures are referred as direct stresses brought by expansion in anthropogenic system and associated interventions in the natural environment. Three indicators—inadequate surface water resources, overexploitation of groundwater resources and land cover change—are considered as pressures.

State describes the condition and tendencies in the groundwater environment and its trend induced mainly by human activities. Five indicators—well statistics, groundwater extraction, level, quality and recharge—are considered to discuss the state of groundwater environment.

Impacts deal with effects on the anthropogenic system and on the environment itself due to changes in the state of natural environment, and contribute to the vulnerability of both natural and social system. However, the vulnerability to change varies between different systems depending on their geographic, economic, and social conditions; exposure to change, and capacity to mitigate or adapt to the change. Decline in groundwater level, decline in

Fig. 3 Methodology (**a**) and DPSIR framework (**b**) to analyze Kathmandu Valley's groundwater environment



production capacity of wells, land subsidence and public health are considered as indicators of impact.

Response consists of action of the anthropogenic system to modify/substitute the drivers, to reduce/prevent pressure, to restore/influence state and mitigate/reduce the impact. Responses address issues of vulnerability of both people and the environment, and provide opportunities for enhancing human well-being by means of sustainable use of groundwater resources. Three indicators—groundwater monitoring, environment standard and guidelines, and Melamchi water supply project—are discussed from the perspective of response to address the issues.

Results and discussions

Driver

Population growth, urbanization and increase in tourism are main drivers exerting pressures on the valley's groundwater environment. Expansion in population reduces per capita water availability and increases water demand. Urbanization, on the other hand, refer to more water-intensive life-style, decrease in rechargeable areas and increase in pollution of groundwater. All these factors reflect to more pressure on the groundwater environment. And, expansion in tourism industry is the primary reason for increasing number of hotels in the valley. Those hotels are extracting groundwater as a reliable source to meet their high water demand. Hotels are the second largest group of groundwater consumer and consume 13.94% of total groundwater extraction (Table 3).

Population expansion

Kathmandu Valley has been the center of administration, economy, education and politics since a long ago. As a result, population is ever increasing mainly by migration. During 1991–2001, valley's population has increased from 1.08 to 1.59 million within surface watershed; and from 1.03 to 1.53 million within the groundwater basin (Table 1). Corresponding increase in population density

Table 1 Summary of driver, pressure, state, impact and response indicators in 1991 and 2001

Indicators	1991	2001
Driver		
Population growth within GW basin (area: 327 km^2)[a]	Population: 1.03×10^6	1.53×10^6
	Population density: ~3,150 person/km^2	~4,690 person/km^2
	Annual growth rate during 1991–2001[b]:	3.96%
Urbanization within GW basin	Urban area[c]: 31.0 km^2 in 1984	97.5 km^2 in 2000
	Urban population[a]: 0.61×10^6	1.29×10^6
Increase in tourism	Tourists arrival[e]: 0.29×10^6 (in 1991)	0.56×10^6 (in 2007)[f]
	Number of hotel wells[c]: 23 (until 1991)	62 (1999–2000)
Pressure		
Inadequate surface water resources	Expansion in social system, urbanization, rising economic activities and quality of life are water intensive; that has reduced per capita surface water availability	
Land cover change (1984–2000)[c]	Urban area: 31.0 km^2	Urban area: 97.5 km^2
	Non-agricultural area: 35.7 km^2	Non-agricultural area: 184.1 km^2
Over-extraction of GW resources	Extraction[d]: 40 MLD (or 14.6 MCM/year)	Extraction[c]: 59.06 MLD (or 21.56 MCM/year)
	Recharge: 9.6 MCM/year (Table 6)	Recharge: 9.6 MCM/year (Table 6)
State		
Well statistics	Total wells[d]: 115 numbers	Total[c]: 386, production well: 249, Abandoned wells >00
GW extraction	Extraction[d]: 40 MLD (or 14.6 MCM/year)	Extraction[c]: 59.06 MLD (or 21.56 MCM/year)
	Recharge: 9.6 MCM/year (Table 6)	Recharge: 9.6 MCM/year (Table 6)
	Rainfall: 1,755 mm/year = 150.93 MCM/year (at 86 km^2 recharge area)	Rainfall: 1,755 mm/year = 150.93 MCM/year (at 86 km^2 recharge area)
GW level	Shallower towards southern part, decreasing towards NW–SE and W–E direction. In general, water level rise from June/July and declines from November/December	
GW quality	Shallow is characterized by coliform bacteria, high manganese, iron, locally nitrate and BOD; and deep by high iron (1–3 mg/l), manganese (0.02–0.42 mg/l), BOD, arsenic and dissolved gases such as ammonia (1.05–6.5 mg/l) and methane. EC, NH_4-N and arsenic increases from north towards the central area	
Recharge	4.61–14.6 MCM/year (Table 6), average value = 9.6 MCM/year	4.61–14.6 MCM/year (Table 6), average value = 9.6 MCM/year
Impact		
Decline in GW level	13–33 m during mid-1980s–2000 in northern area[d]	1.38–7.5 m during 2000–2008 in the NWSC well-fields
Decline in production capacity of wells (l/s)	Decline during mid-1980s–2000: 7.89 in Dhobikhola, 4.97–36.17 in Bansbari, 19.10 in Gokarna, 31.31 in Bhaktapur/Bode, and 15.17–27.81 in Manohara	
Land subsidence	No monitoring and no evidence of land subsidence so far, but few studies have cautioned the possibility of land subsidence in areas with significant decline in water level and high percentage of compressible clay and silt in the subsoil	
Public health	GW fulfils 50% of the valley's water demand. However, its quality is under threat because of solid waste disposal and effluent discharge into rivers and open ground. Bacterial indicators, which cause water borne diseases, are already detected in the groundwater samples. And waterborne diseases have been the cause for 16.5% of total deaths in the Teku Hospital in the valley (cited in ICIMOD 2007, pp. 66)	

Table 1 continued

Indicators	1991	2001
Response		
GW monitoring	Monitoring was started since early 1970s, but was limited to the duration of a particular project only	Continuous monitoring since 1999 under the initiation of Metcalf & Eddy and later continued by GWRDP
Environmental standard and guideline	MoEST developed environmental standard guidelines through NBSM (2001, 2003); however, implementation remains poor in practice	
Melamchi Water Supply Project	The project is supposed to bring 510 MLD water from off-the-valley source in three stages, to fulfill valley's water demand until 2030, and expected to reduce pressure on GW	

MCM Million cubic meters, *GW* ground water, *EC* electrical conductivity, *MoEST* Ministry of Environment, Science & Technology

[a] Sub-district level data from Central Bureau of Statistics (CBS) of Nepal and author calculated for respective scales

[b] Exponential growth rate calculated using $r = (1/t) \times \ln(P_t/P_0)$; where P_t = population after 't' years from the base period, P_0 = base year population

[c] Acres International (2004)

[d] Metcalf & Eddy (2000)

[e] United Nations (1997)

[f] MTCA (2007)

within groundwater basin is 3,150–4,690 persons/km^2 (Table 1). Considering a case of 2001, with estimated groundwater extraction of 59.06 MLD (Table 1) and population of 1.53 million, per capita groundwater extraction becomes 38.6 l/capita per day. Thus, increase in 0.50 million people during 1991–2001 is equivalent to 19.3 MLD of groundwater extraction. It clearly shows how population expansion imposes pressure on the groundwater environment. Assuming a constant rate of extraction, 2.5 million people in 2020 (KVTDC 2002) would pump 96.5 MLD or 35.22 MCM/year of groundwater; thus, would exert more pressure on already stressed groundwater environment by means of increase in water demand and degradation in water quality.

Urbanization

Kathmandu Valley started to develop as an urban center after liberalization of Nepal in 1952. However, urbanization gained momentum only from early 1970s, when urban infrastructures (such as roads and water supply system) started to develop at a rapid rate. Taking advantage of weak planning and/or poor implementation of planning, urban areas are expanding in very haphazard and unplanned way, following *people–land–building–infrastructure* type of housing process (ICIMOD 2007). Urban population has increased from 0.61 (within 3 municipalities and 1 VDC) to 1.29 million (within 5 municipalities and 33 VDCs) from 1991 to 2001 (Table 1); which accounts respectively for 59.4% and 83.8% of total population in the groundwater basin. This has led to increase in urban areas from 31.0 to 97.5 km^2 during 1984–2000 (Table 2).

Table 2 Land covers change in the Kathmandu Valley (Acres International 2004)

Land cover type	Area at 1984		Area at 1996		Area at 2000	
	km^2	%	km^2	%	km^2	%
Agriculture	409.5	64.0	333.1	52.1	275.7	41.1
Forest	194.4	30.4	209.5	32.7	206.8	31.0
Non-agriculture	35.7	5.6	97.1	15.2	184.1	27.6
Total	639.6	100.0	639.6	100.0	666.6	100.0
Urban area	31.0	4.8	83.8	13.1	97.5	14.6

Considering water demand as 120 l per capita a day (lpcd) for urban area and 80 lpcd for rural areas (source: discussion with Kathmandu Upatyaka Khanepani Limited, KUKL, officials during field visit in August 2008), urban people use 40 lpcd more than rural people. So, 0.68 million increase in urban population during 1991–2001 is equivalent to 27.2 MLD water demand. Considering 50% of that comes from groundwater (Khatiwada et al. 2002), direct impact of urbanization would be equivalent to 13.6 MLD extraction of groundwater. The figure could be much higher if we consider high rate of migration towards the Kathmandu Valley during a decade-long civil-disorder in the country. However, there are no census data after 2001 to estimate pressure on groundwater resources due to urbanization from migration.

Apart from the increase in groundwater extraction, increase in volume of solid waste, their haphazard disposal and leachate from those sites contributes to degradation of groundwater quality. Reduction in permeable area as a result of increase in built-up areas apparently limits supply to the groundwater reserve. Combined effect of all these factors, related to urbanization, is increasing vulnerability of the valley's groundwater environment.

Tourism

Tourism arrival has increased from 0.29 to 0.56 million during 1991–2007 (Table 1). And, the Kathmandu Valley is the first destination for tourists because of its cultural, social and natural uniqueness. With the increase in tourism, hotels and restaurants are increasing. Considering a case of hotels, there are more than 100 hotels in the Kathmandu Valley (ranging from normal to star hotels) which are using groundwater to meet their relatively higher water demand. This study, with data from Acres International (2004), shows 57% of the hotels pump from shallow aquifer and 43% from deep aquifer. The average discharge from deep aquifer is 181 m^3/day (max ~864 and min ~10.8); and that from shallow aquifer is 27 m^3/day (max ~216 and min ~2.7) (calculated with data from Acres International 2004). If we further take average of groundwater extraction by hotels, it would become 93.3 m^3/day (max ~864 and min ~2.7) (calculated with data from Acres International 2004). This is direct pressure from expansion on tourism industry into groundwater resources.

Pressure

Pressures are referred as direct stresses brought by expansion in anthropogenic system and associated interventions in the natural environment. Pressure on valley's groundwater environment comes from inadequate surface water, over-exploitation of aquifer and decrease in rechargeable areas (i.e. limiting supply to the aquifers).

Inadequate surface water resources

Inadequate surface water to meet municipal water demand is a major source of pressure on the groundwater environment. Expansion in social system, urbanization, rising economic activities and quality of life are water intensive; that has reduced per capita surface water availability. At the same time, uncontrolled disposal of municipal waste on rivers and their flood plains due to lack of responsible management is rendering surface waters highly to excessively polluted (Hoffmann 1994; Khadka 1993). As a result, Nepal Water Supply Corporation (NWSC), an agency responsible for municipal water supply, introduced groundwater in their supply system since mid-1980s. Currently, the NWSC gets 36% of its dry season supply from groundwater (source: unpublished NWSC data of July 2008). However, municipal water supply are intermittent, poorly managed, often polluted, and level of service is inadequate. This has driven several industries, private sectors, institutions, numerous individuals and communities to supplement their water supply by pumping large quantities of groundwater. Lack of regulation on groundwater extraction has driven pressure on groundwater environment, and expected to aggravate further in coming years in the absence of management intervention.

Overexploitation of groundwater resources

After groundwater became accessible with affordable technology, different agencies in need of water (such as NWSC, hotels, industries, government and private institutions, hospitals, housing companies and individuals) continued to pump groundwater. But, no institutional responsibility was felt necessary to impose regulation on pumping. As a result, 59.06 MLD or 21.56 MCM/year of groundwater is being pumped from the valley's aquifers (Table 1); which exceeds recharge of 9.6 MCM/year (Table 4). These figures suggest valley's aquifers are already overexploited.

Land cover change (decrease in recharge areas)

Land cover of the Kathmandu Valley has changed towards non-agricultural type in last two decades. The non-agricultural area has increased from 5.6 to 27.6% during 1984–2000 (Table 2). Particularly, urban area has increased from 4.8 to 14.6%. In contrast, forest area of surrounding watersheds has decreased by 40% during 1955–1995 (Pradhan 2004). These data indicate recharge areas could have decreased along with the change in land cover, which affects adversely on supply to the groundwater reserve. In addition, conversion of rural land into urban has led to increased pumping in many areas, and more importantly, extensive pollution of both surface streams and shallow aquifer due to direct disposal of municipal solid waste and wastewater in rivers and their flood plains.

State

State describes the condition and tendencies in the groundwater environment and its trend as a result of pressure brought by drivers. This section analyses state of groundwater environment from the perspective of number of wells in shallow and deep aquifers, volume of groundwater extraction, groundwater levels, groundwater quality and annual recharge into the aquifers.

Well statistics

Deep wells were drilled in the valley probably for the first time in 1960 to study hydrogeology of the aquifers (Kharel

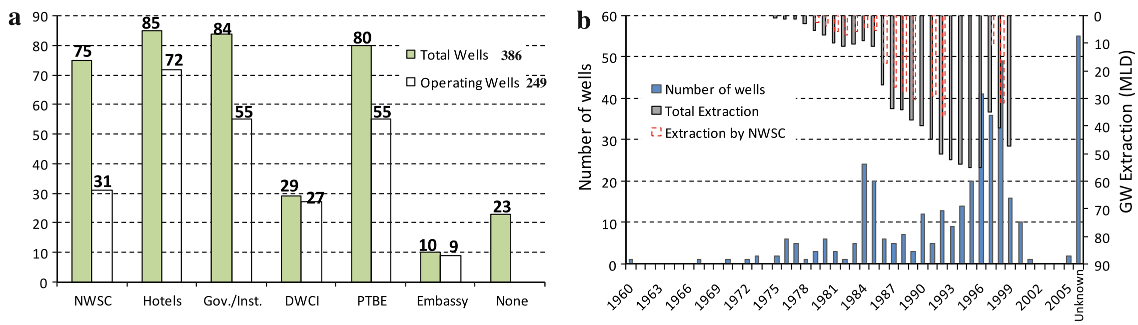


Fig. 4 Numbers of wells and their ownership (**a**); drilling of wells and GW extraction over time (**b**) (Data source: Acres International 2004 and Metcalf & Eddy 2000)

et al. 1998). More wells were drilled in 1963 under US Aid for the Department of Irrigation to investigate deep groundwater potential. During 1972–1980, investigation wells were drilled by Binnie & Partners under World Health Organization (WHO) grant. From early 1980s, private hotels and industries started to drill their own wells to meet escalating water demand, after municipal water supply became insufficient and irregular. Apart from hotels and industries, the NWSC also introduced groundwater into its water supply system from mid-1980s (Metcalf & Eddy 2000); and constructed additional wells to operate six well-fields (as shown in Fig. 1). After mid-1980s, many wells have been drilled by NWSC, hotels, government institutions, industries and private sectors. The trend shows majority of wells (225 numbers) were drilled during 1990–2000 to extract 40–55 MLD of groundwater (Fig. 4b). Currently, there are 386 wells (114 shallow, 222 deep and other dug wells) in the valley except shallow/dug wells drilled for individual purpose; however, only 249 are in operation (Fig. 4a). More than 100 abandoned wells could be a source of pollution to both shallow and deep aquifers.

Groundwater extraction

Groundwater was extracted for the first time in 1971. However, significant extraction was observed only after mid-1980s when the NWSC introduced groundwater in their water supply system. After then, valley's groundwater environment is continuously under pressure from increasing extraction; as shown by increasing extraction from the NWSC wells: 2.3 MLD in 1979, 5 MLD in 1985, 18 MLD in 1986, 26 MLD in 1987 (Binnie & Partners 1988) and 29.2 MLD in 1999 (Table 3). Until 1997, shallow aquifers were not much extracted by private sectors probably due to lack of affordable technology to drill in shallow depth. However, shallow aquifers are being widely used for private, domestic and industrial purpose in these days. Combined extraction from all types of wells (shallow, deep and dug wells) by the NWSC and private sectors is estimated at 59.06 MLD (Table 3) that fulfills 50% of the valley's water demand (Khatiwada et al. 2002). The NWSC has a major share in total groundwater extraction (Table 3), and fulfills 36% of its dry season supply from groundwater (source: unpublished NWSC data of July 2008).

Table 3 Estimated groundwater extraction from Kathmandu valley aquifer (Metcalf & Eddy 2000)

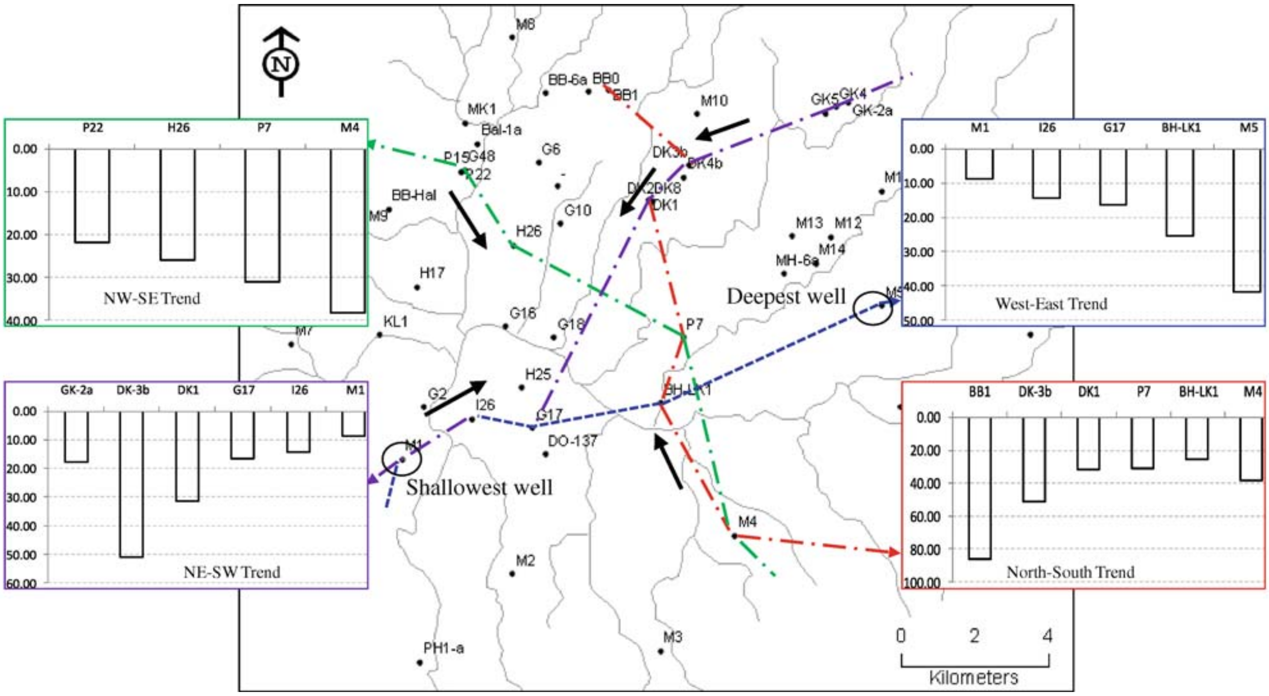
Owner	DTW (MLD)	STW (MLD)	DW (MLD)	Total (MLD)
NWSC	23.79	2.06	3.31	29.17
Hotel	5.50	0.90	0.12	6.53
PTBE	2.47	1.30	0.71	4.48
DWCI	0.07	0.32	0.19	0.58
Govt./inst.	5.22	0.41	0.03	5.67
Embassy	0.43	0.00	0.00	0.43
Total	37.49	5.00	4.37	46.86
Domestic and private use (bulk estimation)				13.20[a]
Total	37.49	5.00	4.37	59.06

DTW Deep tube well, *STW* shallow tube well, *DW* dug well, *PTBE* plastic, textile and bottler's enterprises, *DWCI* dying, washing and carpet industries, *Govt./inst.* government/institutions, *MLD* million liters a day

[a] 13.20 = 6.40 [52% of household (85,343) using hand pump, rower pump and dug wells and consume at 75 l/day] + 0.98 [6% of household (9,847) are using water vendor and consume at 100 l/day] + 1.50 [30 institutions and schools are using dug wells and shallow wells and consume at 50,000 l/day] + 2.22 [18% of household (29,541) using springs and spouts and consume at 75 l/day] + 2.10 [30 tankers with 7 trips a day at 1,000 l/trip]

Groundwater level

Reliable information on water level trend in shallow and deep aquifers is limited due to poorly spaced monitoring wells and discontinuity in monitoring. The data in 2006 show that static water levels are shallower towards southern part, decreasing towards NW–SE and W–E direction, decreasing from Gokarna to Dhobi Khola well-field and gradually increasing towards south-west in NE–SW direction; and general trend of groundwater flow is towards



Note: Static Water Level of M5 = (Graph value+60) mbgl.

Fig. 5 Static water level trend along different X-sections on pre-monsoon (May) of 2006 (Data source: Groundwater Research and Development Project/Department of Irrigation, Kathmandu, Nepal)

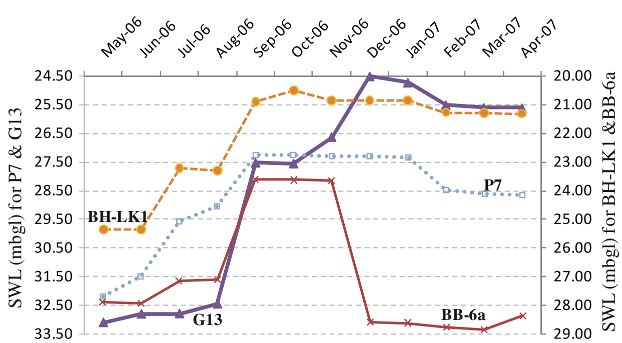


Fig. 6 Static water level hydrographs at selected wells (Data source: Groundwater Research and Development Project/Department of Irrigation, Kathmandu, Nepal)

the center of the basin (Fig. 5). The trend is similar in all the seasons (pre-monsoon, monsoon and post-monsoon). The deepest water level is observed on eastern (M5 well) and the shallowest on western (M1 well) part of the groundwater basin. Hydrographs of May 2006–April 2007 at selected wells in northern and central areas shows seasonal fluctuation (Fig. 6); that resembles recharging indication. In general, water level start rising from June/July and declines from November/December. The clear response of BB-6a well to rainfall is probably due to its location in the recent flood plain covered with sand and gravel.

Groundwater quality

Earlier studies have discussed variation in groundwater quality in shallow and deep aquifers (Jha et al. 1997; Kharel et al. 1998; Metcalf & Eddy 2000; Khadka 1993). Shallow aquifers are polluted by anthropogenic activities such as disposal of sewage, industrial effluents, leachate and infiltration from polluted streams; and are characterized by coliform bacteria, high concentration of manganese, iron, locally nitrate and BOD (De Zanger 2002). And, deep aquifers in central part of the basin are characterized by high concentrations of iron (1–3 mg/l), manganese (0.02–0.42 mg/l), BOD, arsenic and dissolved gases such as ammonia (1.05–6.5 mg/l) and methane (ENPHO 1999; Metcalf & Eddy 2000; Acres International 2004). The deep aquifer water quality is primarily influenced by sedimentary make-up of the aquifer which consists of fluvio-lacustrine deposits (of Pliocene-Quaternary period) intercalated with black clay, peat and lignite (Metcalf & Eddy 2000), and are rich in organic matters as reported in Fujii and Sakai (2001). Bacterial contamination in deep wells is probably due to poor design, installation and improper or no sealing of abandoned wells (Metcalf & Eddy 2000). Spatial variation in quality parameters as reported by Chapagain et al. (2007) shows electrical conductivity (EC) increases from north towards the central area, which is

Table 4 Calculation of annual rainfall, recharge and extraction to/from the valley's groundwater basin

Rainfall: Total annual rainfall in the valley = 1,755 mm (Acres International 2004)

Total rechargeable area in the groundwater basin: 86 km^2 (JICA 1990)

Rainfall within rechargeable area: (1,755/1,000) m × 86 × 10^6 m^2/year = 150.93 MCM (MCM: million cubic meters)

Recharge: Recharge from 86 km^2 rechargeable areas = 4.61 MCM (Gautam and Rao 1991)–14.6 MCM (Binnie & Partners 1988), average of these two estimates = 9.6 MCM/year

Extraction: Extraction from the valley's aquifers = 59.06 MLD (million liters a day) (Table 3) = (59.06 × 10^6/1,000) m^3 × 365 (per year) = 21.56 MCM/year

Table 5 Aquifer depletion at selected locations during the dry season (data source: water level monitoring data from Groundwater Research and Development Project/Department of Irrigation, Kathmandu, Nepal)

Location	WID	Previous water level (mbgl)		Current water level (mbgl)		Decline (m)
		Base year	SWL	Current year	SWL	
Bansbari WF	Bal-1a	2000	5.27	2008	10.85	5.58
	M8	2001	12.75	2008	14.52	1.77
Gokarna WF	GK-2a	1999	16.41	2008	23.91	7.50
	GK4	2000	16.60	2008	20.18	3.58
Dhobi Khola WF	DK1	1999	28.90	2008	30.73	1.83
	DK8	2001	3.89	2008	5.27	1.38
Manohara-Bhaktapur/Bode WF	BHK-1	1999	37.68	2006	42.00	4.32
	M5	2001	93.33	2008	98.87	5.54
Pharping WF	M1	2001	8.48	2008	8.85	0.37
Central area	I26	2000	7.37	2008	13.08	5.71
	G17	2000	10.68	2008	11.68	1.00

SWL Static water level, *WID* well identification number, *WF* well-field, *mbgl* meter below the ground level

related possibly to higher sediment–water interaction and poor groundwater recharge in central part of the valley. Ammonium-nitrogen (NH_4-N) and arsenic (As) also have similar trend. High NH_4-N in central part indicate reducing environment possibly due to decomposition of organic matter; which could be a reason for elevated levels of arsenic in those areas.

Recharge

Groundwater recharge is a complicated phenomenon, especially considering recharge into deep aquifers. The amount of precipitation is the primary factor; however, recharge depends on surface characteristics and hydrogeology as well. Kathmandu Valley receives large amount of precipitation (1,755 mm/year, Table 4); but aquifer recharge is limited by widely spread silty lacustrine deposits interbedded with impermeable black clay. This prevents easy access of percolating rainwater to the aquifers. Rechargeable areas are concentrated towards margins of the northern and southeastern part of the groundwater basin (Fig. 1) and cover 86 km^2 area (26% of 327 km^2 basin area) (Table 4). Major rechargeable areas are Tokha, Budhanilakantha, Sundarijal, Gokarna, Bansbari, Dhobikhola, Manohara, Sankhu, Tehecho, Chapagaon, Chunikhel, Bungmati, Sunakothi and Godavari. Earlier studies have estimated that recharge into the valley's deep aquifers varies within 4.61–14.6 MCM/year (Table 4), however, details of recharge system is not yet known. If we consider 9.6 MCM/year (the mean of 2 extreme estimates), the recharge is limited to 44.5% of estimated groundwater extraction and 6.4% of rainfall (values are shown in Table 4). These figures clearly show the case of groundwater mining. It also reveals the prospects for further research need to explore possibilities for storing remaining rainfall in the valley's aquifers.

Impact

Impacts deal with effects on the human system and on the environment itself due to changes in state of environment, and contribute to vulnerability of both natural and social systems. Adverse effect of overexploitation include depletion in groundwater reserves (water level and well yield), well failure and land subsidence; and that of poor water quality is related to public health.

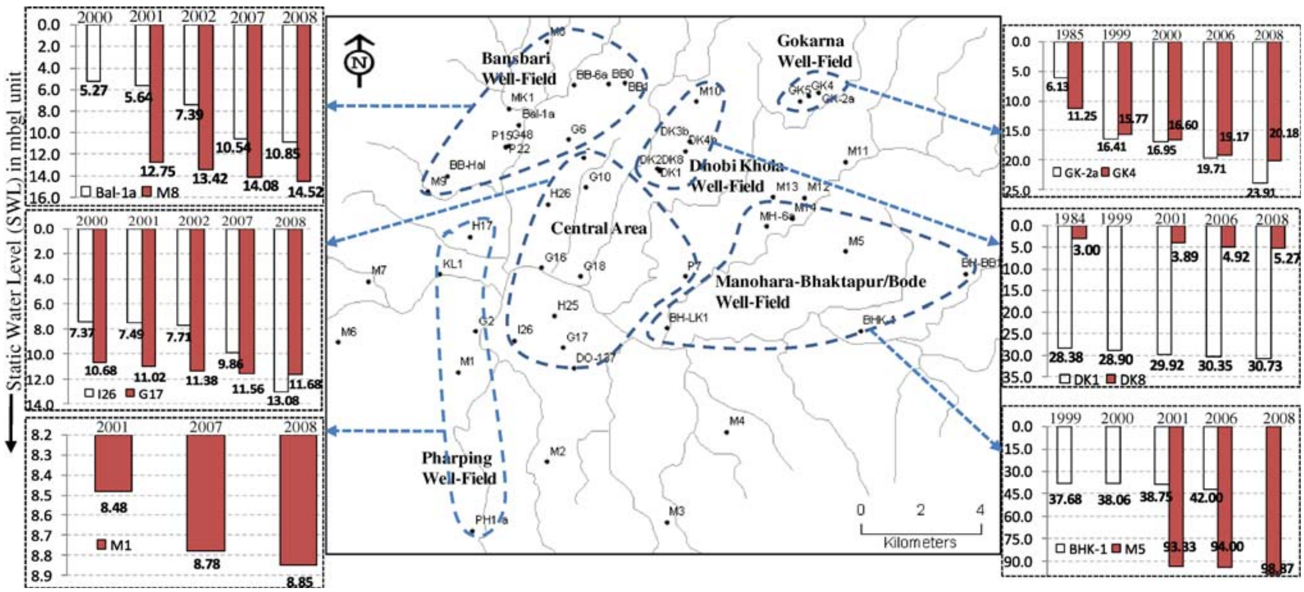


Fig. 7 Decline in static water level over time at different locations within the groundwater basin (Data sources: groundwater level before 1999 from Acres International (2004) and after 1999 from Groundwater Research and Development Project/Department of Irrigation, Kathmandu, Nepal)

Table 6 Decline in well yield (l/s) (data source: Acres International 2004 and Metcalf & Eddy 2000)

SN	WID	Well field	Areas within GW basin	Previous discharge		Q (l/s) in 1999	Decline in Q
				Year	Q (l/s)		(l/s)
1	DK5	Dhobi Khola	Northern areas: NWSC well-fields	1983	27.89	20.00	7.89
2	BB2	Bansbari		1984	20.46	15.49	4.97
3	BB3	Bansbari		1984	43.24	21.67	21.57
4	BB4	Bansbari		1984	44.11	10.00	34.11
5	BB5	Bansbari		1985	41.00	15.00	26.00
6	BB6a	Bansbari		1984	43.67	7.50	36.17
7	BB8	Bansbari		1984	40.58	20.83	19.75
8	GK1	Gokarna		1985	35.77	16.67	19.10
9	GK3	Gokarna		1984	29.85	11.67	18.18
10	BH4a	Bhaktapur/Bode		1985	46.31	15.00	31.31
11	MH4	Manohara		1985	39.75	11.94	27.81
12	MH6b	Manohara		1983	35.00	16.67	18.33
13	MH7	Manohara		1985	38.50	23.33	15.17
14	H30	–	Central areas	1996	22.00	10.00	12.00
15	G24	–		1996	7.33	5.83	1.50
16	G33	–		1996	11.33	8.33	3.00
17	G52	–		1996	7.33	0.60	6.73

WID Well identification number, *GW* groundwater, *l/s* liters per second, *Q* discharge

Decline in groundwater levels

Groundwater levels declined by 13–33 m during 1980–2000 in heavily pumped northern area of the basin (Metcalf & Eddy 2000); while during 2000–2008, it declined by 0.37–7.50 m in the NWSC well-fields (Table 5). Relatively more decline in the Gokarna well-field is related to larger extraction by the NWSC from this area. The water level is gradually decreasing over the time in all the well-fields as shown in Fig. 7. Based on extraction activities, impact on the groundwater level can be described under four time periods (Kharel et al. 1998): 1960–1983 as low impact (starting of groundwater extraction), 1983–1988 as visible impact (start of the NWSC well-fields), 1988–1993 as increasing impact (increasing number of private wells) and 1994 onwards as large impact (haphazard pumping without regulation).

Decline in production capacity of wells

Discharge from the wells is also going down compared to the time of installation. This study, based on analysis in selected NWSC wells for the period of mid-1980s–1999, shows well yields (l/s) have decreased by 7.89 in Dhobikhola, 4.97–36.17 in Bansbari, 18.2–19.1 in Gokarna, 31.31 in Bhaktapur/Bode and 15.17–27.81 in Manohara well-fields (Table 6). Higher decline in well yields in the NWSC well-fields corresponds to decline in groundwater levels.

Land subsidence

As a result of groundwater mining from deep aquifer and subsequent lowering of piezometric head, overlying aquitard (clay and silt layers) and deep aquifer is expected to get consolidated by reducing pore water pressure. This may result in subsidence or settlement of the ground surface. Areas with risk of potential land subsidence are those, where declines in groundwater levels are greatest and subsoil structure contain a high percentage of compressible clay and silt layers. Such conditions are believed to exist in some areas towards northern and central part of the groundwater basin (JICA 1990; Kharel et al. 1998; Binnie & Partners 1973, 1988). However, no efforts have been made to determine if land subsidence is taking place; and no evidence of land subsidence recorded so far.

Public health

Water pollution is a serious public health issue in the Kathmandu Valley. Most of the solid waste and wastewater from urban areas are being discharged directly into rivers and/or open ground. Such practices are responsible for deteriorating surface and groundwater quality especially at shallow depth. Bacterial indicators capable of spreading waterborne diseases are observed in groundwater samples, which are the most serious threat to public health caused by insanitary sewage disposal (Karn and Harada 2001). The waterborne diseases (such as diarrhea, dysentery, cholera, and skin diseases) have been the cause for 16.5% of total deaths in the Teku Hospital of the valley (Metcalf & Eddy 2000). These facts support pollution of groundwater that fulfill major fraction of municipal water demand, has significant public health impact. To examine a detailed extent of impact is beyond the scope of this paper.

Response

The Government of Nepal, in close collaboration with related stakeholders, has made several attempts to improve the water environment through development programmes, organizational adjustments, and research activities. Few important initiatives are endorsement of Water Resources Act (1992); development of environment standard guidelines for discharging industrial wastewater; attempt to recharge shallow groundwater through dug wells and ponds; rainwater harvesting to reduce pressure on groundwater resources, etc. In addition, initiatives such a groundwater monitoring, and Melamchi Water Supply Project to bring additional 510 MLD water from off-the-valley sources are other important responses aimed at reducing pressure on the valley's groundwater environment by means of developing knowledgebase and alternative supply augmentation. However, there is no single responsible institutions and/or authority to monitor, manage and regulated groundwater use; and most particularly to record well installation or utilization.

Groundwater monitoring

Groundwater levels in the valley's aquifers were observed since early 1970s. Unfortunately, they were limited to the duration of particular projects (e.g. Binnie & Partners 1973, 1988; JICA 1990). After a long gap, Metcalf & Eddy in association with CEMAT consultant designed and initiated groundwater monitoring in 1999 under a project "Urban Water Supply Reforms in the Kathmandu Valley". Fifty wells (8 in shallow and 42 in deep aquifers) were selected for groundwater levels; and 50 wells for water quality monitoring. Those wells were evenly distributed within the basin. After completion of the project in 2001, Groundwater Resources Development Project (GWRDP) under Department of Irrigation (DOI) took the responsibility of monitoring. However, number of monitoring wells in shallow and deep aquifers is inadequate to fully understand the situation within the valley.

Environment standard guidelines

Ministry of Environment Science and Technology (MoEST), the responsible agency to determine environmental standard guidelines, has set the maximum tolerance limits for three types of effluents through NBSM (2003). They consist of industrial waste into surface water, wastewater from treatment plants into surface water, and industrial effluents into public sewers. In addition, general standard has been determined as the tolerance limit of wastewater effluents discharged into surface waters and public sewers for nine different industries: leather, wool processing, fermentation, vegetable ghee and oil, dairy products, sugar, cotton textiles, soap, and paper and pulp (NBSM 2001). However, the implementation of these standards remains poor in practice.

Melamchi Water Supply Project

In a bid to reduce pressure on the groundwater environment in the face of escalating water demand, the Melamchi Water Supply Project (MWSP) is underway to bring 510 MLD water to the Kathmandu Valley from off-the-valley sources. It is expected to be completed in three stages (Stage I: 170 MLD from the Melamchi River, Stage II: 170 MLD from the Yangri river, and Stage III: 170 MLD from the Larke river) MWSDB (1998) and expected to meet the water demand until 2030 (Shrestha 2002). This initiative helps to conserve the groundwater environment by means of reducing groundwater extraction, and increasing/maintaining recharge from relatively permeable river beds. Furthermore, water level in the rivers is expected to increase and make them capable of carrying away their loads, thus reducing pollution to groundwater resources.

Conclusions and recommendations

The DPSIR analysis shows anthropogenic systems (population growth, urbanization and tourism industry) are acting as driving force to exert pressures on the groundwater environment by means of reducing per capita surface water resources, reducing recharge to the aquifer and over-pumping the groundwater. As a result, number of wells and corresponding extraction is increasing above the recharge. Overexploitation of groundwater has lowered the groundwater levels by 13–33 m during 1980–2000 and 1.38–7.5 m during 2000–2008 in the NWSC well-fields, declined well yield by 4.97–36.17 l/s in the northern productive aquifers during mid-1980s–1998, and raised a concern on risk of land subsidence in areas with high percentage of compressible clay and silt layers. Even though this paper has developed the knowledgebase of the groundwater environment, it is unable to suggest sustainable groundwater management scenario. For this, we need better understanding of the aquifer storage capacity, flow path, reliable and adequate information on water levels, rechargeable areas and volume of recharge. Therefore, it is recommended to develop groundwater model of the Kathmandu Valley's aquifers and suggest management scenarios incorporating the effect of climate change as well.

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