Application of Multivariate Statistical Analysis for Water Quality Protection in Shallow Groundwater Aquifer of Kathmandu Valley

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ABSTRACT
Groundwater is a major natural resource for drinking purposes in the many countries of the world including both developed and developing countries. However, increasing anthropogenic activities resulting from haphazard urbanization have mounted heavy stresses on groundwater quality in Kathmandu, the main urban centre of Nepal, where, people largely depend upon groundwater to meet day-to-day water needs. Advanced statistical techniques such as principal component analysis (PCA), factor analysis (FA) and correlation analysis (CA) were subjected to groundwater quality datasets from shallow aquifer in Kathmandu, the main urban centre of Nepal to identify the pollution sources. Discriminant analysis (DA) confirmed the seasonal variation of water quality data into four seasons providing 92.9% correct classification. Box-whisker plot also showed that compared to the dry season, groundwater sources sampled during the wet season were more contaminated. The temporal trend of nitrate-N, one of the possible indicators of anthropogenic activities was studied using the datasets sampled in different time windows from 1999 to 2008. Although, mean annual nitrate-N concentration has slightly decreasing trend over the period from 1999 to 2008, extremely high nitrate-N concentrations have been observed indicating its vulnerability to contamination. The results of this study can be informative to local water quality managers as well as professions who are interested in the similar problem in the other places. Moreover, systematic investigations on the current status and trends of groundwater quality and its influencing factors will facilitate to design the comprehensive management strategies to protect groundwater sources from anthropogenic activities and prevent further deterioration of the affected groundwater aquifer systems in urban area of developing countries.

1. INTRODUCTION

Groundwater is a major natural resource for drinking purposes in the many countries of the world including both developed and developing countries. In USA, 26% of the drinking water supply is based on groundwater resources (NGWA, 2010) and in Nepal, more than 50% of drinking water is derived from groundwater (Jha et al*.,* 1997; Khatiwada et al., 2002). But, several anthropogenic processes resulting from haphazard urbanization have mounted heavy stress on such valuable natural resources in underdeveloped and developing countries. In general, shallow groundwater aquifers are susceptible to fluctuation of water quality within relatively short time scales and therefore can be used as an indicator of anthropogenic activities at and/or near the ground surface such as disposal of solid waste, leaching of septic materials and infiltration of sewage and wastewater from poorly managed sewerage systems. Seasonal variations influence water quality such that it presents different characteristics in different seasons. Therefore, characterization of seasonal changes in water quality due to natural or anthropogenic inputs is an important aspect (Ouyang et al., 2006). Accurate assessment of water quality monitoring data, which are required to know the pollution sources and their controlling factors, is a difficult task. The effective methods that can be adopted to evaluate water quality changes and pollution sources are multivariate techniques (Chapman, 1992). Applying multivariate techniques to water quality data sets without missing useful information is imperative to extract meaningful information such as spatial-temporal patterns, significant parameters and latent pollution sources (Shrestha and Kazama, 2007; Zhang et al., 2009; Zhao et al., 2011). PCA/FA provides information regarding the most meaningful parameters, which describe whole data set rendering for data reduction with minimum loss of original information (Vega et al., 1998; Wunderlin et al., 2001). Similarly, the box–whisker plot is a tool that helps in identifying the basic statistical features of a large data set through visual displays (Bhattacharjee et al., 2005).

In underdeveloped countries like Nepal, urban land use, incorporating the effects of increased population, domestic water use, solid waste and industrial wastewater, are positively associated with increases in water pollution. Several researchers have studied the groundwater quality of Kathmandu (Khadka, 1993; Chettri and Smith, 1995; Jha et al., 1997; ENPHO, 1999; Khatiwada et al*.,* 2002; GWRDB, 2000, 2001, 2003; JICA and ENPHO, 2005; Warner et al*.,* 2008; Pathak et al., 2009; Pant, 2011). As reported in several previous studies, anthropogenic activities influence the shallow groundwater regime warranting regular monitoring. However, systematic investigations on the current status and trend of groundwater quality and its relation to various anthropogenic activities, type of sources and seasonal variations have not been carried out in the region. Therefore, it has become imperative to elucidate and investigate the factors effecting groundwater quality.

The objectives of this study were to: (1) identify the pollution sources and seasonal variation in shallow groundwater aquifer of Kathmandu using well-proven multivariate methods; DA, PCA, FA and CA, (2) determine the current status of water pollution and temporal trend of nitrate-N, one of the possible indicator of anthropogenic activities, using the datasets sampled in different time windows from 1999 to 2008, (3) identify the significance differences to each parameters with respect to seasons using non-parametric Kruskal Wallis test and Box and Whisker plot. Moreover, this study aimed to facilitate the design and development strategies that can protect the environment and prevent further deterioration of the affected groundwater sources in study region.

2. STUDY SITE DESCRIPTIONS

The study site is located at Kathmandu valley (337 sq. km.), a part of upper Bagmati river basin, Nepal, which includes five of the total municipalities of country including three major cities; Kathmandu, Lalitpur and Bhaktapur (Fig. 1).

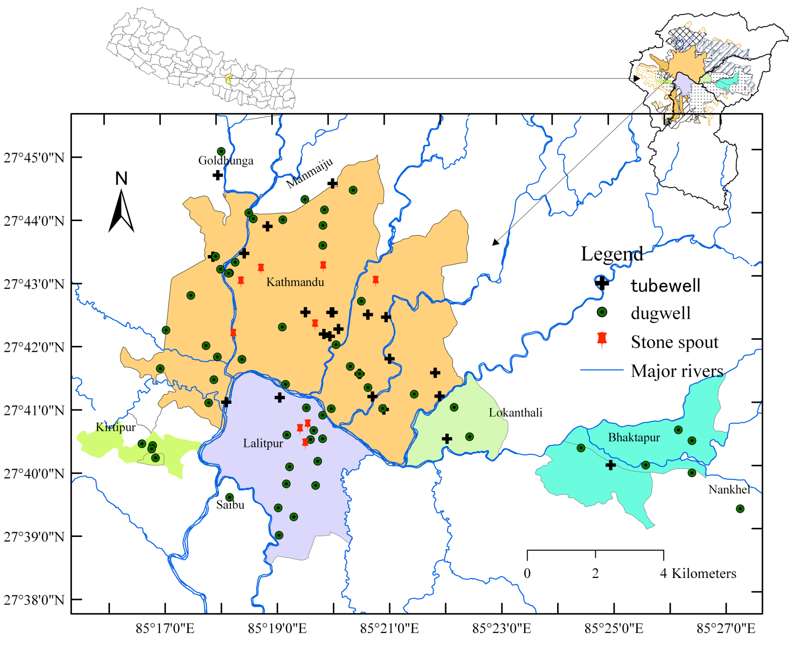

Figure 1. Study area with sampling site

The Kathmandu valley can be considered to be a closed groundwater basin with several independent or interconnected aquifers. In general, the aquifers in the Kathmandu valley can be divided into shallow and deep systems that provide residents with drinking water. The upper unconfined aquifers are occur at depths below 10 m, composed of unconsolidated coarse sediments but become confined at a greater depth due to the presence of extensive clay layers. The shallow aquifers are recharged mostly along the basin margins, directly from precipitation and by supply from several small rivers.
In Kathmandu, people rely heavily on groundwater to meet day-to-day water needs because of the inadequate and unreliable public water supply. People use a variety of groundwater sources

comprising of dug wells, tube wells, stone spouts and deep tube wells (Khadka, 1993). Most people use either tube wells or dug wells to tap shallow groundwater for logistic and economic reasons. In addition, stone spouts are one of the traditional and trusted alternatives to public water supply in Kathmandu. These spouts are excavated brick-lined structures that tap the shallow groundwater, which can also be a part of a series of spouts. They are distributed throughout the valley, both in dense urban and village settings. But, increasing population and urbanization has put pressure on water quality of those shallow groundwater aquifer. The valley's population increased from 0.41 million in 1954 to 1.65 millions in 2001 and further to approximately 3 million in 2011. Out of 3 million, urban population constitutes over 60% of its total population, accounting for nearly 30% of the country's total urban population. Rapid urbanization in Kathmandu is stretching municipal boundaries, converting open spaces and agricultural fields into highly populated areas. The unplanned and haphazard urbanization and uncontrolled migration of population in the valley have lead to poor drainage and sanitation. The solid wastes are disposed along the riverbanks and the untreated wastewaters from domestic and industrial areas are directly discharged into the rivers rendering them as open sewers. Although five municipal wastewater treatment plants (WWTP) have been constructed over the years in Kathmandu valley, none, except for one is partially functional. The total installed capacity of the existing WWTPs is less than 10% and functioning WWTP accounts less than 5% of total demand for the urban areas (Nyachhyon, 2006).

2. MATERIALS AND METHODS

2.1. Groundwater Quality Parameters

The data sets on quality parameters of water samples collected from shallow groundwater aquifer of Kathmandu including dug wells, shallow tube wells and stone spouts by first author with very limited resources and optimal utilizing the others' data, sampled in different time windows from 1999 to 2008 were analysed. Nitrate-N along with other water quality parameters were sampled and analysed by the first author during the September and October of 2008 from a total of ninety sources from the shallow wells including 58 dug wells, 23 shallow tube wells and 9 stone spouts. Sampling locations are shown in Fig. 1. Locations for water sampling were chosen to represent a better spatial distribution in different hydrogeological settings and land-use type throughout the valley. The water sampling and analytical procedures have been described in previous works (Pathak et al., 2009). These water quality parameters along with other previous data sets (ENPHO, 1999; ENPHO and JICA, 2005) were utilized to study the status of groundwater pollution in various types of groundwater source and temporal trend of nitrate-N over the period from 1999 to 2008. In addition, the data sets of 120 water quality sampling sites comprising 16 quality parameters obtained from ENPHO (ENPHO, 1999) and 253 water quality sampling sites comprising 8 water quality parameters obtained from ENPHO and JICA (ENPHO and JICA, 2005), were used to study the influence of anthropogenic activities on groundwater quality of shallow aquifer in Kathmandu. Further, selected groundwater quality parameters sampled during the wet and dry seasons by the Ground Water Resources Development Board (GWRDB) of Nepal (GWRDB, 2000, 2001, 2003) were used to trace the impact of seasonal variations on the groundwater quality.

2.2. Land Use Change

Land use map of 1978 and satellite images of 1989 and 2006 were analysed using image processing and GIS techniques to identify the increase of urban area in Kathmandu valley. Urban area was extracted using ERDAS IMAGINE 9.x based on unsupervised classification and then compared with land use map of 1978 obtained from Department of Survey, Government of Nepal.

2.3. Statistical Techniques

In this study, PCA/FA were subjected to water quality data to obtain composite variables, which was expected to identify pollution factors affecting water quality and latent pollution sources. The description of multivariate techniques and the methodology used for their application are detailed in Vega et al. (1998). Before the factor analysis, the Kaiser-Meyer-Olkin (KMO) and Bartlett's test were performed to examine the suitability of the data set for factor analysis. KMO is a measure of sampling adequacy that indicates the proportion of variance which is common variance, i.e., which might be caused by underlying factors. Similarly, Bartlett's test of sphericity indicates whether correlation matrix is an identity matrix, which would indicate that variables are unrelated. Spearman's rank correlation coefficient was used to calculate the correlation between the variables. The seasonal dataset of four seasons: pre-monsoon, monsoon, post-monsoon, and winter, was subjected to DA with measured parameters. Box and Whisker plot was also applied to selected water quality parameter to identify their significance differences in seasons.

3. RESULTS AND DISCUSSION

3.1. Identification of Major Pollutant Sources

The KMO results for the two datasets (1999 and 2005) were 0.66 and 0.63 respectively, and the significance levels by Bartlett's test are all equal to 0 (< 0.05), showing that factor analysis was effective in reducing dimensionality. From the 1999 and 2005 groundwater quality datasets, PCs were extracted to distinguish the anthropogenic processes on the symmetrical correlation matrix computed with the 16 and 8 variables, respectively. Tables 1 and 2 indicated that the first five components and three components extracted have eigen values greater than 1, and account for 78% and 60% of the total variance in the 1999 and 2005 data, respectively.

Table 1: Principal Component loadings and explained variance for the five components with Varimax normalized rotation in 1999 data set

Parameters	Component 1	Component 2	Component 3	Component 4	Component 5
Temperature	0.01	**0.67**	-0.38	0.01	-0.31
PH	0.05	0.01	0.09	0.06	**0.89**
Dissolved Oxygen	-0.29	-0.33	-0.01	-0.25	0.44
Conductivity	**0.72**	0.45	0.45	0.13	0.00
Total Hardness	**0.97**	0.15	0.04	0.15	-0.01
Calcium	**0.89**	0.11	-0.03	0.22	0.03
Magnesium	**0.86**	0.17	0.12	0.02	-0.07
Chloride	0.27	-0.12	**0.82**	0.06	0.03
Nitrate-N	-0.06	0.08	**0.83**	-0.33	-0.05
Total Coliform	0.03	-0.14	**0.75**	0.38	0.21
E.coli	0.07	-0.22	0.39	**0.69**	0.16
Iron	0.06	0.44	-0.18	**0.70**	-0.17
Manganese	0.47	-0.09	0.00	**0.69**	-0.06
Turbidity	0.21	**0.58**	-0.13	**0.63**	0.00
Ammonia-N	0.37	**0.80**	-0.28	0.10	0.06
Orthophosphate	0.18	**0.82**	0.29	-0.09	-0.01
Explained variance	3.59	2.76	2.67	2.25	1.21
Explained variance (%)	22.41	17.25	16.67	14.07	7.55
Cumulative % of variance	22.41	39.67	56.34	70.41	77.95

In the 1999 data set, PC1 represents the hardness loading which explains the greatest amount of variance (22%). The high loading factor of conductivity is likely due to the contribution of high concentrations of dissolved ions in the groundwater. PC2, which accounts for 17% of the total variance, contains high loadings of temperature (0.67), turbidity (0.58), phosphate (0.82) and ammonia (0.8). The variables nitrate-N (0.83), chloride (0.82) and total coliform (0.75) contribute most strongly to the third component (PC3), which explains 17% of the total variance associated with anthropogenic activities influencing the shallow aquifers, such as septic tank leachate, domestic sewage, industrial effluent, and solid waste disposal. The significant correlation of nitrate-N with chloride (0.6), nitrate-N with total coliform (0.40) and chloride with total coliform (0.6) also support this interpretation. PC4 explains 14% of the variance, which is mainly related to ferrous iron (0.7), manganese (0.69), turbidity (0.63) and *E. coli* bacteria (0.69), assumed to be indicative of industrial pollution. PC5 projects 8% variance relating to high loadings of pH. PC5 projects 7.6% variance relating to high loadings of pH.

Similarly, in the data set of 2005, PC1, which accounts for 23% of total variance, contains high loading for ferrous iron (0.84), manganese (0.74) and ammonia (0.66), which is attributed to the influence of domestic and industrial wastes. PC2 explains 21% of variance and is associated with high negative loading of pH (–0.83) and positive loading of depth (0.60) and conductivity (0.71). PC3 accounts for 15% of total variance and is associated with high loadings for nitrate and age of the groundwater sources. This indicates that long-term urban anthropogenic activities may be directly related to nitrate contamination in the traditional water sources, such as stone spouts and some dug wells installed at old urban centres that have been used as "safe" drinking water sources for hundreds of years in Kathmandu.

Table 2: Principal Component loadings and explained variance for the three components with Varimax normalized rotation in 2005 data set

Parameters	Component 1	Component 2	Component 3
Age	0.08	0.08	**0.79**
Nitrate-N	-0.33	-0.02	**0.66**
Iron	**0.84**	0.20	-0.12
Manganese	**0.74**	-0.29	-0.09
Ammonia-N	**0.66**	-0.14	0.01
PH	0.11	**-0.83**	-0.23
Depth	-0.07	**0.60**	-0.32
Conductivity	-0.04	**0.71**	0.06
Explained variance	1.83	1.71	1.24
Explained variance (%)	22.83	21.39	15.44
Cumulative % of variance	22.83	44.22	59.67

3.2 Status and trend of nitrate-N - possible indicator of anthropogenic activities

Based on land use map of 1978 and satellite images of 1989 and 2006, we found that the urban area of the valley expanded about fourfold from 1978 to 2006 (30 sq. km. in 1978 to 69 sq. km. in 1989 and further to 107 sq. km. in 2006) as shown as Fig. 2.

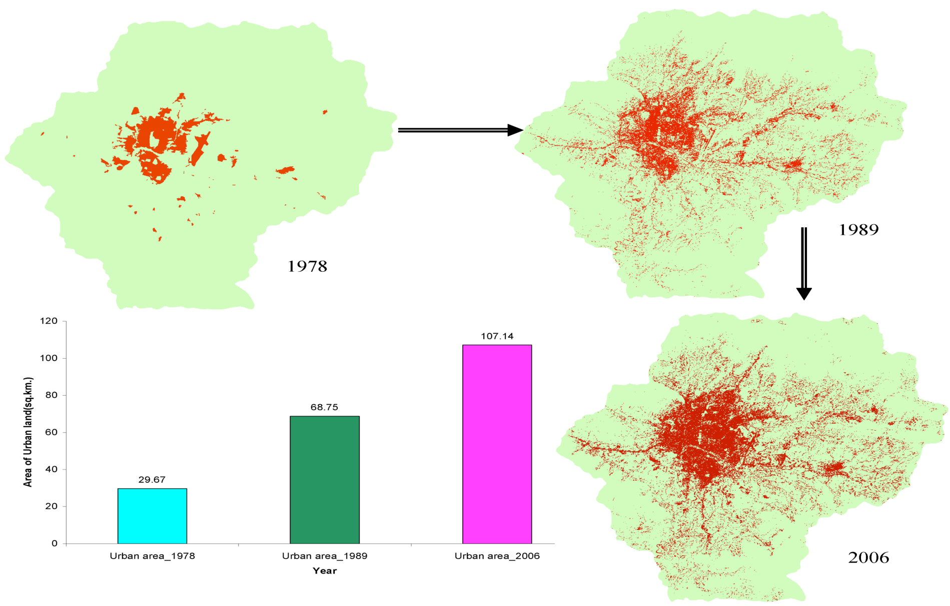

Figure 2. Increase of urban area (red colour indicates urban area) in Kathmandu valley during the period of 1978 to 2006

Rapid increase in urban land use contributed the rapid growth of urban population and anthropogenic activities. The main contribution to the rapid growth of urban population and anthropogenic activities in the valley is migration. For instance, between 1981 and 1991 the valley's urban population increased by over 82 %, in which migration accounted for 59 %, the largest ever since the 1950s. The urban population in the valley increased from 0.18 million in the 1950s to 0.99 in 2001 (ICIMOD, 2007), and further to approximately 3 million in 2011. Different anthropogenic activities at shallow depth such as leaking septic and sewer systems and disposal of human waste are attributed to shallow groundwater contamination. Nitrate-N is commonly used as an environmental indicator to trace the impact of anthropogenic activities on groundwater. It is noted that the average nitrate concentration decreased from 7.73 mg/L in 1999 to 5.21 mg/L in 2005, which is higher than present average value 4.22 mg/L in shallow groundwater aquifers of Kathmandu (Pathak et al., 2011b). Natural denitrification process occurring in the shallow aquifer of Kathmandu could be the reason for decreasing nitrate-N. Pathak and Hiratsuka (2010) reported the reduction of nitrate-N concentration in the shallow aquifer of Kathmandu due to denitrification phenomena investigating the relationship between nitrate-N and iron. Their work was the first attempt to report the reduction of nitrate due to denitrification processes occurring in shallow aquifer of Kathmandu valley. This fact was further verified by Nakamura et al. (2011), using nitrate-nitrogen and oxygen isotope technique.

Although, mean annual nitrate-N concentrations has slightly decreasing trend over the period from 1999 to 2008, extremely high nitrate-N concentrations (>10 mg/L) have been observed indicating its vulnerability to contamination. Extremely high values (up to 26 mg/L) have been observed, particularly in the northern areas of the valley and old urban areas. Spatial variation of nitrate-N and factors affecting its concentration are given in Fig. 3.

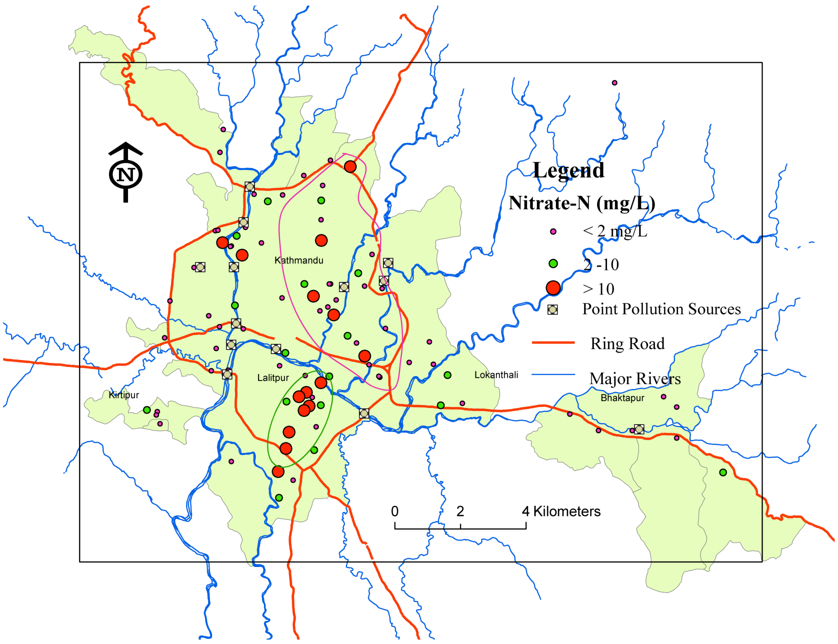

Figure 3. Spatial distribution of nitrate-N in shallow aquifer of Kathmandu modified from Pathak et al. (2011b) (Data source: nitrate-N concentration map has been prepared based on water quality data sampled from shallow aquifer of Kathmandu in September – October of 2008 by first author: River networks and administrative boundary maps are from Department of Survey, Government of Nepal

The northern part of the valley is dominated by sandy formations (categorized as high vulnerable to groundwater pollution), where haphazard disposal of solid waste and non-existing of WWTPs are common. Bittner (2000) also identified a plume of high nitrate (63.3 mg/L) in the shallow aquifers in the Chabahil that is located at northern part of valley. In addition, groundwater in areas of intensive washing activity as a consequence of the use of detergents has increased the concentrations of phosphate along with nitrate-N. In the southern part of the Bagmati river (encircled by green line in Fig. 3), nitrate were observed higher in concentrations even categorized as low vulnerable zones based on intrinsic aquifer vulnerability index are because of the haphazard disposal of untreated wastewater and leach from septic tanks for a long time (Pathak and Hiratsuka 2011a). WWTPs are not almost functioning except for a few in the Kathmandu valley and functioning WWTP accounts less than 5% of total demand. In this region, a very old urban area such as Patan is located, where many households use septic tanks which are not connected to sewer lines. Groundwater pollution can only be prevented in the area if wastewater disposal system is provided for all households.

In many countries, agricultural sources are the main cause of nitrate contamination. However, for the shallow aquifers in the Kathmandu, urban sources are worse than the contamination problems linked to agricultural activities. Higher nitrate-N concentrations (> 10 mg/L) were more frequently observed in urban area than in agricultural field. Comparisons were made of the median and upper-quartile summary statistic between agricultural and urban areas. The median concentration of nitrate-N in samples collected from urban areas (3.2 mg/L) was higher than that in samples collected from agriculture areas (1.1 mg/L). The median of the upper-quartiles of nitrate-N from urban areas (11.5 mg/L) is more than twice that of the agricultural areas (4.05 mg/L). Similar trend had been reported in previous studies (Chettri and Smith 1995). An investigation using nitrate nitrogen and oxygen isotope ratios to trace sources, (Nakamura et al. 2011) reported that human waste is the major source of nitrate contamination in the shallow groundwater aquifers of Kathmandu. PCA/FA and CA also provided the information about the possible influences of urban activities on groundwater quality of Kathmandu. Urban sources rather than agricultural sources are the principal sources of groundwater contamination in urban areas of underdeveloped and developing countries, where haphazard urbanization, poor drainage and sanitation are common.

3.3 Seasonal Water Quality Variations

The seasonal dataset of four seasons: pre-monsoon, monsoon, post-monsoon, and winter, was subjected to DA with measured parameters. The stepwise DA resulted in the three discriminating functions: discriminate function 1 (69.9% of total variance) with *p* values of 0.000, Wilk’s lambda (a test statistic to test differences between the means of identified groups for which a near zero value denotes high discrimination between groups) of 0.018 and discriminant function 2 (21.3% of total variance) with *p* value of 0.000, Wilk’s lambda of 0.154 and discriminant function 3 (8.8% of total variance) with *p* value of 0.000, Wilk’s lambda of 0.512. The DA yielded the corresponding correlation matrix assigning 92.9% correctly. The plot between first two discriminant factors (Fig. 4) resulted in the four seasons, which showed clearly separated four clusters in winter, pre-monsoon, monsoon and post-monsoon seasons.

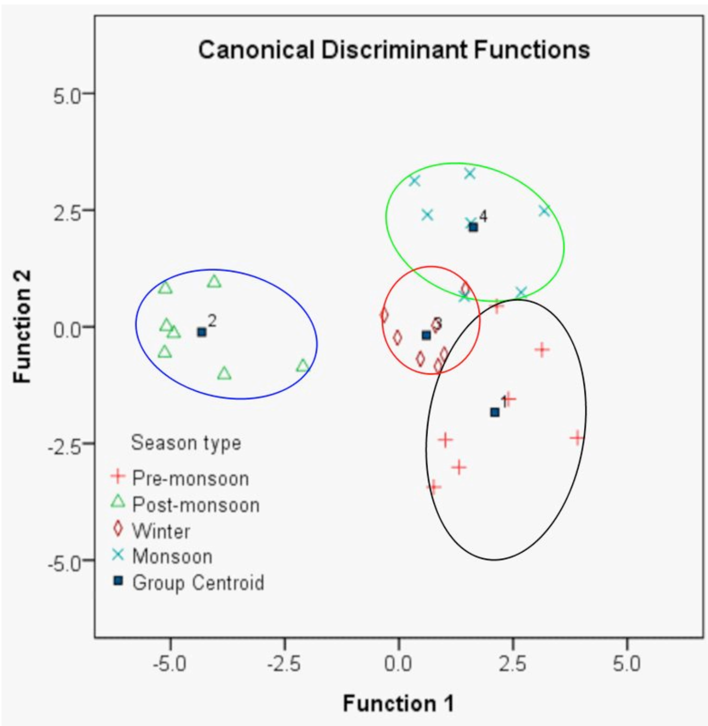

Figure 4. Plot of discriminant functions showing four seasonal clusters

Box and Whisker plot also showed that groundwater sources sampled during the wet season were more contaminated compared to the dry season. Contaminants originated at or near ground surface due to different anthropogenic processes, tend to be highest during the wet season corresponding to high rainfall intensity and groundwater recharge, compared to the drier winter season (Fig. 5). An analysis of 30 years of rainfall data at Kathmandu indicates that rainfall (1125.6 mm) during the wet season (June to September) is about 80% of total average annual precipitation. At the same time, corresponding recharge are typically highest at the same period i.e. wet season. It follows that contaminant concentrations tend to be higher during the wet season, in which the rising water tables due to the higher amount of recharge through porous sandy soils is accompanied by an increase in the transport of contaminants, i.e. from leaching of septic tanks, the poorly managed sewerage system and solid waste disposal.

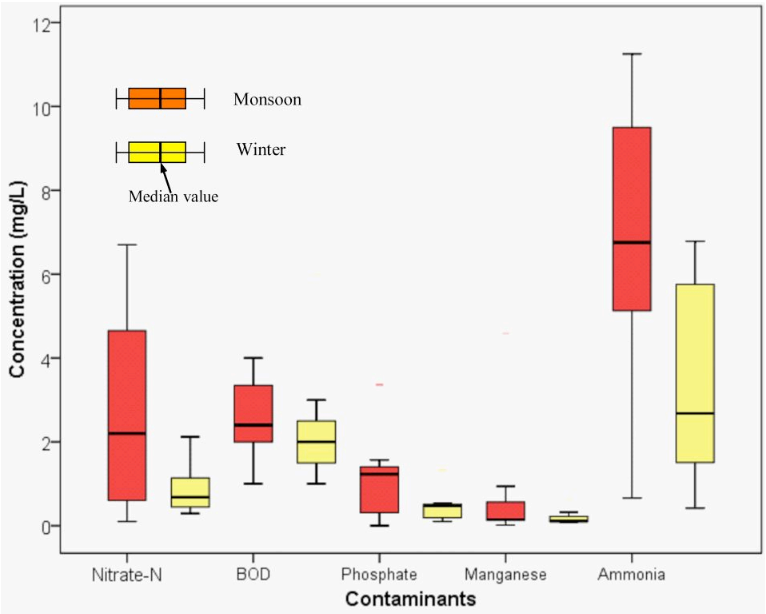

Figure 5. Box-Whisker plot selected contaminants in the wet season and dry season

4. CONCLUSIONS

Current status, trend and factors governing groundwater quality in shallow groundwater aquifer of Kathmandu were investigated. Results of PCA/FA revealed that the principal component has high loading factors of nitrate-N, chloride and total coliform, which is associated with anthropogenic activities influencing the shallow aquifers, such as septic tank leachate, domestic sewage, industrial effluent, and solid waste disposal. The significant correlation of nitrate-N with chloride, nitrate-N with total coliform and chloride with total coliform also support this interpretation. In addition, high loadings for nitrate and age of the groundwater sources to the same principal component indicate that long-term urban anthropogenic activities influencing shallow groundwater aquifers.

As one of the possible indicators of anthropogenic activities, nitrate-N trend was studied using the data sets sampled in different time windows from 1999 to 2008. Although, mean annual nitrate-N concentrations in the study area has slightly decreasing trend over the period from 1999 to 2008, many sampled sources were still highly contaminated by nitrate-N (up to 26.4 mg/L) indicating its high vulnerability to contamination. This study also revealed that urban sources rather than agricultural sources are the principal sources of groundwater contamination. Impact of seasonal variations on groundwater quality was also discussed. The application of DA confirmed the seasonal variation of the water quality data with 92.9% correct classification. Box–Whisker plots facilitated to investigate the patterns of water quality and pollution sources in different seasons.

This study illustrates the utility of advanced statistical techniques for analysis, interpretation of spatial and temporal datasets and identification of factors affecting groundwater quality which can be informative to local water quality managers as well as professions who are interested in the similar problem in the other places. Moreover, systematic investigations on the current status and trends of groundwater quality and its influencing factors will facilitate the design and development strategies that can protect the environment and prevent further deterioration of the affected aquifer systems.

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