European Water 37: 3-14, 2012.

Groundwater in the Kathmandu Valley: Development dynamics, consequences and prospects for sustainable management

V. P. Pandey[1]*, S. Shrestha[2] and F. Kazama[1]

[1] *International Research Center for River Basin Environment (ICRE), University of Yamanashi, 4-3-11, Takeda, Kofu, Yamanashi 400-8510, Japan*

[2] *Water Engineering and Management Field of Study, School of Engineering and Technology, Asian Institute of Technology, P.O. Box 4 Klong Luang, Pathumthani 12120, Thailand.*

* *tel. +81-55-220-8670, fax +81-55-220-8193; e-mail: e_vishnupandey@yahoo.com*

Abstract: This paper performs an integrated analysis of existing knowledge, facts and findings about groundwater development and management in the Kathmandu Valley (Nepal) and presents it as a useful knowledgebase for the stakeholders including policy makers. It first describes how groundwater is an important resource in the valley and then discusses its availability, development dynamics, consequences (both negative and positive) of excessive development and ways forward in terms of research and management intervention need towards sustainable management of the groundwater resources in the area. With the evidences of groundwater availability, unsustainable trends of groundwater development, visible negative consequences and low level of progress in achieving groundwater sustainability, the paper suggests the need to invest in groundwater monitoring, research and conservation under an effective institutional set up and leadership. It is believed that the contents of this paper would be very useful for all the stakeholders as the right knowledge produced at right time.

Key words: Groundwater management, groundwater depletion, institutions, Kathmandu Valley, Nepal.

1. INTRODUCTION

The Kathmandu Valley which nestles capital of Nepal is located in central part of the country in between 27°32’13”- 27°49’10” N latitudes and 85°11’31”- 85°31’38” E longitudes (Fig 1). The valley is located at upstream of the Bagmati River Basin (BRB), which is one of the stressful basins in the country in terms of freshwater vulnerability to environmental change (Pandey et al. 2010a). Freshwater in the upper part of the BRB is even more stressful due to both high stress and less adaptive capacity (Pandey et al. 2009; 2011a). Groundwater, therefore, has been and will continue to be an important source of water supply in the area.

Groundwater basin in the valley (Fig. 1) covers almost half of the total watershed area. The basin in 2001 was home for 1.53 million people, with 84.3% living in urban areas (Pandey et al. 2010b). The population is expected to have increased by approximately 2.5 times in the last decade, though official data are yet to be released. In the recent past, water demand of the valley has raised abruptly by increasing population and industrial activities. It has led to heavy exploitation of the groundwater resources. As a result, the population in the valley is reeling under acute water shortage with water supply of only a half of estimated 280 Million-Liters-a-Day (MLD) water demand (KVWSMB 2008). Due to the short-supply, in addition to individual households, large volume water consumers like housing complexes, hotels and industries have been increasingly mining groundwater simultaneously.

Even though nearly half of the total water supply during wet season and 60-70 percent during dry season comes from groundwater (ICIMOD 2007), groundwater is being developed without due consideration to resource distribution over space and time. As a result, annual extraction is exceeding recharge; leading to tremendous depletion in groundwater levels. However, no one knows for sure, the current exact figures of how much water is being extracted, how quickly the groundwater level is falling, or how the groundwater quality is being affected because of inadequate institutional responsibility in monitoring groundwater resources and its impact. On the other hand, the valley receives 80% of 1,755 mm annual rainfall during monsoon season (June-September) (Acres International 2004). This huge amount of rainfall and strong seasonality (80% rainfall during rainy season) could be a boon for increasing amount of the supply if the abundant rain during monsoon season could be harvested and used for recharging the aquifers in the valley. An understanding of groundwater storage potential (total as well as its spatial distribution) of the aquifers helps to estimate the recharge potentials.

In the last five decades several studies have been carried out to understand the geological formations, groundwater quality, hydrogeology, and groundwater availability in the aquifers of the valley (Table 1). The studies have generated good information of groundwater system and resource. However, no efforts have been made to make an integrated analysis of existing knowledge, facts and findings about groundwater development and management and present them as a useful knowledgebase for the stakeholders including policy makers. The objective of this paper is to produce an aggregated picture of groundwater resources availability, groundwater development dynamics, its consequences (both positive and negative) and prospects for sustainable management of groundwater resources in the Kathmandu Valley. The result is expected to be useful for all the stakeholders interested in understanding the groundwater situation of the Kathmandu Valley.

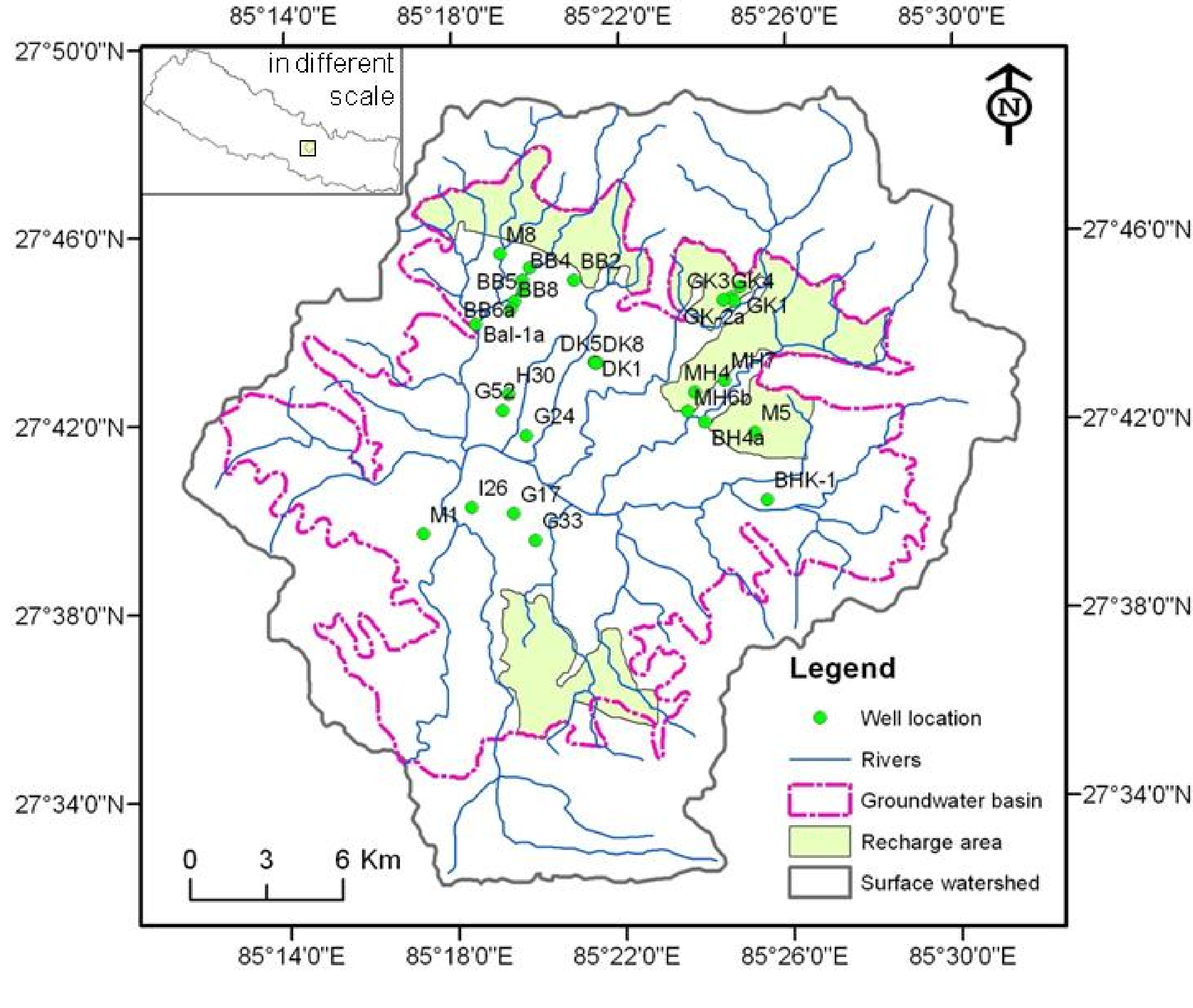

Figure 1. Kathmandu Valley in central Nepal (data sources: surface watershed boundary, groundwater basin boundary and recharge areas from JICA (1990); river networks from NGIIP (2004); well locations from Acres International (2004) database). Green dots are location of wells shown in Table 2 and Table 3.

Table 1. A partial list of groundwater-related knowledge generation in the Kathmandu Valley (Pandey et al. 2011b)

Knowledge / Information	Source
Geometry of hydrogeologic units	Metcalf and Eddy (2000); Pandey and Kazama (2011)
Hydrogeology (Hydraulic conductivity/Transmissivity, storage coefficient, groundwater storage)	Binnie and Partners (1973; 1988); JICA (1990); Metcalf and Eddy (2000); KC (2003); Pandey and Kazama (2011); Pandey and Kazama (2012)
Groundwater extraction database	Metcalf and Eddy (2000); Acres International (2004)
Groundwater levels	GRDP/DoI, Kathmandu, Nepal
Water quality	JICA (1990); Khadka (1993); Jha et al. (1997); Kharel et al. (1998); ENPHO (1999); Karmacharya and Pariyar (1999); Metcalf and Eddy (2000); Khatiwada et al. (2002); Acres International (2004); ENPHO (2005); Gurung et al. (2007); Chapagain et al. (2009); Chapagain et al. (2010); etc.
Recharge to aquifer	Binnie and Partners (1988); JICA (1990); Gautam and Rao (1991)
Current status of groundwater environment (DPSIR analysis)	Pandey et al. (2010b)
Groundwater model	JICA (1990); Acres International (2004). But continuously updated groundwater model is not available
Vulnerability of shallow aquifer to pollution	Pathak et al. (2009)
Surface & groundwater interaction	Study on progress by the authors
Future status of groundwater under climatic and non-climatic change	Study on progress by the authors
GIS data: surface topography, land cover, river networks etc.	NGIIP (2004)

'GRDP/DoI' is Groundwater Development Project/Department of Irrigation

2. GROUNDWATER AVAILABILITY

In the valley, there are three general hydrogeologic layers in descending order as shallow aquifer, aquitard, and deep aquifer. Estimated thickness of the shallow aquifer varies from 0 to 85m, clay aquitard (that vertically separates shallow and deep aquifer) from less than 5m to more than 200m, and that of the deep aquifer from 25m to 285m (Pandey and Kazama 2011). The shallow aquifer is thicker towards the northern part of the groundwater basin while the deep is towards the central and southern part. Total volumes of shallow and deep aquifers are estimated at 7,260 Million-Cubic-Meters (MCM) and 56,813 MCM, respectively (Pandey and Kazama 2011).

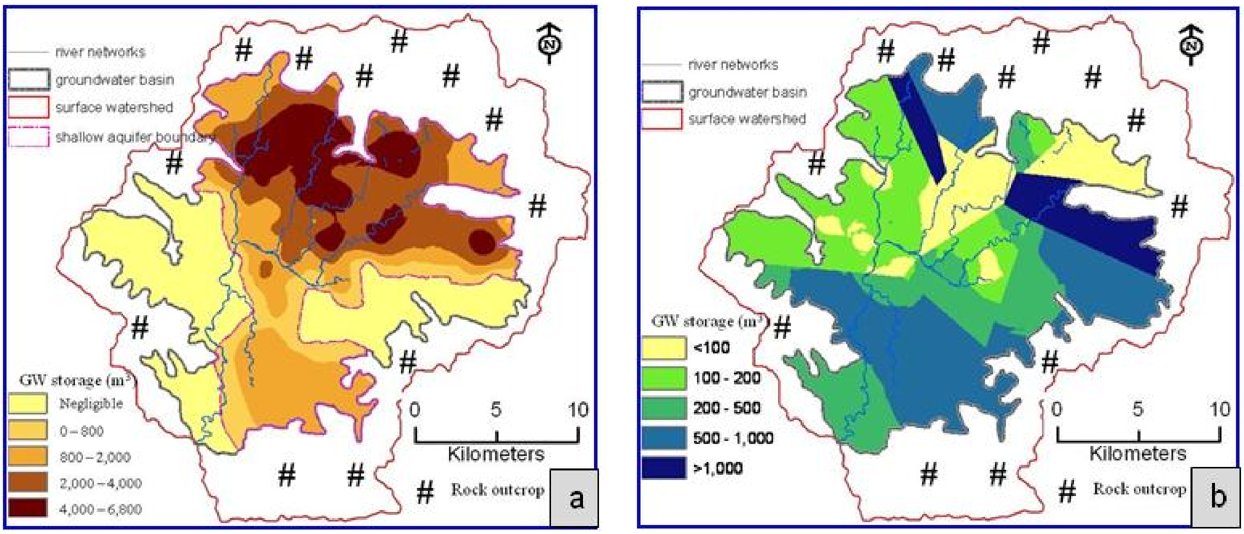

Figure 2. Groundwater storage volume per 20m x 20m grid cell in (a) shallow aquifer and (b) deep aquifer (Pandey and Kazama 2012)

Groundwater storage potentials of those aquifers are certainly much lesser than their volumes because only the voids can hold water. The storage potential estimated by multiplying aquifer volume with storage coefficient (specific yield in case of shallow aquifer) shows that shallow aquifer has high storage volume per unit area (as high as ~6,800 m3/grid cell compared to less than 1,000 m3/grid cell in the most parts of deep aquifer) (Fig. 2) as well as total over the entire shallow aquifer (total = 1,452.25 MCM) (Pandey and Kazama 2012). The same study based on water level data of July, 2008 in 22 wells in shallow aquifer further estimates that shallow aquifer has huge potential (226.5 MCM) to store water in the empty space between current and assumed upper limit of the groundwater level. This estimate, though did not consider dynamics of groundwater flow and recharge characteristics, are still useful preliminary estimate for planning purpose.

Filling the aquifers up to their full potentials may be difficult to achieve. Some parts of them are filled by natural recharge from rainwater (especially during monsoon season). The major natural recharge areas in the valley are located towards northern part and some areas towards southern part in the valley (Fig. 1) where thickness of the clay layer is expected to be minimal. The annual recharge to the aquifers estimated by several earlier studies (Binnie and Partners 1988; JICA 1990; Gautam and Rao 1991) using various approaches varies widely. Considering an average of them (as discussed on Pandey et al. 2010b) as a representative one, annual recharge to the aquifers in the valley is 9.6 MCM/year. The groundwater availability could further be increased by artificial and/or managed aquifer recharge, which of course, is resource-intensive and needs further investigation of the aquifer systems to understand the flow paths and flow velocity; however, would help understand the artificial recharge potentials (location, recharge volume, etc).

3. GROUNDWATER DEVELOPMENT DYNAMICS

Groundwater extractions from the valley's aquifers were started from early seventies. Nearly after a decade, private hotels, government institutions and industries started to drill their own groundwater wells to cope with escalating water demand after municipal water supply became insufficient and irregular. Apart from hotels and industries, the Nepal Water Supply Corporation (NWSC) also introduced groundwater into its water supply system from mid-eighties (Metcalf and Eddy 2000). Since then, groundwater extraction increased continuously. Taking an example of the NWSC wells, they extracted 2.3MLD in 1979, 5MLD in 1985, 18MLD in 1986, 26MLD in 1987 (Binnie and Partners 1988) and 29.2MLD in 1999 (Metcalf and Eddy 2000). As shown in Fig. 3, total groundwater extractions (by NWSC and private sectors) is increasing continuously, for example, 3.75 MCM/year in 1982 to 12.17 in 1987, 21.26 in 1999 and 25.52 in 2009. The extraction has already exceeded recharge since mid-eighties and the gap between recharge and the extraction is widening (Fig. 3). Management intervention to regulate groundwater extraction was needed since that time; unfortunately it is not getting priority even today. If the extraction from the groundwater reserve is continued at the same rate as in 2001 (i.e., 59.06 MLD or 21.56 MCM/year, shallow and deep aquifers in the valley will be emptied in less than 100 years (Pandey et al. 2010b). Additionally, the extraction will tend to increase further with ever increasing population and industrial and tourism activities in the valley and will further worsen the negative consequences like depletion of groundwater level, drying of wells, decline in design yield of wells and land subsidence. Considering future growth in water demand and sustainable use of groundwater resources it has become imperative to bring the policy and programs into effect for fixing the groundwater extraction within manageable limits. It would help to protect further deterioration of the groundwater environment. Continuous monitoring of the groundwater extraction, which is certainly not taking place in the valley, could be the first step in that direction.

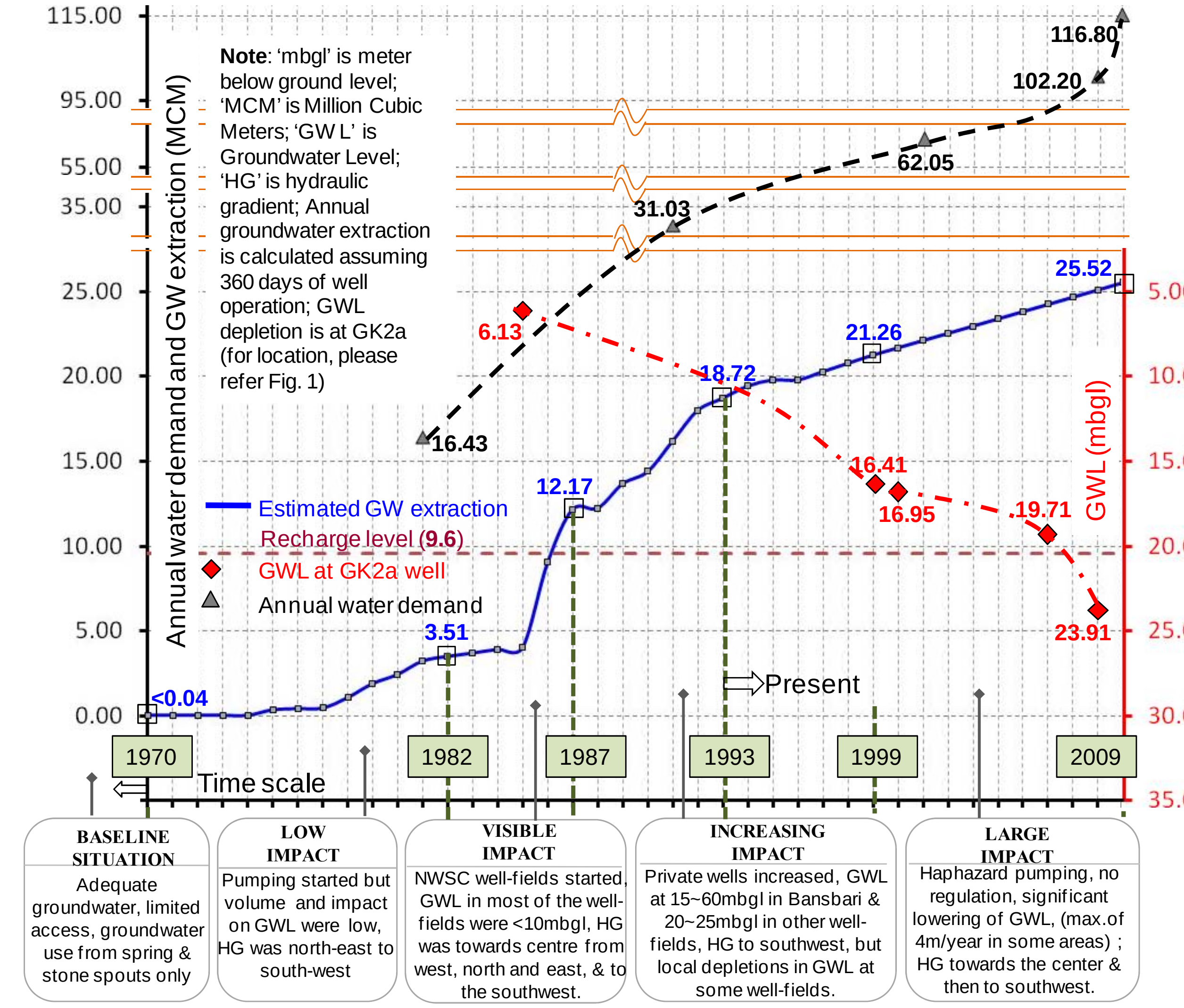

Figure 3. Groundwater development dynamics and its impact on groundwater level.
(data sources: daily water demand of 1981/1991/2001 from ICIMOD (2007), of 2008 from KVWSMB (2008) and that of 2009 from Dhakal (2010); daily groundwater extraction during 1970-1999 from Metcalf and Eddy (2000), that of 2009 from Dhakal (2010) and that between 1999 and 2009 were calculated by linear interpolation; recharge level from Pandey et al. (2010); groundwater level before 1999 from Acres International (2004) and after 1999 from Groundwater Research and Development Project/Department of Irrigation, Kathmandu, Nepal; and qualitative description of impact from Kharel et al. (1998))

4. CONSEQUENCES OF EXCESSIVE GROUNDWATER DEVELOPMENT

Groundwater development in the Kathmandu Valley without due care of resource availability and recharge has already shown number of consequences (both negative and positive). They are broadly classified and discussed under three categories: (i) reduced availability of groundwater resources, (ii) institutional and policy reforms, and (iii) groundwater-focused collective discussions.

4.1 Reduced availability of groundwater resources

The availability of groundwater resources has been reduced as a consequence of excessive withdrawal of groundwater resources. They are reflected in terms of depletion in groundwater level, decline in design yield of wells, degradation in groundwater quality and shrinking aquifer volume due to land subsidence.

4.1.1 Depletion in groundwater levels

Overexploitation of groundwater has lowered groundwater levels by 13~33m during 1980~2000 (Metcalf and Eddy 2000) and 0.37~7.50m during 2000~2008 (Table 2) in the NWSC well-fields. The water level is gradually decreasing over the time in all the well-fields (Pandey et al. 2010b). And consequences such as drying of wells and stone spouts are appeared visually in these days. The impacts on groundwater level based on extraction activities are described by Kharel et al. (1998) as: low impact during 1970~1982 (starting of groundwater extraction), visible impact during 1982~1987 (start of the NWSC well-fields), increasing impact during 1987~1993 (increasing number of private wells) and large impact from 1993 onwards (haphazard pumping without regulation).

Table 2. Aquifer depletion at selected locations during the dry season (Pandey et al. 2010b)

Location	WID	Previous water level (mbgl)		Current water level (mbgl)		Depletion (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; well location is shown in Fig 1.

4.1.2 Decline in design yield of wells

Design discharge of groundwater pumping wells is also declining compared to the time of installation. Analysis of well yield in selected NWSC wells for the period of mid-1980s~1999 shows well yields (liters per second, l/s) have declined 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 3). Higher decline in well yields in the NWSC well-fields corresponds to depletion in groundwater levels.

4.1.3 Degradation of groundwater quality

Several studies over different point of time report variation in groundwater quality in shallow and deep aquifers (Khadka 1993; Jha et al. 1997; Kharel et al. 1998; Metcalf and Eddy 2000; ENPHO 2005; Chapagain et al. 2009). Groundwater in shallow aquifer is contaminated by E.-coli and nitrates probably due to improper domestic and industrial waste management system and that in deep aquifer is contaminated by ammonia, arsenic, iron and heavy metals. Though deep aquifer water quality is primarily influenced by sedimentary make-up of the aquifer (Chapagain et al. 2010), bacterial contamination are observed in some wells which probably is due to poor design, installation and improper or no sealing of abandoned wells (Metcalf and Eddy 2000). Therefore, some efforts are needed to seal off several abandoned wells. Vulnerability of shallow aquifer water to contamination is increasing with excessive development of groundwater resources coupled with unsustainable practices for waste management.

Table 3. Decline in well yield (liters per second) (Pandey et al. 2010b)

SN	WID	Well field	Areas within GW basin	Previous discharge		Q (l/s) in 1999	Decline in Q (l/s)
				Year	Q (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, Q: Discharge; well location is shown in Fig 1.

4.1.4 Shrinking aquifers volume due to 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 and shrink the total volume of aquifers. 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 (Binnie and Partners 1973; 1988; JICA 1990; Kharel et al. 1998). However, no efforts have been made so far to determine if land subsidence is taking place; and therefore no evidence of land subsidence are available. It is suggested to initiate monitoring of land subsidence.

4.2 Institutional an policy reforms

A number of attempts have been made to change in institutional set up and policy since late 1960s with the objective of groundwater development and conservation. The first institution was established in 1968 by the Government of Nepal (GoN) under the name of 'Department of Groundwater Survey' with the objective of developing groundwater resources for economic prosperity. It was renamed as the Groundwater Resources Development Board (GRDB) in 1976 and mandated to be a primary government agency responsible for groundwater investigation, basic data generation, monitoring and development. However, its effectiveness limited to the groundwater development for irrigation in southern plains of the country and monitoring of groundwater level and quality in the Kathmandu Valley (after 2001) through its implementing agency Groundwater Resources Development Project (GRDP).

The GoN further established Water and Energy Commission in 1975 and its permanent secretariat (Water and Energy Commission Secretariat, WECS) in 1981 to accelerate integrated development of water and energy. However, it focused on developing water resources policy and planning at a very general level and did not pay attention on groundwater resources. In 1992, ownership of water resources was vested on the state through Water Resources Act (1992). For regulating the use of water resources through permits, District Water Resource Committee (DWRC) – consisting of representatives from most of the water-sector-related government agencies functioning in the district – was established in 1993. It was mandated as the authority to issue licenses for the use of water resources. However, issuing groundwater licenses was never practiced even after the establishment of the authority.

Table 4. Pre-existing institutional arrangement relating to groundwater in Nepal (modified after Tuinhof and Nanni 2004)

Government agency	Groundwater-related tasks
Ministry of Irrigation (formerly Ministry of Water Resources)	
- Groundwater Resources Development Board (GRDB)	– Oversees policy related to groundwater
- Groundwater Resources Development Project (GRDP)	– Implementing body of GRDB
Ministry of Physical Planning & Works (MoPPW)	
- Department of Water Supply & Sewerage (DWSS)	– Drinking water supply (surface & groundwater) in areas outside the coverage of NWSC & KUKL.
- Nepal Water Supply Corporation (NWSC)	– Regulation, operation and management of drinking water supply (surface & groundwater) in urban centers outside the Kathmandu Valley
- Kathmandu Valley Water Supply Management Board (KVWSMB)	– Regulation and management of groundwater resources in the Kathmandu Valley
- Kathmandu Upatyaka Khanepani Limited (KUKL)	– Operation of water supply (including groundwater) in the Kathmandu Valley
Ministry of Industry(MoI)	
- Department of Mines and Geology (DoMG)	– Geological survey and databases
Ministry Environment (MoE)	– Groundwater quality protection
- Department of Hydrology & Meteorology (DHM)	– Collection & storage of climate data
Ministry of Energy	
- Water & Energy Commission Secretariat (WECS)	– Apex body for water resources policy & planning
District Water Resource Committee, in which, most of the water-sector-related government agencies are represented	– Authority to issue licenses for the use of water resources (including groundwater)

In lack of clear mandate to a particular authority for regulating and managing groundwater resources and/or overlapping of groundwater-related responsibilities of several ministries and departments (see Table 4), groundwater regulation and management in the Kathmandu Valley remained as “nobody’s responsibility”. To address the overlaps in responsibilities, a groundwater bill was developed at the initiative of the GRDB and was sent to parliament in 2004. The bill proposed to amend the existing Water Resources Act (1992) for making provisions for establishment of an Underground Water Authority in charge of groundwater data collection/processing, use planning, regulation, monitoring, research and management throughout the country. Unfortunately, the bill is still pending as the Parliament was dissolved after the bill was registered.

In 2006, the GoN established Kathmandu Valley Water Supply Management Board (KVWSMB) as an institution having sole authority for groundwater regulation and management in the Kathmandu Valley. In December 2009, the Supreme Court of Nepal issued an order to prepare ‘groundwater use action plan’ for the entire country. It was in response to a writ filed by Pro Public (http://www.propublic.org), a forum for protection of public interest, in June 2003 to issue order for regulating groundwater use in the valley. After the order, the KVWSMB recruited a consulting company to prepare a draft of ‘groundwater management and regulation policy’ for the Kathmandu Valley and the GRDB formed two committees, one (formed in mid-2010) for modifying groundwater bill in the changed context and another one (formed in late-2010) for preparing ‘groundwater use action plan’ for the entire country. The KVWSMB has recently finalized the draft policy and submitted it to the line ministry (Ministry of Physical Planning and Works, MoPPW) in December 2010. It is awaiting approval from the ministry. The policy proposes to amend existing Water Resources Act (1992) to make provisions for controlling haphazard extractions (to balance it with recharge), protecting groundwater quality and promoting rainwater harvesting and recharge programmes to increase groundwater levels. The committees formed by the GRDB are yet to finalize 'groundwater action plan' and revised 'groundwater bill' for the entire country.

The progress in groundwater regulation in the Kathmandu Valley is expected to accelerate after the policy awaiting approval comes into effect. However, the institutional capacity of the KVWSMB should be strengthened by allocating sufficient resources (human and economic) for daily business and research activities and making legislative provisions to apply and enforce the groundwater management policy.

4.3 Groundwater-focused collective discussions

To contribute in sustainable management of groundwater resources in the valley through knowledge sharing, national symposium and expert meeting focusing on groundwater have been initiated since 2009. The first national symposium was organized in December 2009 by Center of Research on Environment Energy and Water (CREEW) and The Small Earth Nepal (SEN) with support from Kurita Water and Environment Foundation (KWEF) and International Research Center for River Basin Environment (ICRE) of University of Yamanashi in Japan. The symposium was attained by more than 75 persons representing large number of government and non-government organizations. After that, a groundwater expert meeting was organized by the KVWSMB in 4-5 July 2010. The expert meeting discussed current status of groundwater environment and identified the research and data gaps to be addressed in future. The 2nd national symposium was held in March, 2011. Such initiatives have played influential roles in raising awareness about groundwater situation and gaining attention of responsible authorities towards groundwater conservation and management.

5. PROGRESS IN ACHIEVING 'GROUNDWATER SUSTAINABILITY'

'Groundwater sustainability' in this context is defined in the same way as Alley et al. (1999) did, that is, it refer to the development and use of the resource in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences. The sustainability represents an optimal state; however, this is neither fixed nor constant but rather time- and space-relevant (De Carvalho et al. 2009). It is a manifold concept approachable from many points of view (hydrological, ecological, economics, social, legal, institutional, inter- and intra-generational and political) (Llamas et al. 2006) and therefore, achieving all the aspects of sustainability at a time is less likely. For evaluating the progress in achieving groundwater sustainability in the Kathmandu Valley, hydrological aspects of sustainability is considered and 'groundwater sustainability infrastructure index (GSII)' (Pandey et al. 2011b) is used as a measure of the sustainability; wherein, the 'infrastructure' refers to the existing knowledge, practices and institutions whose adequate strengthening help achieve sustainability in groundwater management. The index is composed of five components (groundwater monitoring-GwM, knowledge generation and dissemination-KgD, regulatory interventions-ReI, public participation-PuP and institutional responsibility-InR) which disaggregate into 16 indicators.

The results detailed in Pandey et al. (2011b) showed that coverage (spatial and temporal) of monitoring system (groundwater level, extraction, quality and land subsidence) is inadequate and data quality, storage and dissemination aspects are poor in practice. Aquifers are being mined faster than being recharged in the absence of regulatory interventions. Knowledge generation is relatively good, albeit, highly scattered, non-coordinated and inaccessible from a single-window (e.g., public outreach office). Overall situation of the groundwater sustainability in the valley is relatively poor (GSII=0.22) as the value of the GSII lie on the lower side of the sustainability scale (0-1, 1 representing the highest degree of sustainability). It reflects the need of significant attentions to strengthen the sustainability infrastructures and subsequently achieve the goal of the groundwater sustainability. All the components of the index are somewhere near to 'poor' and therefore needs higher attentions; however, they can be arranged in decreasing order of priority (based on their aggregated scores) as follows: ReI (score=0.08), PuP (score=0.17), InR (score=0.25), GwM (score=0.25) and KgD (score=0.33). Even within the ReI, situation of 'economic instruments' is 'very poor' and therefore it should get higher priority.

6. SUMMARY AND CONCLUSIONS

Groundwater aquifers in the Kathmandu Valley are already under stress. Depletion in groundwater levels and decline in design yield of wells have become a common phenomenon. Consequences of excessive groundwater development in a form of reduced availability of groundwater resources are already realized by concerned stakeholders. It has resulted in several responses aimed at reducing stress on groundwater resources. For example, augmenting water supply by bringing water to the area from off-the-valley source (named as Melamchi Water Supply Project), establishment of the KVWSMB as a separate authority in charge for groundwater regulation and management, development of groundwater regulation and management policy (awaiting approval from the line ministry), etc. However, they all are ongoing attempts only.

There is a long-way to go to achieve the goal of 'groundwater sustainability' in the valley. Current status of the sustainability is at the lower side of the sustainability scale (0 to 1, 1 representing the highest degree of sustainability). Improvements in groundwater monitoring by increasing spatial and temporal coverage, further research to enhance understanding of groundwater dynamics and its recharge system, management of existing data/information/knowledge and its disseminations and policies and strategies for public participation in groundwater management and conservation activities could be the immediate next steps in the direction of achieving 'groundwater sustainability'.

The monitoring with satisfactory space and time coverage enables a long-term understanding of groundwater availability and anthropogenic effects (of diversity of uses) on the groundwater resources, and thus, assist in decision making for protecting groundwater environment. The groundwater monitoring may include groundwater levels in both, shallow and deep aquifers, volume of groundwater pumping from each wells, major contaminants, and land subsidence.

In addition to monitoring, identification of critical or stressed groundwater zones from the perspective of both resource availability and quality is essential to help plan future groundwater development activities as well as to limit groundwater extraction volumes from the stressed areas. The extraction limit (volume/rate) could be worked out considering acceptable depletion rates based on recharge dynamics. For that, further research is needed to identify groundwater recharge system (i.e., source, location, probable flow paths, recharges rate, etc) for shallow as well as deep aquifer. This could be achieved by combing groundwater modeling with isotope tracers. Such researches could also assist in examining the possibilities of augmenting groundwater supplies through harvesting of rainwater and using it for recharging the shallow aquifers (artificial and/or managed aquifer recharge) which have huge space available for additional storage (i.e., 226.5 MCM).

It is expected that after the groundwater policy (that is awaiting approval from the ministry) comes into effect, the KVWSMB would play an effective role as an institutional leadership for the sustainable utilization and management of groundwater in the Kathmandu Valley. Though, institutional capacity in terms of resource (human and economic) availability for daily business and research activities could be the limiting factors, a part of that can be overcome by collaborative work with local non-governmental organizations, community-based organizations and academic institutions within and outside the country who are keenly interested to support the KVWSMB in conducting research activities.

ACKNOWLEDGEMENTS

This study was supported financially by Global COE Program of University of Yamanashi and The Takeda Foundation in Japan. The authors would also like to acknowledge several organizations in Nepal (e.g., Center of Research for Environment Energy and Water (CREEW), Kathmandu Valley Water Supply Management Board (KVWSMB), Groundwater Resources Development Project (GRDP), etc.) for supporting and/or providing data/information.

REFERENCES

Acres International (2004) Optimizing water use in Kathmandu Valley (ADB-TA) Project, Final Report. Submitted to Government of Nepal, Ministry of Physical Planning and Works, Acres International in association with Arcadis Euroconsult Land and Water Product Management Group, East Consult (P) Ltd. & Water Asia (P) Ltd.

Alley WM, Reily TE, Franke OL (1999) Sustainability of Ground-Water Resources. U.S. Geological Survey Circular 1186, Denver, CO.

Binnie and Partners (1973) Groundwater Investigations, Kathmandu Water Supply and Sewerage Scheme. A report submitted to the Government of Nepal.

Binnie and Partners (1988) Water supply for Kathmandu and Lalitpur from outside the valley. Final report on feasibility study, Appendix-L (Groundwater resources within the valley).

Chapagain SK, Pandey VP, Shrestha S, Nakamura T, Kazama F (2010) Evaluation of deep groundwater quality in Kathmandu Valley using multivariate statistical techniques. Water Air and Soil Pollution 210(1-4): 277-288.

Chapagain SK, Shrestha S, Nakamura T, Pandey VP, Kazama F (2009) Arsenic occurrence in groundwater of Kathmandu Valley, Nepal. Desalination and Water Treatment 4(1-3): 248-254.

De Carvalho Scp, Carden KJ, Armitage NP (2009) Application of a sustainability index for integrated urban water management in Southern African cities: case study comparison - Maputo and Hermanus. Water SA (Online) 35(2): 44-151.

Dhakal HP (2010) Groundwater depletion in Kathmandu Valley: need for management. A paper presented at International Forum for Sustainable Asia and Pacific (ISAP 2010), Sharing groundwater issues in Asian countries, 12-13 July, 2010, Yokohama, Japan.

Environment and Public Health Organization (ENPHO) (1999) Monitoring of groundwater quality in the Kathmandu Valley, Nepal. A report submitted to Ministry of population and Environment, HMG Nepal (ADB TA 2847-NEP), pp 1-35.

Environment and Public Health Organization (ENPHO) (2005) Groundwater quality surveillance in Kathmandu and Lalitpur municipality area. A joint report of JICA/MPPW/ENPHO, Kathmandu.

Gautam R, Rao GK (1991) Groundwater resources evaluation of the Kathmandu Valley. Journal of Nepal Geological Society 7: 39–48.

Gurung JK, Ishiga H, Khadka MS, Shrestha NR (2007) The geochemical study of fluvio-lacustrine aquifers in the Kathmandu Basin (Nepal) and the implications for the mobilization of arsenic. Environmental Geology 52(3): 503–517.

ICIMOD (2007) Kathmandu Valley Environmental Outlook. International Center for Integrated Mountain Development, Hillside Press (P.) Ltd, Kathmandu. ISBN 978 92 9115 019 9.

Jha MG, Khadka MS, Shrestha MP, Regmi S, Bauld J, Jacobson G (1997) The assessment of groundwater pollution in the Kathmandu Valley, Nepal. A report on Joint Nepal-Australia Project 1995–96, Australian Geological Survey Organization, pp 1–64.

JICA (1990) Groundwater Management project in Kathmandu Valley. Final report Main report and supporting reports, November 1990.

Karmacharya AP, Pariyar CB (1999) Quality of Groundwater in the Kathmandu Valley, Nepal. In: Jha P.K., Baral S. R., Karmacharya S.B., Lekhak H. D., Lacoul P., Baniya C.B. (Eds.) Proceedings of International Conference on Environment and Agriculture. November 1-3, 1998, Kathmandu. Ecological Society (ECOS), Nepal. pp 499-502.

KC K (2003) Optimizing Water use in Kathmandu Valley (ADB TA-3700), Final Draft Report on Groundwater/Hydrogeology in Kathmandu Valley. Jan 2003.

Khadka MS (1993) Groundwater quality situation in alluvial aquifers of the Kathmandu Valley, Nepal. Journal of Australian Geology and Geophysics 14: 207–211.

Kharel BD, Shrestha NR, Khadka MS, Singh VK, Piya B, Bhandari R, Shrestha MP, Jha MG, Munstermann D (1998) Hydrogeological conditions and potential barrier sediments in the Kathmandu Valley. Final Report of the Technical cooperation project – Environment Geology, between HMG Nepal and Federal Republic of Germany.

Khatiwada NR, Takizawa S, Tran TVN, Inoue M (2002) Groundwater contamination assessment for sustainable water supply in Kathmandu Valley, Nepal. Water Science and Technology 46(9): 147–154.

KVWSMB (2008) Annual report 2007/2008 of Kathmandu Valley Water Supply Management Board (KVWSMB).

Llamas MR, Martinez-Santos P, de la Hera A (2006) The manifold dimensions of groundwater sustainability: an overview. In: Ragone S. de la Hera A. and Hernandez-Mora N. (Eds.) Proceedings of the International Symposium on Groundwater Sustainability. National Ground Water Association Press, Ohio, USA. ISBN 1-56034-131-9, pp 105-116.

Metcalf and Eddy (2000) Urban water supply reforms in the Kathmandu valley (ADB TA Number 2998-NEP), Completion report. Volume I & II – Executive summary, main report & Annex 1 through 7. Metcalf and Eddy, Inc. with CEMAT Consultants Ltd., 18 Feb 2000.

NGIIP (2004) National Geographic Information Infrastructure Programme (NGIIP). Department of Survey, Nepal.

Pandey VP, Babel MS, Kazama F (2009) Analysis of a Nepalese water resources system: stress, adaptive capacity and vulnerability. Water Science and Technology/Water Supply 9(2): 213-222.

Pandey VP, Babel MS, Shrestha S, Kazama F (2010a) Vulnerability of freshwater resources in large and medium Nepalese river basins to environmental change. Water Science and Technology 61(6): 1525-1534.

Pandey VP, Babel MS, Shrestha S, Kazama F (2011a) A framework to assess adaptive capacity of the water resources system in Nepalese river basins. Ecological Indicators 11(2): 480-488.

Pandey VP, Chapagain SK, Kazama F (2010b) Evaluation of groundwater environment of Kathmandu Valley. Environmental Earth Sciences 60(6): 1329-1342.

Pandey VP, Kazama F (2011) Hydrogeologic characteristics of groundwater aquifers in Kathmandu Valley, Nepal. Environmental Earth Sciences 62(8): 1723-1732.

Pandey VP, Kazama F (2012) Groundwater storage potential in the Kathmandu Valley's shallow and deep aquifers. In: Shrestha S., Pradhananga D., Pandey V.P. (Eds.) Kathmandu Valley Groundwater Outlook. Asian Institute of Technology (AIT), The Small Earth Nepal (SEN), Center of Research for Environment Energy and Water (CREEW), and International Research Center for River Basin Environment-University of Yamanashi(ICRE-UY). Kathmandu, Nepal, pp 31-38.

Pandey VP, Shrestha S, Chapagain SK, Kazama F (2011b) A framework for measuring groundwater sustainability. Environmental Science and Policy 14(4): 396-407.

Pathak D., Hiratsuka A, Awata I, Chen L (2009) Groundwater vulnerability assessment in shallow aquifer of Kathmandu Valley using GIS-based DRASTIC model. Environmental Geology 57(7): 1569–1578.

Tuinhof A, Nanni M (2004) Nepal: approach to mitigation of groundwater arsenic contamination including new groundwater legislation. Sustainable Groundwater Management Lessons from Practice, The GW.MATE Case Profile Collection, No. 12, World Bank, Washington D.C., USA.