Groundwater contamination assessment for sustainable water supply in Kathmandu Valley, Nepal

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Abstract A study was carried out to assess the water quality situation of groundwater sources in Kathmandu Valley, Nepal. Groundwater has remained to be a major water supply source for a population of 1.5 million at present in the valley. The focus of this study was to evaluate the extent and sources of groundwater contamination. Water sampling was carried out in selected deep wells and shallow sources. The level of pollution was evaluated by comparing the water quality results with WHO guidelines. The major problems with the dug wells, hand pumps and spouts were found to be the elevated nitrate and mercury contents. The deep wells located on the central aquifer were found to have a serious threat of ammonia pollution. Deep wells were also found to have iron, manganese and mercury concentrations exceeding the guideline values. Multivariate statistical analysis was carried out to cluster the sampling sources and identify the common factors describing the potential sources and possible mechanisms associated with the contaminants. The results suggested that disintegration of the sediment organic matter under strong reducing environment leads to the origin of the unusual water qualities at the central confined aquifer. This process may be microbiologically mediated and occurs with the simultaneous reduction of species such as arsenic, iron, manganese and sulfate. Both natural and anthropogenic water quality problems were observed in the groundwater system of Kathmandu valley. Attention should be focused to consider distinct strategies to address these problems.

Keywords Ammonia; groundwater; Kathmandu; mercury; multivariate data analysis; nitrate; organic matter

Introduction
This research is focused on the groundwater sources of Kathmandu Valley in Nepal. The small intra-mountain valley situated at an altitude of about 1,300 m above the sea level covers an area of roughly 500 km². The valley constitutes the country’s single largest urban economy and has a population of 1.5 million. The current piped water supply demand in Kathmandu Valley is about 150 million litres per day (MLD), but the combined supply of groundwater and surface water in the dry season varies between 65 and 85 MLD. Even in the wet season, the supply only reaches 140 MLD. As the surface water yield is crucial during the dry season, a policy of conjunctive use of groundwater and surface sources has been implemented and on an average the contribution of the latter remains close to 50 per cent of the total supply. Because of supply deficit problems, water is distributed intermittently. A large scale “Melamchi Water Supply Project (MWSP)”, which will bring 170 MLD of water from outside of the valley during its first phase, is in progress and expected to complete by 2008. Present anticipations indicate that the groundwater use will be continued even after the completion of MWSP.

The valley basin is comprised of a thick band of Pliocene-Quaternary fluvio-lacustrine sediments. The deep aquifer system can be divided into three groundwater zones based on hydrogeological considerations. The northern zone, forming the main aquifer, has the upper deposits composed of unconsolidated and highly permeable micaceous quartz and gravel materials. Because of relatively higher permeability and shallowness, most of the Nepal Water Supply Corporation (NWSC) production well fields are located in this region. In the central zone, the upper deposits are composed of impermeable very thick stiff black
clay with peat and lignite bands. Unconsolidated low permeable coarse sediments underly-
ing the clay bed constitute a confined aquifer. The urban cores of Kathmandu and Lalitpur
(Patan) are located in this middle region, therefore, the majority of the private deep wells
extract groundwater from this aquifer. The formation of the southern part is characterized
by a thick impermeable clay and basal gravel of low permeability. The unconfined aquifer
system also constitutes a major water source for numerous spouts, dug wells and hand
pumps throughout the valley.

This study was designed to assess the quality of groundwater which is being used for
water supply purposes. Emphasis was made to cluster the sampling sources together based
on common hydrochemical properties and identify mutual factors describing the origin of
these properties. Efforts were also made to establish correlations among different water
quality parameters. With these, analysis attempts were finally made to identify the potential
sources and possible mechanisms associated with the contaminants.

Materials and methods
Groundwater samples were collected from 31 sampling sites in November 2000. The
sampling sites included 12 NWSC deep wells, 10 private deep wells, 5 dug wells, 2 hand
pumps and 2 spouts. A schematic map of the sampling locations is shown in Figure 1.
Parameters such as temperature, pH, dissolved oxygen (DO), electrical conductivity (EC),
oxidation-reduction potential (ORP), ferrous iron (Fe, II) and ammonia (NH₃) were meas-
ured immediately at the collection sites using the potable probes and HACH kits. The water
samples intended for the analysis of heavy metals were acidified at the site. The samples
were transported to the laboratory of Department of Urban Engineering (DUE), the
University of Tokyo where the metal species were analyzed by Inductively Coupled
Plasma – Atomic Emission Spectrophotometer (ICP-AES) and Inductively Coupled
Plasma-Mass Spectrometer (ICP-MS). The anion analysis was carried out with Ion

![Figure 1 Location of sampling sources](https://iwaponline.com/wst/article-pdf/46/9/147/426524/147.pdf)
Chromatography and nitrate (NO$_3^-$), NH$_3$, and dissolved organic carbon (DOC) contents were also measured at the DUE laboratory.

Multivariate data analysis was carried out using statistical package SPSS 10.0 for WINDOWS (SPSS Inc., Chicago, Illinois, USA). A matrix comprising of 31 cases for the sampling sites and 44 variables for the water quality parameters including those determined at the site and at the laboratory were analysed with Principal Component Analysis and Hierarchical Cluster Analysis methods.

**Results and discussion**

**General trends**

In general, the dug wells, hand pumps and spouts were found to have elevated levels of NO$_3^-$ and mercury (Hg) contents. Relatively high levels of NH$_3$, Fe, manganese (Mn), chloride (Cl$^-$) and sulfate (SO$_4^{2-}$) were also observed in these sources. The deep wells located on the central aquifer were found to have a serious threat of NH$_3$ pollution. The deep wells located on the northern zones had EC values in the range of 160–260 µS/cm, however, these values for the deep wells from the central and southern zone were in the range of 432–1,178 µS/cm. The shallow well ORP values were found to be positive and concentrated around 130–150 mV suggesting oxic conditions in the aquifer. The NWSC wells in the south were also found to possess positive ORP values. However, the deep well ORP values in the central zone were negative and crowned around –100 mV, suggesting strong reducing conditions in the aquifer. Unusual DOC concentrations of greater than 15 mg/L were revealed in the five deep wells of the central zone.

A summary of the results showing the parameters exceeding the World Health Organisation (WHO) drinking water quality guideline values is given in Table 1. The arsenic (As) content was found to exceed the guideline value in four wells from the central region where extremely high values of some other parameters such as DOC, NH$_3$ and phosphate (PO$_4^{3-}$) were observed. Most of the wells were found to have exceeding Hg levels with highest concentration observed on a dug well from the Lalitpur core area, which could possibly be originated from industrial sources. Deep wells were also found to have Fe, Mn and Hg concentrations exceeding the guideline values. Four deep wells on the central region were found to have exceeding As guideline values.

**Multivariate statistical analysis**

Hierarchical cluster analysis: The joining of the clusters is shown with a dendogram in Figure 2. The clustering clearly showed a distinct pattern of three groups of the sampling sources. The wells in the north and south were put in the first group whereas the shallow sources and the deep wells from the central zone made up the second and third group, respectively. As shown in the Figure 2, the topmost position of N4 and N8 indicated that the

<table>
<thead>
<tr>
<th>Parameters</th>
<th>WHO guideline value (WHO, 1996)</th>
<th>No. of samples exceeding the guideline*</th>
<th>Highest concentration observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_3$, mgN/L</td>
<td>1.3</td>
<td>19</td>
<td>62.0</td>
</tr>
<tr>
<td>NO$_3^-$, mgN/L</td>
<td>12</td>
<td>5</td>
<td>25.0</td>
</tr>
<tr>
<td>Fe, mg/L</td>
<td>0.3</td>
<td>12</td>
<td>12.1</td>
</tr>
<tr>
<td>Mn, mg/L</td>
<td>0.1</td>
<td>17</td>
<td>1.17</td>
</tr>
<tr>
<td>As, µg/L</td>
<td>10</td>
<td>4</td>
<td>73.8</td>
</tr>
<tr>
<td>Hg, µg/L</td>
<td>1</td>
<td>23</td>
<td>303.0</td>
</tr>
<tr>
<td>DOC, mg/L</td>
<td>0.2–15**</td>
<td>5</td>
<td>63.6</td>
</tr>
</tbody>
</table>

* Total number of samples = 31, ** Typical range in groundwater (Thurman, 1985)
pair had the shortest distance among all cases and were combined at the first step. This suggested that this pair had the most similar characteristics of the water quality parameters. The other pairs having close distances were N2 and N3; S8 and S9; N6 and N7; P7 and P8, P1 and P10; N9 and P6.

A general trend on the clustering indicated that the water quality in private wells at the center is well differentiated to the water quality at the north and south zones. Interestingly, the water quality of the shallow wells were found closer to the northern and southern zones indicating that the chemical characteristics of the northern aquifer is closer to the unconfined aquifer than the confined aquifer at the center. Comparing dendogram with the location of the wells shown in Figure 1, it can be concluded that the similar water quality pattern is normally exhibited by the wells situated on the periphery of the core area where as the wells located on radial proximity indicate a dissimilarity. This clearly explains the anomalies shown by P9 and N9. After rearranging the sampling locations as per the order obtained from clustering as shown Figure 2, plots showing the concentration of selected chemical species were made and shown in Figure 3. As shown in Figure 3, the major cations dominating the shallow wells were calcium (Ca), magnesium (Mg), sodium (Na) and potassium (K). However, in addition to these metals, Mn and Fe were also found significantly in deep wells. Major anions found in the shallow wells were NO\textsubscript{3}\textsuperscript{–}, Cl\textsuperscript{–}, and SO\textsubscript{4}\textsuperscript{2–} where as the anions dominating in the deep well samples were PO\textsubscript{4}\textsuperscript{3–} and HCO\textsubscript{3}–. The central wells were found to have extremely high content of DOC and NH\textsubscript{3} where other species such as Fe, Mn and HCO\textsubscript{3}– dominated. The average total ion densities of the second and third clusters were 2.5 and 3.3 times higher than that of the first cluster.

Principal component analysis: The correlation matrix of the variables revealed strong positive correlations \((r > 0.7)\) between several parameters such as: EC and Mg (0.86), EC

![Figure 2 Dendogram using ward method obtained from hierarchical cluster analysis (N = NWSC wells, S = shallow sources, P = private wells)](https://iwaponline.com/wst/article-pdf/46/9/147/426524/147.pdf)
and Ca (0.74), EC and boron (B) (0.71), strontium (Sr) and Ca (0.86), cobalt (Co) and nickel (Ni) (0.92), NH\(_3\) and DOC (0.78), NH\(_3\) and PO\(_4^{3-}\) (0.87), NH\(_3\) and HCO\(_3^-\) (0.77), NH\(_3\) and vanadium (V) (0.72), DOC and PO\(_4^{3-}\) (0.85), DOC and HCO\(_3^-\) (0.75), PO\(_4^{3-}\) and phosphorus (P) (0.97), cesium (Cs) and HCO\(_3^-\) (0.73). These strong associations could primarily be put into two distinct groups: firstly, the elements contributing to the conductivity of water as of the strong dependency between EC, Mg, Cl, Ca, B, Na, Sr and V. Secondly, the strong associations between DOC, NH\(_3\), PO\(_4^{3-}\), P and HCO\(_3^-\) and Fe(II) indicated the parameters contributing to the typical characteristics of the non-rechargeable and stagnant groundwater. The major exchangeable ions, Na and Ca (0.38), Na and Mg (0.57), Sr and Ca (0.86), Sr and Mg (0.53), Sr and Na (0.31) were found to be correlated positively indicating the origin of major cations to be dissolution/precipitation processes. The major anions in the shallow wells, SO\(_4^{2-}\), NO\(_3^-\), and Cl\(^-\) were found to be well correlated, where as the major anions in the deep wells HCO\(_3^-\) and PO\(_4^{3-}\) were also well correlated.

The component analysis of the hydrochemical data revealed eleven factors greater than unity and the first five factors accounted for 63.82% of the variability of the original variables. Factor 1 explained 24.51% of the variability and the variables having strong correlation with this factor were NH\(_3\) (0.92), P(0.85), HCO\(_3^-\) (0.84), PO\(_4^{3-}\) (0.82), DOC(0.81), Temp. (0.81), Cs (0.774) and silicon (Si) (0.79), titanium (Ti) (0.65), Fe(II) (0.64), vanadium (V) (0.62) and chromium (Cr) (0.61). The strong association of these parameters with factor 1 indicated a strong linkage of these parameters with the process described by factor 1 which is presumably the disintegration of the sediment organic carbon (SOC). The parameters strongly associated with the first factor should be the active reactants or by-products associated with this process in the central aquifer. The observed unusually high concentration of NH\(_3\), PO\(_4^{3-}\), DOC and HCO\(_3^-\) and Fe (II) strongly support this hypothesis.
Factor 2, which explained 18.01% of the variability, was found to be participated in mainly by EC (0.876), Mg (0.76), Ca (0.76), Na (0.73), B (0.64), rubidium (Rb) (0.64), NO$_3^-$ (0.60), Sr (0.58), antimony (Sb) (0.56), zirconium (Zr) (0.52), and SO$_4^{2-}$ (0.51) and could be interpreted as relating mainly to the origin of minerals in the groundwater due to dissolution and precipitation processes. Factor 3 explained 8.43% of the variability and the participating elements were the trace metals Zr (0.60), molybdenum (Mo) (0.58), lanthanum (La) (−0.72), Ni (−0.69), and Co (−0.59). Factor 4 explained 6.62% of the variability and the participating elements were selenium (Se) (0.68), Sr (0.52), Bi (0.40), DO (0.41), and Ca (0.40). Factor 5 explained 6.25% of the variability and the participating elements were Co (0.46), Ni (0.45), Sb (0.40), silver (Ag) (0.45) and tin (Sn) (0.48).

A component plot between factor 1 and factor 2 is shown in Figure 4. The points in this plot are the variables and the coordinates of each variable are its factor loadings. The variables strongly associated (having a higher loadings) with factor 1, for example, NH$_3$, P, PO$_4^{3-}$, DOC, Cs, Fe (II), As, Co are found at the proximity of the horizontal zero line. Similarly, the variables strongly associated with factor 2, for example, Rb, Na, Ca, Mg, Cl$^-$ are found towards the vertical zero line. The variables having associations with both the factors, for example, EC, B, V, ORP are found away from the zero lines.

It is interesting to note here that in a similar study carried out at the Hanoi City in Vietnam, similar factors were extracted from a set of similar water quality data (Tran et al., 2001). The study also indicated DOC, NH$_3$, Fe and As as the contributors to factor 1 and Mg, Cl, Sr, Si, Na, Mn, EC and ORP as the major contributors to factor 2. This resemblance points towards a possibility of establishing similar indicators identifying the groundwater contamination.

Figure 5 shows the correlations between factors 1 and 2 and the sampling wells have been shown as per their location in different regions. The shallow source samples and the deep well samples from the south appeared at the negative side of factor 1 and positive side of factor 2. However, the north deep well samples were clustered at the negative side of both factors. The wells from the central zone appeared on the positive side of factor 1 and mostly on the neutral zone of factor 2. This clearly indicates the influence of dissolution/precipitation processes on the shallow well samples. The deep well samples from the central zone were found to have a strong influence on the process described by factor 1. The highest loading or the extreme positioning of P1 and P10 indicated the severe influence of this phenomenon in these wells. However, the deep well samples from the north zone could be interpreted as least influenced by the former as well as latter processes.
In Figure 5, a linear trend of pollution among the NWSC and private wells is clearly observed.

**Conceptual model describing the ground water pollution**

The results outlined above are in accordance with other previous studies. JICA (1980) reported the presence of dissolved-in-water gas comprising methane (CH$_4$), carbon dioxide (CO$_2$) and nitrogen (N$_2$) in the fluvio-lacustrine deposits in the central zone. The study reported that the groundwater obtained from the gas reserve area contained a high concentration of NH$_4^+$, HCO$_3^-$, free hydrogen sulfide (H$_2$S), Fe (II) and potassium permanganate (KMnO$_4$) value. These features were also reported by JICA (1990). Based on the tritium and carbon-14 dating analysis, JICA study estimated the age of the groundwater in the central aquifer to be in the range of 9,000 to 28,000 years (JICA, 1990). However, based on the analysis of chlorine-36, Creswell et al. (2001) estimated the groundwater age to be in the range of 200,000 to 400,000 years. These observations lead to the conceptualization of the mechanisms which give rise to the highly polluted water quality particularly in the central zone. This aquifer is comprised of sand and gravel beds containing dark clays, lignites, and peats and contains non-rechargeable, stagnant or “fossil” groundwater. Under a strong reducing environment a process of disintegration of the organic matter is undergone in the sediments. The sediment organic carbon (SOC) is eventually oxidized to dissolved inorganic carbon (DIC), inorganic nitrogen species and DOC which include humic and fluvic acids. This process is microbially mediated and occurs with the simultaneous reduction of iron, manganese, SO$_4^{2-}$, or CO$_2$. The sequence of reduction (Fe III to Fe II, Mn IV to Mn II, SO$_4^{2-}$ to S, CO$_2$ to CH$_4$, N$_2$ to NH$_4^+$) is dependent on many surrounding factors (Stumm and Morgan, 1996). The observed ORP values down to –195 mV in the deep wells from the central zone and the exceptionally long groundwater age clearly indicated the stable state of the reducing environment. This process of SOC disintegration eventually leads to the evolution of the high concentration of the NH$_3$ and other natural gases in the aquifer. When the microorganisms oxidize sediment organic matter SOC to DIC and DOC, phosphate nutrient is released into the bulk water (Buckau et al., 2000). In this study, one of the indicators of this process is the observed strong relationship of DOC with PO$_4^{3-}$ (r = 0.85). Build up of dissolved phosphate may under suitable conditions bring about the precipitation of metal phosphate minerals. Stregnite (FePO$_4$.2H$_2$O) is a commonly found species in freshwater sediments (Stumm and Morgan, 1996).
Alternatives for management

The concentration of various parameters and the foregoing discussion revealed that the deep aquifer appears to have natural groundwater quality problems particularly in the central zone. As this aquifer is of “non-rechargeable” type, only a limited extraction should be permitted. Nitrate and Rb is known to originate from anthropogenic sources. Therefore, the cause of the pollution of the shallow aquifer is presumably attributed to the unmanaged discharges originating from both domestic and industrial wastes. These issues must be addressed with earnest importance as the water from the shallow sources is consumed untreated. It is recommended to consider both short and long term strategies to address these problems. As a large scale surface water supply project is in the pipeline, the groundwater dependency is expected to ease after the completion of the project. However, without a proper licensing and tariff system, groundwater use will be continued as surface water will be available only at higher cost. Therefore, a short term strategy should be: identify the polluted wells, use the water from polluted wells only after a thorough treatment and a long term strategy should be: monitor the groundwater quality continuously, prepare and implement a comprehensive ground water quality management plan. Considerably more attention should be focused on delineation of contaminated areas and formulation of a strategy of either the withdrawal from clean sources only or treatment.

Conclusions

The groundwater sources, meeting half of the water supply demand in Kathmandu valley, were found to have both natural and anthropogenic contamination problems. Shallow sources were found to be contaminated with nitrate and mercury. The deep wells of northern and southern aquifers were found relatively clean where as excessive concentrations of ammonia, dissolved organic matter, iron and manganese were found in the deep wells from the central aquifer. A comparison with WHO guidelines revealed that these waters pose significant health problems. A situation of minimal hydraulic contact with the upper aquifer leads to a strong reducing environment in the central aquifer. Simultaneous processes of microbial disintegration of sediment organic matter and reduction of some chemical species leads to the origin of unusual concentrations of ammonia, dissolved organic carbon, iron and manganese. Attention must be focused to have both short and long-term management strategies.

References


