Asian Journal of Water, Environment and Pollution, Vol. 12, No. 4 (2015), pp. 43–59.
DOI 10.3233/AJW-150017

Urban Pollution of Bagmati River Corridor within the Densely Populated Kathmandu Valley in Nepal

Y.J. Khadka, M.Z. Iqbal[1]* and K.J. De Nault[1]
Environmental Programs, University of Northern Iowa, Cedar Falls, IA 50614, USA
[1]Department of Earth Science, University of Northern Iowa, Cedar Falls, IA 50614, USA
✉ m.iqbal@uni.edu

Received April 22, 2015; revised and accepted September 26, 2015

Abstract: The Bagmati River within the Kathmandu Valley in Nepal was studied for its water quality and heavy metal distribution in the riverbed sediments. Water and sediment samples were collected from 10 sites for chemical analysis. The Water Quality Index (WQI) of the river was calculated using nine water quality parameters recommended by the National Sanitation Foundation (NSF): Dissolved Oxygen (DO), *E. coli*, temperature, pH, Biochemical Oxygen Demand (BOD), turbidity, Total Dissolved Solids (TDS), nitrate, and phosphate. Out of the 100 water samples, 77 were in the Bad category, six in the Medium category, and the remaining 17 were in the Good to Excellent categories. The two parameters that significantly impacted the WQI values were DO (range: 0.07 – 8.25 mg/L) and *E. coli* (range: 200 – 1.3×10^7 number per 100 ml). The highly impacted zone has urban/industrial land use where the average TDS (592 mg/L) is 34% higher than that observed (442 mg/L) at the urban sites immediately upstream. Sediment samples were analyzed for heavy metals of major environmental concern: As, Co, Cr, Cu, Mn, Ni, Pb and Zn. The urban/industrial areas are highly vulnerable to future impairment, especially with their possible influx from the numerous industrial sources.

Key words: Bagmati river, heavy metals, Nepal, water pollution, water quality index.

Introduction

The degrading state of urban water bodies is a worldwide environmental concern.This is of particular concern in developing countries where untreated industrial and municipal wastewaters directly discharged into rivers and lakes (Jiang et al., 2015; Paul and Meyer, 2001). Urban rivers also get significant loads of pollution from storm runoff, which contains debris and contaminants flushing through roofs, streets and roads. Pollutants in the runoffs include atmospheric deposition, fertilizers, pesticides, and vehicular exhausts and tears. These are common sources of inorganic and organic compounds, oils, greases and heavy metals (Geissen et al., 2015; Stroomberg et al., 1995).

An important aspect of urbanization is landscape transformation, which greatly affects the hydrology of a watershed. Compared to the natural soil surfaces, urban surfaces are highly paved and thus impermeable (Ahiablame et al., 2013; Paul and Meyer, 2001). This lowers the rate of vertical infiltration of rainwater, resulting in high surface runoff and flash floods. An area that is paved more than 75 percent is likely to increase runoff from 10 to 55 percent of total precipitation (Tourbier, 1994). As most of the urban streams are highly channelized, it further increases the risk of high peak discharge and flooding. Channelized streams are not only vulnerable to higher riverbed erosion, they also increase the amount of suspended solids in the water

*Corresponding Author

(McMahon and Harned, 1998). Agriculture is another key source of water pollution. Of particular importance are the fertilizers and pesticides, which eventually find their ways to surface and groundwater bodies. Among various inorganic and organic compounds, phosphorus and nitrogen form the major bulk of these applications and are responsible for the widespread eutrophication of rivers, lakes and coastal waters (Holmroos et al., 2012; Fraterrigo and Downing, 2008; Carpenter et al., 1998).

In the recent decades, heavy metals have raised issues of environmental concern (Bai et al., 2012; Singh et al., 2005). This is primarily due to their widespread use in industries, automobiles, and household appliances and their increasing levels in water bodies. These have potential impacts on human and environmental health. Due to the constant biogeochemical cycling of elements, presence of heavy metals in natural waters and sediments is expected. But, even a slight increase in their natural concentration makes them potentially toxic to the aquatic environment. Such toxicity could bring about changes in the natural cycling of other chemicals and nutrients. It can form new compounds, and bring about changes in diversity and density of aquatic flora and fauna (Moore and Ramamoorthy, 1984). Aluminum (Al), arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), mercury (Hg), molybdenum (Mo), nickel (Ni) and zinc (Zn) are among the commonly examined heavy metals. These metals are extensively used in the industrial processes and are widely distributed in the environment. Many of them are potentially toxic to plants and animals (Yadav, 2010; vanLoon and Duffy, 2005).

Heavy metals in rivers and lakes are largely retained by sediments, suspended particles, and organic matter. The large particles eventually settle to the bottom and become a source of dissolved metals in the water column. The study of heavy metals in sediments is important because many aquatic plants and animals directly feed from sediments. They are likely to uptake these metals that could be potentially toxic to them (Zhang et al., 2014; Ouyang et al., 2002). The concentrations of heavy metals in sediments largely depend upon factors such as sediment types and particle sizes. Clay minerals generally contain higher concentrations of metals than carbonate sediments. Similarly, elemental concentrations are found to increase with decreasing grain size (Turekian and Wedepohl, 1961). It is important to evaluate the association between different types of metals and stream sediments. Biochemical behaviour of these metals in different environmental conditions forms an important aspect of water quality studies. Association of metals with moving particles is especially important because the sediments can act both as sinks and sources of heavy metals in water bodies (Salomons and Forstner, 1984).

Identifying the level of pollution in water bodies is important for the development of conservation and mitigation programmes. Different water quality monitoring techniques have been developed over the years for various uses such as drinking, swimming, aquaculture, or recreational purposes (Abbasi and Abbasi, 2012; USEPA, 1997). The Water Quality Index (WQI),which is developed by the National Sanitation Foundation (NSF), has been one such technique for classifying the state of surface water bodies. This index mostly represents water bodies in natural condition and can be applied for use in recreational and aesthetic purposes (Tyagi et al., 2013).

The hydrology of a region is always influenced by precipitation, evapotranspiration, runoff, groundwater flow, and weathering phenomena. Although the above factors have important roles in regulating and maintaining ecological integrity, they can have serious negative impacts on urban water bodies. For instance, the seasonal variations in flow rates and runoff are found to significantly alter pollutant and sediment influx to water bodies (Wang et al., 2013; Vega et al., 1998).

This study is focused on the Bagmati River that forms a major drainage system in the Kathmandu Valley of Nepal. The river is a key source of surface water to its inhabitants. However, despite being a high value resource in terms of drinking water supply, irrigation, industries, and cultural aspects, the Bagmati River and most of its tributaries have been under tremendous pressure from municipal and industrial activities in recent decades (ADB and ICIMOD, 2006; ICIMOD et al., 2007). Studies have shown that the quality of water in the Bagmati River has been severely degraded in the recent decades. It is now considered to be one of the most polluted rivers in the world (Bhatt and McDowell, 2007; Kannel et al., 2007a). The Kathmandu Valley has seen extremely high rates of population growth over the last five decades, from about 0.18 million in 1954 to an estimated 2.18 million in 2009 (Pradhan, 2004; Thapa and Murayama, 2010).

To meet the demand for water, most of the rivers inside the valley have been tapped or diverted. This has compromised the quantity and quality of water in the rivers (Bhatt and Gardner, 2008). One of the major effects of this population explosion is the generation of large amounts of municipal and industrial wastes. Because of inadequate infrastructure to manage these wastes, they are discharged into the rivers causing degraded condition of the Bagmati River and its tributaries (Devkota and Watanabe, 2005; Kannel et al., 2006; Kannel et al., 2007a; Pokhrel and Viraraghavan, 2005).

The current investigation was conducted in the Bagmati River watershed with three primary objectives; (1) delineate contaminant hotspots in the watershed to prioritize areas for immediate remedial measures. This would allow regulatory agencies to address probable human health disasters in the watershed; (2) identify probable zones of high metal toxicity in order to control long-term ecological damage to the Bagmati River system; and (3) determine probable impact of rainfall on the surface water quality in the study area. This information would particularly help in routing the huge volume of garbage that moves through the stream channel after intense rain events. To achieve the above objectives, multiple chemical parameters were assessed and then used to calculate the National Sanitation Foundation's recommended Water Quality Index (WQI) for the sampling sites. Additionally, distribution of heavy metals in river sediments and their possible contaminant sources were investigated.

Study Area

The study was focused on the Bagmati River within the Kathmandu Valley in Nepal (Figure 1a). Kathmandu Valley is the economic, political and cultural hub of Nepal. The highly urbanized cities that lie within the valley include Kathmandu (the capital city), Bhaktapur and Lalitpur, which make the Kathmandu Valley one of the most densely populated areas in South Asia. The area has an estimated 2.18 million people inhabiting about 684 sq. km (Thapa and Murayama, 2010). Within the Kathmandu Valley, the Bagmati River is the primary source of water for domestic, industrial and irrigation purposes. The source of the river is the northern hills of Shivapuri National Park. The river cuts through the highly urbanized section of the valley before heading towards the Ganges River in India.

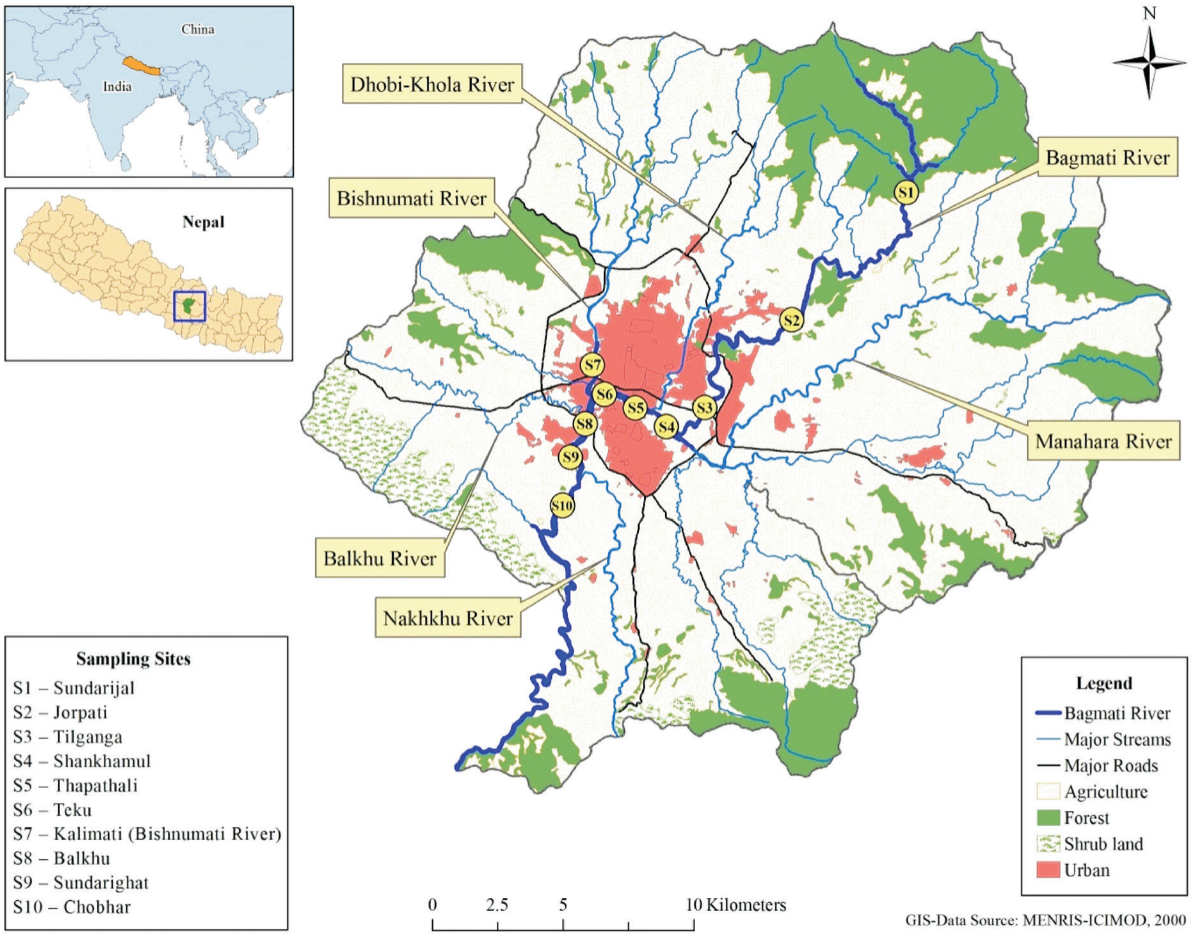

Figure 1a: Map showing the study area and the sampling sites (MENRIS-ICIMOD, 2000).

Climate and Geology

The Kathmandu Valley is located between latitudes 27°31’55” N and 27°48’56” N and longitudes 85°11’11’ E and 85°31’52’ E. The area is in the mid-hills of Nepal, which is located at the centre of the Himalayan region. The valley has a sub-tropical cool temperate climate. It receives an annual rainfall of about 1440 mm, the most of which occurs during the monsoon season from June to September (CBS, 2008; Savada, 1991; Thapa and Murayama, 2010). The air temperature varies from –1 °C (30 °F) in winter to 35 °C (95 °F) in summer. The relative humidity in the area varies from 50% in dry seasons to more than 80% during the monsoon months.

Topographically, the Kathmandu Valley is an intramontane basin, which is surrounded by hills up to 2700 m high. The average altitude of the valley floor is 1336 m above sea level (CBS, 2008; Shrestha et al., 1999; Thapa and Murayama, 2010). The valley extends roughly 30 km north-south and 35 km east-west producing a bowl-shaped topography. The valley used to be a lake during Plio-Pleistocene period. Thus, the basin is filled with lacustrine and deltaic river sediments composed mainly of unconsolidated clay, silt, sand and gravel. The age of the river sediments ranges from late Pliocene to present (Gurung et al., 2007; Kannel et al., 2007b). The area topography shows important influences on its water quality. Because the valley is surrounded by hills, rainwater from the watershed boundaries runs off to the main channel with a high velocity. As a result, high dissolved oxygen is observed in the headwater region due to high water turbulence, causing increased levels of aeration and low organic nutrient content in water.

In contrast, biochemical oxygen demand tends to be high in urban areas where municipal wastes run down the topographic slope as a part of surface runoff (Pradhan, 2005). The bedrock geology of the valley is mostly dominated by metamorphic rocks although the rock types vary along the flow path of the river. Common rock types found in the valley consist of gneiss, quartzite, phyllite, granite, slates, schist, limestone, sandstone and shale (Shrestha et al., 1998). Gneiss and schist are common in the headwater region, with the lower reaches mostly consisting of fine grained phyllite, slate, shale, claystone, mudstone and limestone (Bhatt and McDowell, 2007).

The Bagmati River is mostly fed by mountain streams from the north and by numerous creeks draining the uplands on either sides of the valley. The main channel has direct hydrological connections with an upper unconfined aquifer over the northern half of the valley (Figure 1b). This Late Quaternary formation consists of discontinuous sand, silt and clay lenses, which is up to 20 m thick at places but gradually tapers towards the centre of the valley. Underlying the Late Quaternary shallow aquifer is a clay-rich aquitard which gradually thickens toward the southwest section of the valley. Below this aquitard lies a deep, confined aquifer mostly composed of sand and gravel with discontinuous layers of clay, peat and lignite. The confined aquifer recharges mostly from the margins on the northern and the southern parts of the valley where it is connected to the overlying unconfined aquifer. The thickest portion of this aquifer lies around the centre of the valley, showing up to 300 m of thickness. There is no direct hydrological connection of the Bagmati River with the confined aquifer within the valley (Cresswell et al., 2001).

Land Use

The pervasiveness of lacustrine and fluvial sediments in the Kathmandu Valley makes it highly favourable for agriculture. A variety of crops including wheat, mustard, paddy, maize, beans, potatoes and a range of vegetables are planted in the valley plains and along the surrounding hill slopes. Historically, the valley has been extensively used for agriculture due to its fertile soil and abundance of water. However, the growth of urban centres in recent decades has shifted the focus from agricultural fields to the urban areas. Between 1955 and 1996 alone, the urban areas inside the Kathmandu Valley increased by over 200% (Haack, 2009). Land use statistics of 2000 shows 12.6% urban areas in the valley compared to 2.79% in 1967 (Thapa and Murayama, 2008).

Materials and Methods

Water and sediment samples were collected from nine locations along the Bagmati River and one location along the Bishnumati River within the Kathmandu Valley (Figure 1). Since the Bishnumati River adds significant amount of pollution loads to the Bagmati River, site S7 was added to this study for monitoring. The sampling was performed from mid-May through mid-July 2009. This is part of the monsoon season when the majority of the annual rainfall occurs in the area. High flow regions and important hydrologic characteristics of the watershed are expected to be well observed during this window of time. From the ten selected locations, water samples were collected once a week for 10 weeks. Riverbed sediment samples were collected from all these sites once every three weeks where top 2 to 3 inches of soft stream sediments were recovered by a grab sampler. A total of 100 water samples and 30 sediment samples were collected during the study. The water samples were collected in sterile High Density Polyethylene (HDPE) plastic bottles and refrigerated at 4 °C until analysis. The sediment samples were collected in sterile plastic zip-top bags and oven dried at 75 °C. Although most of the analyses were done in Kathmandu the samples were shipped to the University of Northern Iowa, USA for the analysis of dissolved ions in the water and heavy metals in the sediment samples.

Dissolved oxygen (DO), electrical conductivity (EC), total dissolved solids (TDS), temperature, turbidity and pH of the stream water were measured at the site. DO concentration and percent saturation were measured using HACH HQ 40d meter with an attached luminescent dissolved oxygen (LDO) probe. EC, TDS and temperature were measured with a Hanna EC/TDS Probe. Turbidity was measured with a LaMotte 2020 Turbidity Meter and pH was measured using a waterproof pH sensor (pHTestr 3+) by Oakton.

Total suspended solids (TSS) concentrations were measured using 0.7 μm glass fibre filters and Nalgene hand-operated vacuum pump. *Escherichia coli* (*E. coli*) in the water samples were analyzed by counting colonies of fecal coliform growth on pre-treated petri dishes after adding Coliscan gel that detects the enzyme produced by the *E. Coli* group of bacteria during lactose fermentation. Five-day biochemical oxygen demand (BOD_5) in the water samples was analyzed at a local laboratory in Kathmandu called Environment and Public Health Organization (ENPHO). Dissolved chloride, nitrate, phosphate and sulfate were detected with Dionex (Model DX-120) Ion Chromatograph under suppressed conductivity. Total phosphorus (TP) in the sediment samples was analyzed by the Persulfate Digestion - Ascorbic Acid method as described by Clesceri et al. (1998). The heavy metals in the sediment samples were analyzed using a PANalytical MiniPal 4 XRF (X-Ray Fluorescence Spectrometer.

The water quality index (WQI) of the water samples were calculated according to the method described by the National Sanitation Foundation (Brown et al., 1973). The method uses nine water quality parameters, including DO, fecal coliform, pH, BOD, temperature change, TP, nitrate, turbidity and TDS.

Results and Discussions

Water Quality Index

The water quality parameters monitored during the study showed considerable variations among all sites (Table 1). A sharp decrease in the DO level was observed from site S2 downstream. There was a notable increase in *E. coli*, BOD, turbidity, TDS and TSS as the river approached the urban areas. During the field investigation, solid waste dumps along the river banks, open defecation along the banks, discharging sewage pipes, and dead and live cattle in the river were observed. These were common sights as the river approached the more urbanized section of the valley. The water in the urban section virtually looked like wastewater with its gray colour, strong foul odour, and visible organic load. During the study, no fish species were observed in the sampling sites.

Water samples from upstream sites showed distinct variation in Water Quality Index (WQI) compared to downstream urban areas of the valley (Figure 2). Each of the 10 sites selected for this investigation was sampled once a week for 10 weeks. Out of the total 100 water samples collected, 77 samples were in the range of 25 to 50 WQI, putting them in the Bad category. Among others, six samples had Medium WQI (range 50-70), 13 samples had Good WQI (range 70-90) and the remaining four had Excellent WQI (range 90-100). All 13 samples with the Good WQI were from sites S1 and S2, and all four samples with the Excellent WQI were from the site S1 only.

A consistent trend in the WQI along the river was observed throughout the study period. The average WQI at site S1 was Good, at S2 Medium, and at sites S3 onward were Bad (Figure 3). The gradual deterioration of water quality from the rural to the urban areas is presented in Figure 4. An illustration of the average WQI along the study stretch is presented in Figure 4 where sites S2 and S3 indicate a shift in the WQI value of the river. The results distinctly reflect the impact of urbanization on the water quality. As the river left the rural areas, the WQI gradually decreased and the low quality values became more pronounced as it approached more urbanized areas.

Urbanization effects on the water quality mainly occur through the discharge of industrial and municipal wastes and the urban runoffs into the water bodies. These effluents contain both inorganic and organic compounds that alter the physical, chemical and biological properties of the water. In the urban part of the valley, the Bagmati River and its tributaries receive

Table 1: Average values of the water quality parameters obtained during the study

Parameters	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*
Land use	Rural	Rural	Urban	Urban	Urban	Urban/ industrial	Urban/ industrial	Urban/ industrial	Urban	Urban
DO (mg/L)	7.75 (0.36)	4.19 (2.78)	3.21 (1.63)	0.46 (1.01)	2.09 (1.12)	0.16 (0.03)	0.20 (0.17)	0.53 (0.39)	0.14 (0.02)	1.71 (1.87)
E coli (per 100 ml)	10533 (7879)	n/a	2200000 (2160247)	n/a	n/a	4325000 (5192964)	n/a	n/a	n/a	5966667 (3697146)
pH	7.53 (0.25)	7.35 (0.26)	7.34 (0.22)	7.39 (0.16)	7.46 (0.14)	7.37 (0.12)	7.40 (0.15)	7.39 (0.13)	7.40 (0.15)	7.44 (0.14)
BOD (mg/L)	0.43 (0.09)	36.60 (15.52)	262.43 (290.97)	103.27 (74.99)	95.77 (50.47)	98.27 (42.63)	169.20 (100.36)	101.60 (54.34)	124.93 (94.17)	117.43 (92.42)
Temperature (°C)	19.27 (0.75)	23.59 (2.04)	24.14 (1.38)	26.33 (2.62)	26.12 (2.38)	26.44 (2.07)	26.98 (2.49)	26.80 (2.19)	27.21 (2.21)	26.53 (1.84)
Turbidity (NTU)	12.66 (10.78)	146.75 (125.22)	578.84 (367.89)	294.30 (259.63)	257.50 (161.51)	286.20 (154.19)	416.50 (287.26)	408.50 (320.49)	343.60 (210.48)	403.27 (348.47)
TDS (ppm)	19.90 (9.27)	172.80 (131.42)	460.40 (257.33)	411.30 (225.23)	453.60 (232.75)	500.40 (208.49)	719.80 (352.80)	554.70 (254.19)	550.30 (245.88)	475.60 (216.97)
Conductivity (μS/cm)	27.70 (12.43)	247.40 (189.99)	623.20 (348.58)	557.40 (305.31)	613.60 (314.96)	535.23 (215.70)	972.20 (476.29)	750.50 (343.24)	745.00 (332.30)	643.60 (293.40)
TSS (mg/L)	19.42 (20.09)	153.60 (101.23)	472.00 (271.14)	220.50 (105.46)	220.00 (124.82)	307.00 (189.16)	452.00 (365.95)	368.00 (297.11)	372.00 (192.97)	367.00 (285.45)
Phosphate (ppm)	0.00 (0.00)	1.43 (2.35)	9.85 (8.31)	7.09 (6.89)	8.66 (8.50)	9.48 (8.29)	15.33 (13.13)	10.36 (8.25)	10.55 (9.07)	7.79 (7.05)
Chloride (ppm)	1.43 (1.06)	27.98 (26.24)	94.46 (61.61)	69.10 (45.40)	78.27 (46.56)	93.30 (42.06)	118.89 (56.14)	103.13 (54.50)	99.16 (53.48)	82.36 (44.73)
Sulphate (ppm)	0.28 (0.56)	13.46 (9.46)	23.21 (12.55)	20.55 (6.03)	20.75 (6.41)	22.77 (6.54)	26.44 (4.64)	23.68 (6.04)	23.28 (6.87)	22.18 (6.55)

Values in parentheses indicate standard deviation.
n/a – Data not available.

a huge load of effluents from municipal, industrial and wastewater plants. These effluents are either partially treated or left totally untreated before the discharge (Bhatt and McDowell, 2007; Kannel et al., 2006). In general, these anthropogenic activities form the primary sources of pollution in the rivers of the Kathmandu Valley.

Water Quality Parameters

Dissolved oxygen (DO) was a key determinant of the water quality index in this study. A significant correlation between WQI and DO ($r = 0.946$, $p < 0.01$) was observed. Kannel et al. (2007b) also found a strong correlation between DO and WQI of the Bagmati River in their study during 1999–2003. They suggested that DO can be used to predict preliminary WQI of the river. In this study, DO concentrations were found to drop sharply along the river, especially from site S3 onward. This change in concentration occurs in response to the high amount of organic matter in the urban section of the river. In water with high organic content, most of the dissolved oxygen is consumed by decomposer microorganisms. This limits the availability of oxygen to other aquatic organisms as well as affects various redox reactions in water and sediments (Boyd, 2000; Stumm and Morgan, 1996). This could be a reason for the absence of fish species in the river. In another study, Bhatt and McDowell (2007) reported the absence of benthic organisms in the urban section of the Bagmati River. The upper section of the river is reported to have varieties of algae, fishes and insects.

There are slight increase in DO levels at sites S5, S8 and S10 due to stream turbulence. The sampling spots at sites S5 and S8 were close to the bridges upstream that somewhat formed an elevated structure resulting in the turbulence of the water. Just upstream of site

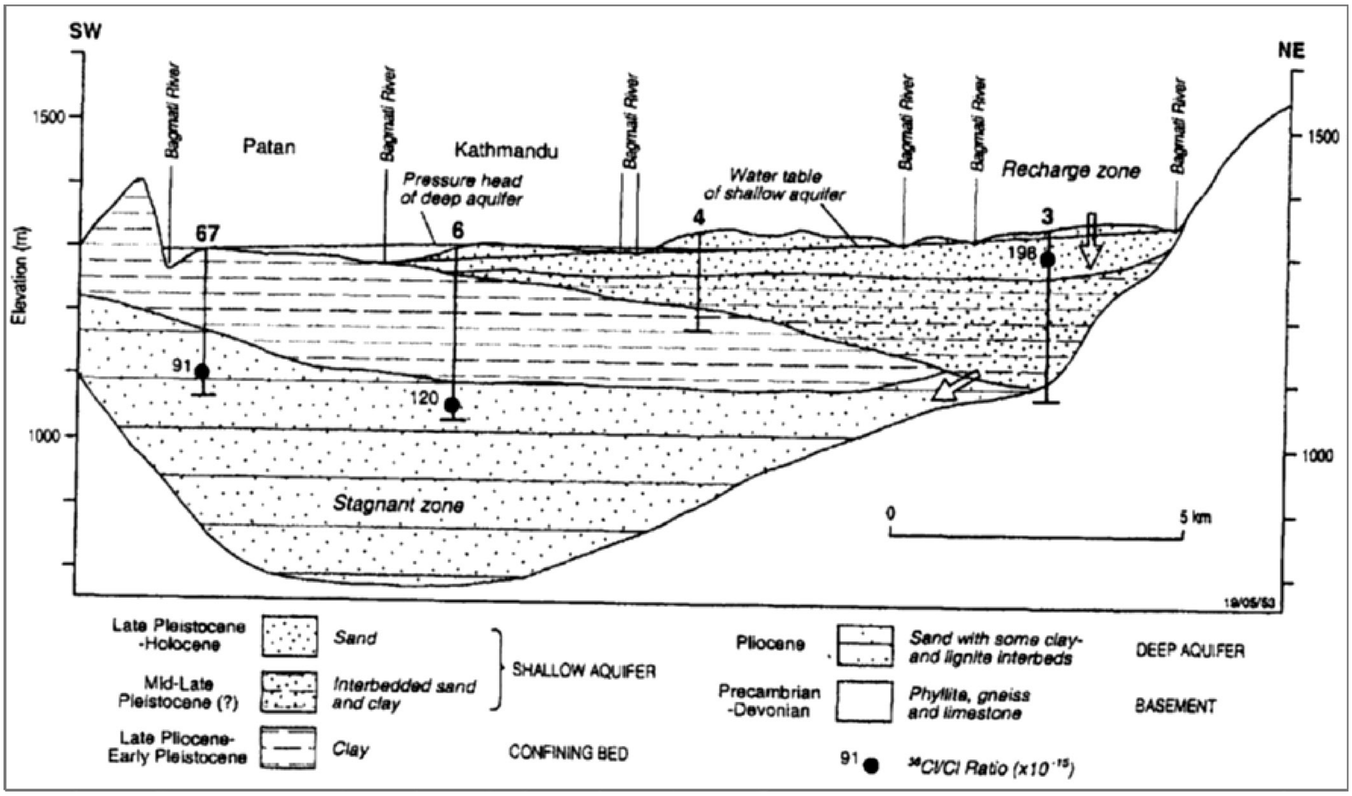

Figure 1b: Geo-hydrologic cross section through the Kathmandu Valley (taken from Cresswell et al., 2001).

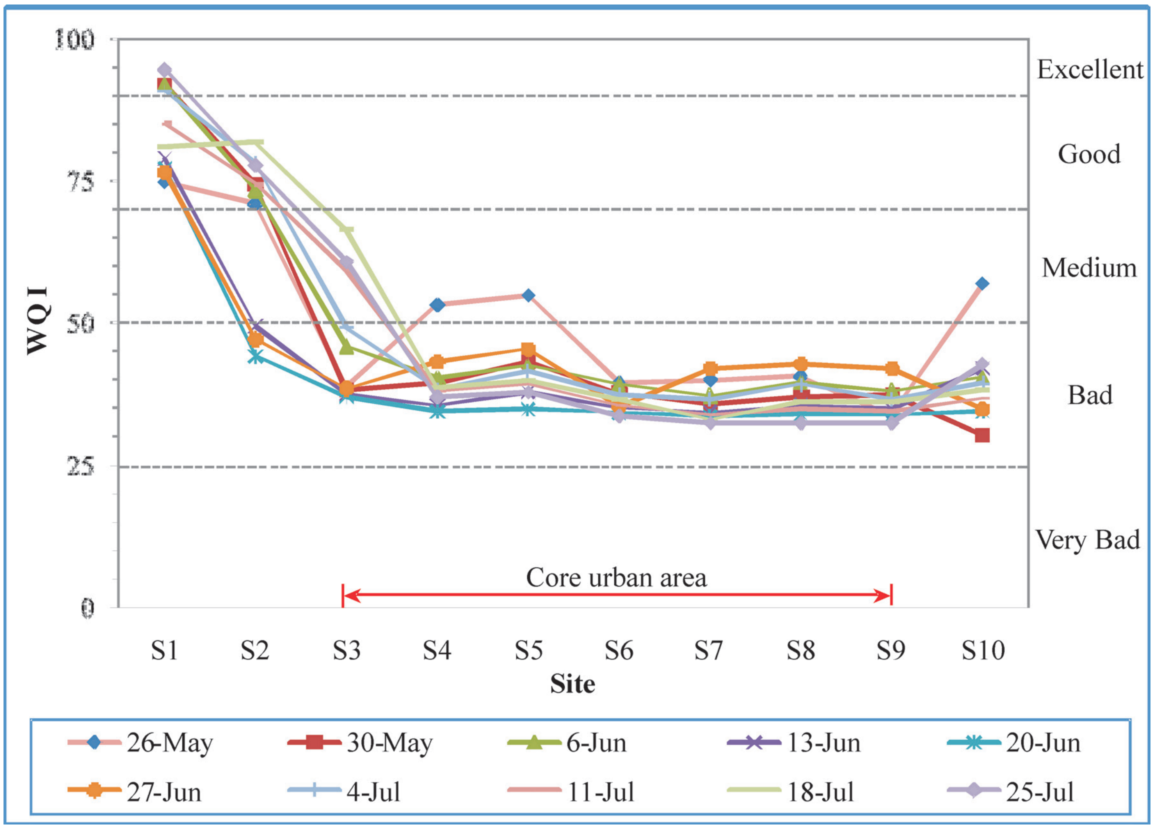

Figure 2: Calculated Water Quality Index values along the Bagmati River.
[WQI: 0-25 = Very bad, 25-50 = Bad, 50-70 = Medium, 70-90 = Good, 90-100 = Excellent]

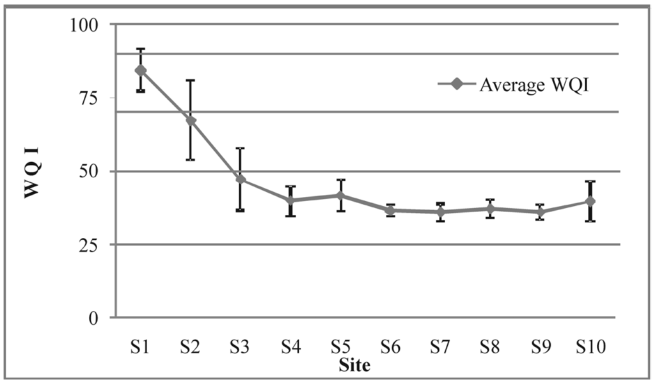

Figure 3: Average trend of the WQI values along the Bagmati River.

S10, the river passes through a gorge that contains large boulders and where the river has a slightly higher gradient, both of which produce greater turbulence. Turbulent condition enhances water to air contacts, which results in the increased dissolution of atmospheric oxygen. However, those increments in the DO level were still too low to support most aquatic life. *E. Coli* was found to be exceedingly high in the urban section of the river, significantly impacting the WQI values. The overall range of *E. Coli* was 200 to 1.3×10^7 number per 100 ml.

Turbidity was also found to significantly influence the water quality of the Bagmati River. Turbidity data in measurements showed a highly increasing trend as the river moved toward the downstream urban areas. From site S2 onward, the river was highly turbid and was high in total suspended solids (TSS) throughout the period of investigation. The bottom of the river was visible only at site S1 during the non-rainy days. All other sites were visibly too murky to look through the water. A high load of suspended solids, mostly of municipal origin (such as food particles) was detected during sampling of water. Outlets from wastewater treatment plants were also identified along the stream channel. The observation pointed more toward the influence of organic effluents than the natural stirring of sediments as the cause of increased turbidity and TSS in the water.

The river also displayed remarkable variation in the total dissolved solids (TDS) along the sites, especially between the rural and the urban sections of the watershed (Figure 5). TDS concentration at site S1 was significantly lower compared to the rest of the sites. Site S1 is the least human influenced site. The impact could be felt from site S2 with the sudden rise in TDS concentration. Yet, significantly higher TDS values were observed from site S3 onward as they represent the urban core of the valley. The effects of natural weathering seemed minimal, as suggested by the low TDS at site S1 that represents a fairly natural state of the river. Thus, the increase in TDS in the urban section could be attributed to the input from human sources. Bhatt and McDowell (2007) also found that the effect of natural weathering on the water quality was insignificant, thereby suggesting anthropogenic sources as the primary cause of contamination.

Nitrate concentrations showed sporadic values at different weeks for different sites. Nitrate was not detected in most samples from the urban sites, starting from S3. A possible explanation for the absence of nitrate could be its denitrification into nitrous oxide and nitrogen gas due to highly reducing environment created by the low DO levels in these sites. Under anaerobic conditions, it is common for microorganisms to use oxygen from nitrate for the oxidation of organic matter (Boyd, 2000). Low levels of nitrate in the urban section of the Bagmati River were also reported by Bhatt and McDowell (2007) and Kannel et al. (2007b), possibly resulting from anoxic conditions.

Phosphate was not detected in the rural section (site S1) of the river throughout the sampling period. The concentrations in the urban section of the river were in the range of 2.5 ppm to 45.8 ppm. In natural waters, phosphate concentration barely exceeds 0.5 ppm (Boyd, 2000). Therefore, the elevated level of dissolved phosphate from site S2 onward shows the effects of anthropogenic discharges into the river. The common sources include industrial and domestic discharge, agricultural runoffs, and animal manures. Heavy loads of suspended as well as bottom sediments can transport high amounts of phosphorus in polluted streams. Phosphorus tends to adsorb onto particulate materials, which later transfers to the dissolved phase as some of the adsorbing minerals dissolve in highly reducing environments.

Based on important water quality indicators and land use, areas around the sampling sites can be prioritized for remedial measures as low, medium, high, and topmost. Specific sites are assessed as follows: rural-low (S1 and S2), urban-high (S3, S4 and S5), urban/industrial-topmost (S6, S7 and S8), and urban-medium (S9 and S10). The average TDS observed (592 mg/L) at the urban/industrial sites is 34% higher than that observed (442 mg/L) at the urban sites immediately upstream. Besides, average TSS at the same urban/industrial sites (376 mg/L) is 24% higher than that recorded at the urban sites. Heavy loads of industrial discharge in addition to municipal effluents has formed a hotspot of pollution in this highly industrialized city centre within the Kathmandu Valley. Specific remedial measures within the watershed or any kind of best management practice guidelines developed for the area should deal with this zone with topmost priority. The urban sites (S9 and S10) immediately downstream of the industrialized zone has been assessed in this study with medium priority because part of the heavy discharge in these sites are derived from the upstream industrial sources. It is expected that stringent regulation of industrial activities in the “hotspot” area would promptly lower the pollution stream moving through sites S9 and S10.

Effects of Rainfall on the Water Quality

The sampling was initiated almost a month before the start of the monsoon in Nepal and continued for another month during the monsoon (Figure 6). For the year 2009, the monsoon in Nepal started around June 23 (MFD, 2010). This study roughly represents the state of the river during the pre-monsoon and the early monsoon months. There were some notable rainfall events during the study period, which seemed to have affected the concentrations of some parameters in the river. Correspondingly, there were indications of alteration in the WQI values of the river due to such precipitation events.

During the first three weeks of sampling the valley did not receive much rainfall, except for a couple of events (Figure 6). There was a dry period of three weeks (from June 7 to June 21) during which only a 5.2 mm rainfall fell on June 12. However, after the onset of the monsoon season, rainfall events were more frequent and of larger magnitude in the subsequent weeks of sampling. During the periods of rain, with dry periods in between, substantial variations were observed in the chemistry of water and in the overall WQI.

Rainfall seemed to have particularly affected the urban part of the river, as shown by the increasing WQI of the river during the precipitation events. The average WQI from sites S3 to S10 showed a fairly positive correlation with the rainfall (Figure 7). This clearly depicts the diluting effects of rainfall in the polluted river.

The annual rainfall amount of 1440 mm seems to be large enough to flush out the pollutants from the rivers of the Kathmandu Valley. During the field work, the flushing capability of the river was visible throughout the valley. Huge dumps of solid wastes that were seen during the initial days of sampling were flushed away once the monsoon season started (Figure 8).

The notable effects of rainfall on the water quality parameters were shown by turbidity, TSS and TDS. Their levels dropped significantly in the river once the monsoon started. DO was also found to be affected by the rainfall events, especially in the urban section. DO levels were relatively lower during the dry periods as compared to the wet periods. Rainwater tends to dilute the organic load and the increased flow in the river creates turbulence in the water which then dissolves more atmospheric oxygen in the water. Chloride, phosphate and sulfate concentrations were also found to decrease during the period of rainfall.

One particular concern, however, remains in regards to the long-term hydrological changes in the watershed. Recent studies showed a gradual change in discharge characteristics of Bagmati River (Sharma and Shakya, 2006). The investigators report that even though the seasonal flows remain constant the monsoon flow rates in the river are temporally decreasing. Also, there are indications of temporal shifting in hydrograph. Analysis of monthly discharge data collected at Karmaiya gauging station reveals that monsoon flow rates have dropped from over 400 m^3/s in 1965 to slightly over 300 m^3/s in 2000. Because the monsoon discharge is very high compared to that in other seasons, mean annual discharge has also dropped from more than 150 m^3/s to around 135 m^3/s (Sharma and Shakya, 2006).

Due to global climate change, many developing countries are vulnerable to extreme weather events. Sometimes these weather events result in substantial economic damage (Monirul and Mirza, 2003). Likewise, Kathmandu valley area has experienced a tremendous growth in urban and industrial activities in recent decades and a change in the average flow rates in the river is evident. Even though rain events are still helping to flush out the high volume of urban and industrial wastes from the stream, the natural process of contaminant flushing may not remain as effective in the future. A stringent regulation of source control seems to be very urgent in the Bagmati study area.

Heavy Metals in the River Sediments

The concentrations of different elements in sediments are presented in Table 2. The table also lists the composition of these elements in natural soils. Derived from Bowen (1979), these natural soil data do not include samples from heavily polluted areas, soils near mineral ores, and serpentine soils, and thereby represent their concentrations in a natural state.

Except for molybdenum and cobalt, the concentrations of all elements in the sediment samples appeared within

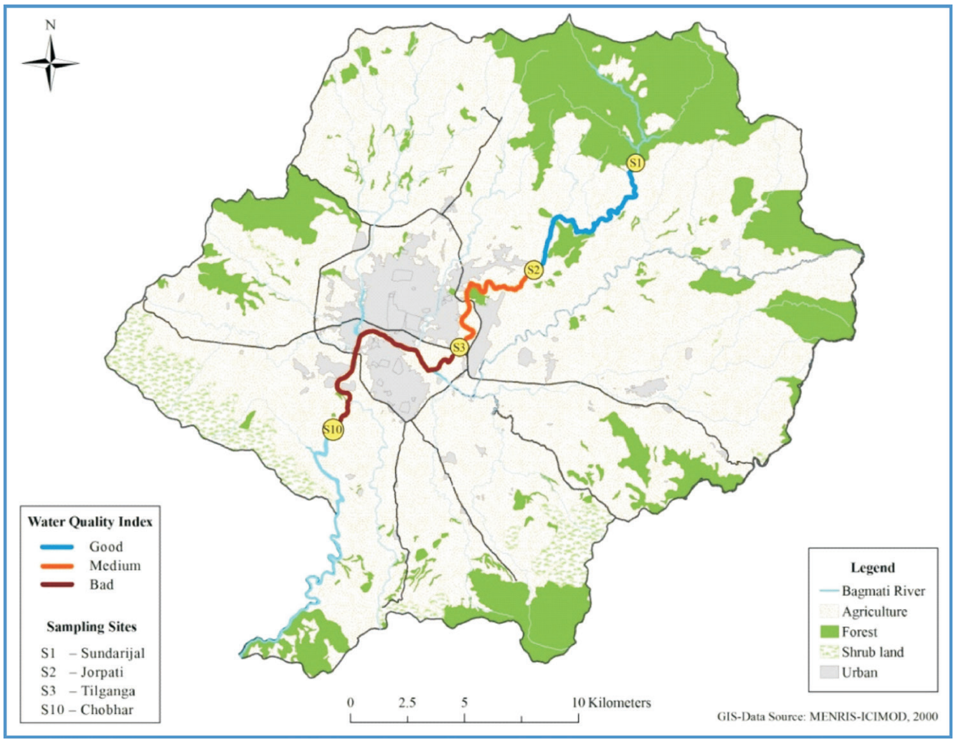

Figure 4: Spatial variation in the WQI along the Bagmati River.

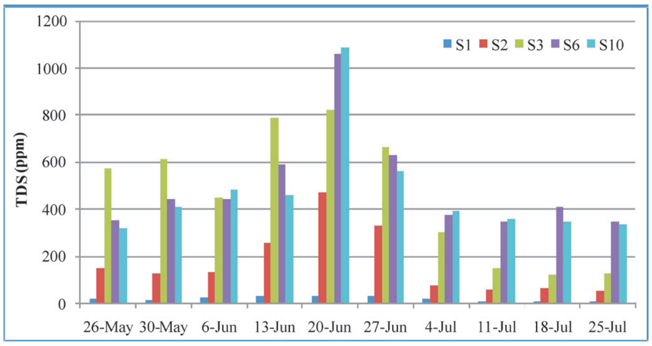

Figure 5: TDS variations at selected sites during the study period.

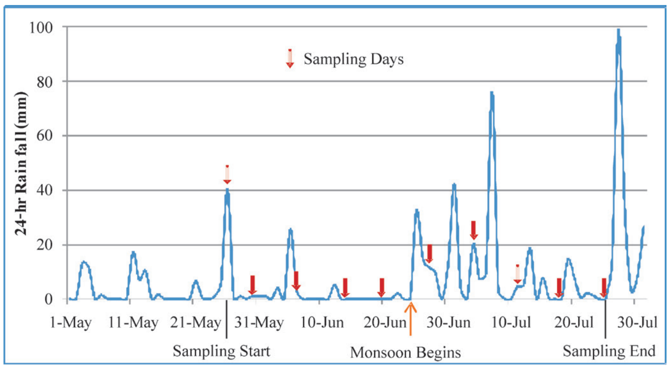

Figure 6: 24-hour rainfall records in the Kathmandu Valley during May-July, 2009. (The 24-hour rainfall for a day is the total recorded rainfall from 5:45 pm the previous day until 5:45 pm that day.) (Data source: MFD, 2010)

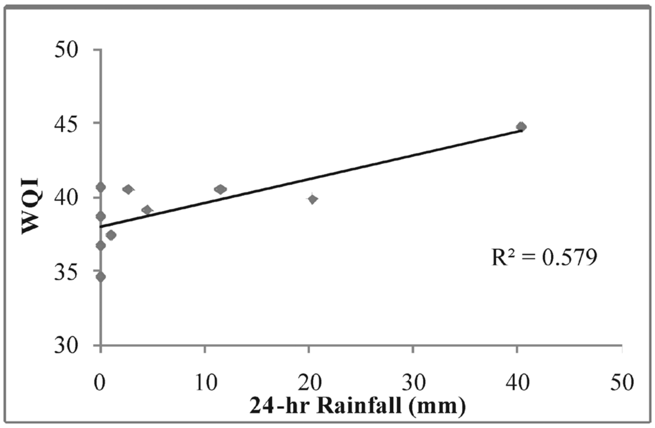

Figure 7: Average WQI (sites S3-S10) vs. rainfall over the urban section of the study area.

the range of natural soil content. Moreover, their average concentrations were closer to the lower limit in the range. These results suggest an unpolluted state of the Bagmati River sediments in comparison with the global soil average for these elements.

Although dominated mostly by the metamorphic rocks like gneiss, quartzite, phyllite and schist, a range of igneous and sedimentary rocks are also distributed along the bedrock in the valley. The headwater region of the river is mostly dominated by gneiss and schist and thus contains an abundance of quartz and mica (mainly biotite) minerals. The lower reaches of the river contain grained phyllite, slate, shale, limestone, sandstone,

Table 2: Elemental concentrations observed in the Bagmati River sediments and their known compositions in the natural soil (derived from Bowen, 1979)

values in mg/kg

Element	*Minimum*	*Maximum*	*Average*	*Standard deviation*	*Natural soil content average (range)*	
Al	4,808.13	11,267.23	7,715.65	1,614.61	71,000	(10,000-300,000)
As	3.37	23.21	6.71	5.16	6	(0.1-40)
Ca	159.62	1,708.47	645.70	268.86	15,000	(700-500,000)
Co	0.80	97.39	14.73	20.82	8	(0.05-65)
Cr	1.31	140.08	49.69	39.17	70	(5-1,500)
Cu	3.28	54.45	23.69	14.13	30	(2-250)
Fe	674.54	5,600.96	2,793.25	1,416.25	40,000	(2,000-550,000)
Ga	6.15	34.69	19.77	6.77	20	(2-100)
K	2,032.40	3,797.70	2,927.16	450.22	14,000	(80-37,000)
Mg	521.16	1,047.02	767.57	167.25	5,000	(400-9,000)
Mn	19.42	3,459.34	637.08	824.25	1,000	(20-10,000)
Mo	1.22	146.93	60.96	45.77	1.2	(0.1-40)
Ni	0.63	94.89	30.65	25.53	50	(2-750)
Pb	17.92	62.71	37.73	9.77	35	(2-300)
Si	24,663.90	40,935.54	32,540.16	4,816.71	330,000	(250,000-410,000)
Sr	72.84	109.57	98.14	8.73	250	(4-2,000)
Ti	88.15	626.73	359.31	158.07	5,000	(150-25,000)
V	19.83	106.45	74.21	23.40	90	(3-500)
Y	21.04	194.54	63.98	35.13	40	(10-250)
Zn	35.45	143.37	77.93	23.90	90	(1-900)
Zr	102.89	390.72	221.88	78.65	400	(60-2,000)

Figure 8: View of the river at site S8 on May 30 (left) and on July 25 (right).

claystone and mudstone. The flat bed sediments are very rich in clay minerals (Bhatt and McDowell, 2007; Shrestha et al., 1998). The abundance of quartz, mica and clay minerals in the valley explains the high amounts of silicon and aluminum in the sediment samples compared to the other elements (Table 2). Moreover, silicon is the second most abundant element (approximately 27.7 % by weight) in the earth's crust after oxygen.

It is followed by aluminum (8 %) and the sequence further goes on to include Fe>Ca>Na>K>Mg and so on (Lutgens and Tarbuck, 2000). The order of some major elements in the samples in decreasing concentration was observed as Si>Al>K>Fe>Mg>Ca>Mn. As opposed to the natural order, the relative abundance of K over Fe, and K and Mg over Ca could be as a result of the prevalence of clay and mica minerals in the samples. Al and Si, and Fe and Mg have been found to occur interchangeably in various compositional varieties in mica and clay minerals (Drever, 1997).

The heavy metals in the sediments of Bagmati River are relatively low in concentration as compared to the Ganges River and other streams in Asia (Table 3). The results suggest that there is no immediate concern in regard to heavy metals in the river sediments. Nevertheless, the information was not sufficient to understand the impact of anthropogenic activities on the distribution of these metals.

The spatial distributions of selected heavy metals in the Bagmati River sediments are shown in Figure 9. The heavy metal concentrations at site S6 were prominently higher in most of the observations compared to the other sites. Site S6 is located almost at the urban centre of the Kathmandu Valley where it serves as the receiving hotspot of industrial pollutant loads from the surrounding areas (Figure 1). In this study, the site is categorized as having urban/industrial landuse (Table 1). Around the site, there are many traditional cottage industries, including textile weaving, brick and tiles, pottery, precious ornaments, traditional food processing, metal handicrafts, carpet making, copper and brass metal utensils, and leather industry.

In the past couple of decades, large industrial activities have also flourished in the area, including shoe manufacturing and cement industries, plastic products, construction materials, carpet dying and readymade garment industries (ICIMOD et al., 2007). In addition, the area has industries that are heavily involved in car battery manufacturing, production of pesticides, treated-wood products, herbicides and insecticides. Surface runoff during rain events and direct discharge from industrial processes carry high loads of pollutants causing the metal concentrations at Site S6 to spike higher in comparison to other sites. Metal concentrations start to get lower further downstream (S7 and S8) due to uptake by aquatic species and chemical dissolution processes.

Another reason for high concentrations of heavy metals at site S6 could be the characteristics of soils in this particular area. The sediment samples from this site were clayey as opposed to the rest of the samples that were mostly sandy. Only site S4 had some clay content in the sediments. Elemental concentrations in sediments are found to fluctuate highly with the grain size. Fine sediments (<50 µm), such as clay minerals, organic matter, and fine particulates of quartz, carbonates, and feldspars, have high surface area and are high in electrical charge, which make them effective ion exchangers. Consequently, fine grained sediments

Table 3: Average concentrations of heavy metals in the sediments of the Bagmati River as well as other rivers from Asia

All values are in mg/kg

River	*Country*	*As*	*Co*	*Cr*	*Cu*	*Fe*	*Mn*	*Ni*	*Pb*	*Zn*	*Pollution source*
Bagmati (this study)	Nepal	6.71	14.7	49.7	23.7	2,793	637	30.7	37.7	77.9	Urban and Industrial
Ganges[a]	India	-	19.2	147	55.0	40,346	1,764	47.0	22.0	105	--
Yangtze[b]	China	15.9	-	87.8	51.6	-	-	40.9	45.2	140	--
To Lich[c]	Vietnam	50.3	19.4	221	117	64,972	896	91.0	132	860	--
Yenshui[d]	Taiwan	-	33.1	190	185	24,000	234	102	31.2	248	--
Rivers of Hokkaido[e]	Japan	12.0	17.6	85.0	26.4	68,100	1,300	47.3	17.6	104	Low anthropogenic influence

[a]Singh et al. (2003) Average concentration in the sediments of the Ganges River in India
[b]Yang et al. (2009) Average concentration in the sediments of the Yangtze River in Wuhan region of China
[c]Marcussen et al. (2008) Average concentration in the sediments of the To Lich River at Hanoi City in Vietnam
[d]Tsai et al. (2007) Average concentration in the sediments of the Yenshui River in southern Taiwan
[e]Ohta et al. (2005) Average concentration in the sediments of the streams from Hokkaido region of Japan

tend to adsorb high amounts of metals. On the contrary, coarse sediments like sand and gravels have small surface area and adsorption capabilities, making them low in metal concentration (Drever, 1997; Salomons and Forstner, 1984). Based on the observations, it can be inferred that high clay content in the sediments played an important role behind the elevated levels of heavy metals at site S6. This pattern was further supported by the results observed at site S4, which was higher in clay content than the rest of the sites. Consequently, site S4 too had relatively high concentration of metals as expected (Figure 9). Other studies have also shown that sediments with small grain size fractions have high concentrations of metals. These sediments are

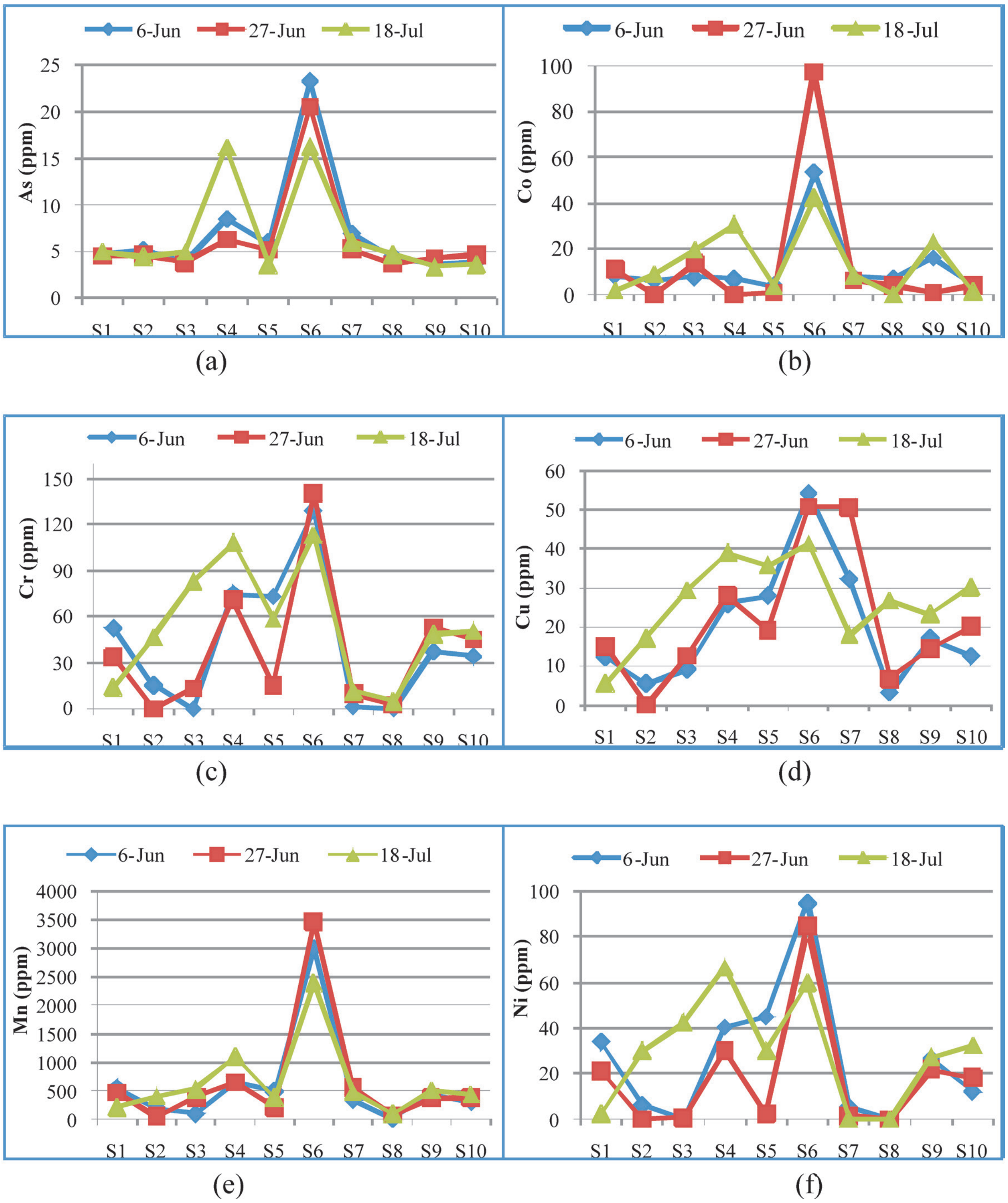

Figure 9: Distribution of (a) arsenic, (b) cobalt, (c) chromium, (d), copper, (e) manganese and (f) nickel in the Bagmati River sediments.

primarily responsible for the bulk transportation of the natural and the anthropogenic metal compounds through water bodies (Banat et al., 1972; Singh et al., 2003; Subramanian et al., 1987; Viers et al., 2009).

Conclusions

The study revealed that the water quality of the Bagmati River along the urban section of the Kathmandu Valley has been seriously deteriorated in the recent years. Out of the total 100 water samples analyzed to determine NSF-WQI, 77 were in the Bad category, six in the Medium category, and the remaining 17 samples were in Good to Excellent categories. All samples from the Good and Excellent categories were from sites S1 and S2, the upstream area of the river where human influence is minimal. All the bad and medium category samples were from the sites S3 and after, comprising the urban section of the river. This scenario was consistent throughout the period of investigation. These results clearly indicate that the water quality of the river is impacted by urban activities. High loads of organic pollutants were observed in the river during the study. The major sources of pollution have been the direct discharge of effluents from households, industries and the badly operated wastewater treatment plants.

Among the water quality parameters studied, dissolved oxygen, *E. coli*, turbidity and total dissolved solids showed definite spatial variations, especially between the rural and the urban sites. They also demonstrated strong influence on the water quality index values of the water samples. Based on important water quality indicators and land use, areas around the sampling sites can be prioritized for remedial measures as rural-low (S1 and S2), urban-high (S3, S4 and S5), urban/industrial-topmost (S6, S7 and S8), and urban-medium (S9 and S10). Heavy loads of industrial discharge in addition to municipal effluents has formed a hotspot of pollution around sites S6, S7 and S8. The average TDS observed (592 mg/L) in this highly industrial zone is 34% higher than that observed (442 mg/L) at the urban sites immediately upstream. Specific remedial measures within the watershed or any kind of best management practice guidelines developed for the area should deal with this particular zone with topmost priority. Due to lack of resources, monitoring water quality in rivers can be difficult in least developed countries like Nepal. Identifying specific parameters that best describe the water quality would greatly help in reducing the cost of the analytical procedures. Based on the results of this study, dissolved oxygen stands out as the most prevalent indicator of water quality. DO values in water depend upon factors like temperature change, turbulence in water, activities of microorganisms, and presence of organic matter. In addition, it indicates the characteristics of the aquatic habitat. Thus, many aspects of water quality can be investigated by studying dissolved oxygen alone. But, it is always best to integrate as many water quality parameters as possible.

Rainfall was also found to significantly affect the water quality of the Bagmati River. Diluting effects of the monsoon rains were prominent along the urban section of the river, which was evident from the rise in WQI values with the increasing rainfall amount. Because the Kathmandu Valley receives a considerable amount of rain every year from the monsoon, rainfall can be an important factor in the quality assessments and the conservation strategies of the Bagmati River. A continuous water quality monitoring throughout the year would be important in developing appropriate management strategies.

The data obtained in this study did not show any high accumulation of heavy metals in the river sediments. Most heavy metals were within the range of natural soil content. Also, the values are lower compared to the major Asian rivers, including the Ganges. A notable observation was the relatively higher levels of heavy metals at site S6. Around this site, there are many traditional cottage industries, including textile weaving, metal handicrafts, copper and brass metal utensils, and precious ornaments. In addition, the area has industries that are heavily involved in car battery manufacturing, and production of herbicides, and insecticides, all serving as potential sources of metals to the Bagmati River. Besides, the sediment from this site is clay-rich as opposed to the sediments from other sites, which are either sandy or very low in clay content. Because of the increased surface area and their ion exchange capabilities, fine sediments (such as clay) tend to adsorb heavy metals at higher rates. This is also a reason why there are elevated levels of heavy metals at site S6. To further understand metal distribution in the Bagmati River, heavy metal concentrations in different grain size fractions should be studied in the future.

Acknowledgements

This study was funded in part by the National Science Foundation and the Roy J. Carver Charitable Trust.

The authors would like to acknowledge the valuable contribution of Maureen Clayton and Chad Heinzel to this project.

References

Abbasi, T. and S.A. Abbasi (2012). Water Quality Indices. Elsevier B.V.

ADB, ICIMOD (2006). Environment assessment of Nepal: Emerging issues and challenges. Asian Development Bank, International Center for Integrated Mountain Development, Kathmandu.

Ahiablame, L.M., Engel, B.A. and I. Chaubey (2013). Effectiveness of low impact development practices in two urbanized watershed: Retrofitting with rain barrel/ cistern and porous pavement. *Journal of Environmental Management*, **119:** 151-161.

Bai, J., Xiao, R., Zhang, K. and G. Gao (2012). Arsenic and heavy metal pollution in wetland soils from tidal freshwater and salt marshes before and after the flow-sediment regulation regime in the Yellow River Delta, China. *Journal of Hydrology*, **450-451:** 244-253.

Banat, K., Forstner, U. and G. Muller (1972). Schwermetalle in Sedimenten von Donau, Rhein, Ems, Weser, und Elbe im Bereich der Bundesrepublik Deutschland. *Naturwissenschaften*, **12:** 525-528.

Bhatt, M.P. and K.H. Gardner (2008). Variation in DOC and trace metal concentration along the heavily urbanized basin in Kathmandu Valley, Nepal. *Environmental Geology*. DOI: 10.1007/s00254-008-1562-z.

Bhatt, M.P. and W.H. McDowell (2007). Evolution of chemistry along the Bagmati drainage network in Kathmandu Valley. *Water Air Soil Pollution*, **185:** 165-176.

Bowen, H.J.M. (1979). Environmental Chemistry of the Elements. Academic Press Inc., New York.

Boyd, C.E. (2000). Water Quality: An Introduction. Kluwer Academic Publishers, Norwell, Massachusetts.

Brown, R.M., McClelland, N.I., Deininger, R.A. and M.F. O'Connor (1973). A water quality index – Crashing the psychological barrier. Advances in Water Pollution Research. Pergamon Press, Oxford, England.

Carpenter, S.R., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N. and V.H. Smith (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, **8(3):** 559-568.

CBS (2008). Environmental statistics of Nepal. Central Bureau of Statistics, National Planning Commission Secretariat, Government of Nepal, Kathmandu.

Clesceri, L.S., Greenberg, A.E. and A.D. Eaton (1998). Phosphorus. *In:* Standard methods for the examination of water and wastewater, 20th ed., American Public Health Association, Washington, D.C.

Cresswell, R.G., Bauld, J., Jacobson, G., Khadka, M.S., Jha, M.G., Shrestha, M.P. and S. Regmi (2001). A first estimate of ground water ages for the deep aquifer of the Kathmandu Basin, Nepal, using the radioisotope chlorine-36. *Ground Water*, **39(3):** 449-457.

Devkota, D.C. and K. Watanabe (2005). Impact of solid waste on water quality of Bishnumati River and surrounding areas in Kathmandu, Nepal. *Journal of Nepal Geological Society*, **31:** 19-24.

Drever, J.I. (1997). The Geochemistry of Natural Waters: Surface and Groundwater Environments. Third ed. Prentice Hall, Inc., New Jersey.

Fraterrigo, J.M. and J.A. Downing (2008). The influence of land use on lake nutrients varies with watershed transport capacity. *Ecosystems*, **11:** 1021-1034.

Geissen, V., Mol, H., Klumpp, E., Umlauf, G., Nadal, M., Ploeg, M., Zee, S.E. and C.J. Ritsema (2015). Emerging pollutants in the environment: A challenge for water resource management, **3(1):** 57-65.

Gurung, J.K., Ishiga, H., Khadka, M.S. and N.R. Shrestha (2007). The geochemical study of fluvio-lacustrine aquifers in the Kathmandu Basin, Nepal and the implications for the mobilization of arsenic. *Environmental Geology*, **52:** 503-517.

Haack, B. (2009). A history and analysis of mapping urban expansion in the Kathmandu Valley, Nepal. *The Cartographic Journal*, **46(3),** 233-241.

Holmroos, H., Hietanen, S., Niemisto, J. and J. Horppila (2012). Sediment resuspension and denitrification affect the nitrogen to phosphorus ratio of shallow lake waters. *Fundamental and Applied Limnology*, **180:** 193-205.

ICIMOD, MoEST, UNEP (2007). Kathmandu valley environment outlook. International Center for Integrated Mountain Development, Ministry of Environment, Science and Technology, United Nations Environment Program, Kathmandu.

Jiang, T., Fischer, T., Lu, X. and Hongming He (2015). Large Asian rivers: Impacts from human activities and climate change. *Quaternary International*, **380-381:** 1-4.

Kannel, P.R., Lee, S., Kanel, S.R. and S.P. Khan (2006). Chemometric application in classification and assessment of monitoring locations of an urban river system. *Analytica Chimica Acta*, **582:** 390-399.

Kannel, P.R., Lee, S., Kanel, S.R., Khan, S.P. and Y.S. Lee (2007a). Spatial-temporal variation and comparative assessment of water qualities of urban river system: A case study of the River Bagmati Nepal. *Environmental Monitoring and Assessment*, **129:** 433-459.

Kannel, P.R., Lee, S., Lee, Y.S., Kanel, S.R. and S.P. Khan (2007b). Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. *Environmental Monitoring and Assessment*, **132:** 93-110.

Lutgensm, F.K. and E.J. Tarbuck (2000). Essentials of Geology. Seventh ed. Prentice Hall, New York.

Marcussen, H., Dalsgaard, A. and P.E. Holm (2008). Content, distribution and fate of 33 elements in sediments of rivers receiving wastewater in Hanoi, Vietnam. *Environmental Pollution*, **155:** 41-51.

McMahon, G. and D.A. Harned (1998). Effect of environmental setting on sediment, nitrogen, and phosphorus concentrations in Albemarle-Pamlico drainage basin, North Carolina and Virginia, USA. *Environmental Management*, **22(6):** 887-903.

MENRIS-ICIMOD (2000). Kathmandu Valley GIS database. Mountain Environment and Natural Resources Information System. International Center for Integrated Mountain Development, Kathmandu.

MFD (2010). Weather forecast. Meteorological Forecasting Division, Government of Nepal. Retrieved July 06, 2010, from http://www.mfd.gov.np/

Monirul, M. and Q. Mirza (2003). Climate change and extreme weather events: Can developing countries adapt. *Climate Policy*, **3:** 233-248.

Moore, J.W. and S. Ramamoorthy (1984). Heavy Metals in Natural Waters: Applied Monitoring and Impact Assessment. Springer-Verlag, New York.

Ohta, A., Imai, N., Terashima, S. and Y. Tachibana (2005). Influence of surface geology and mineral deposits on the spatial distributions of elemental concentrations in the stream sediments of Hokkaido, Japan. *Journal of Geochemical Exploration*, **86:** 86-103.

Ouyang, Y., Higman, J., Thompson, J., O'Toole, T. and D. Campbell (2002). Characterization and spatial distribution of heavy metals in sediment from Cedar and Ortega rivers subbasin. *Journal of Contaminant Hydrology*, **54:** 19-35.

Paul, M.J. and J.L. Meyer (2001). Streams in the urban landscape. *Annual Review of Ecology and Systematics*, **32:** 333-365.

Pokhrel, D. and T. Viraraghavan (2005). Municipal solid waste management in Nepal: Practices and challenges. *Waste Management*, **25:** 555-562.

Pradhan, B. (2005). Water quality classification model in the Hindu Kush-Himalayan region: The Bagmati River in Kathmandu Valley, Nepal. Report submitted to International Center for Integrated Mountain Development, Ministry of Environment, Science and Technology, United Nations Environment Program, Kathmandu.

Pradhan, P.K. (2004).Population growth, migration, and urbanization: environmental consequences in Kathmandu Valley, Nepal. *In:* Environmental Change and its Implications for Population Migration. J.D. Unruh, M.S. Krol and N. Kliot (eds), Kluwer Academic Publishers, Dordrecht, The Netherlands.

Salomons, W. and U. Forstner (1984). Metals in the Hydrocycle. Springer-Verlag, Heidelberg, Berlin.

Sharma, R.H. and N.M. Shakya (2006). Hydrological changes and its impact on water resources of Bagmati watershed, Nepal. *Journal of Hydrology*, **327:** 315-322.

Shrestha, O.M., Koirala, A., Hanisch, J., Busch, K., Kerntke, M. and S. Jager (1999). A geo-environmental map for the sustainable development of the Kathmandu Valley, Nepal. *GeoJournal*, **49:** 165-172.

Shrestha, O.M., Koirala, A., Karmacharya, S.L., Pradhananga, U.B., Pradhan, P.M. and R. Karmacharya (1998). Engineering and environmental geological map of the Kathmandu Valley. Department of Mines and Geology, HMG, Kathmandu.

Singh, K.P., Mohan, D., Singh, V.K. and A. Malik (2005). Studies on distribution and fractionation of heavy metals in Gomti river sediments, a tributary of the Ganges, India. *Journal of Hydrology*, **312:** 14-27.

Singh, M., Muller, G. and B. Singh (2003). Geogenic distribution and baseline concentration of heavy metals in sediments of the Ganges River, India. *Journal of Geochemical Exploration*, **80:** 1-17.

Stroomberg, G.J., Freriks, I.L., Smedes, F. and W.P. Cofino (1995). Quality assurance and quality control of surface water sampling. *In:* Quality Assurance in Environmental Monitoring. P. Quevauviller (ed.). VCH, Weinheim, Germany.

Stumm, W. and J.J. Morgan (1996). Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters. Third ed. John Wiley and Sons, New York.

Subramanian, V., Grieken, R.V. and L.V. Dack (1987). Heavy metals distribution in the sediments of Ganges and Brahmaputra Rivers. *Environmental Geology and Water Sciences*, **9(2):** 93-103.

Thapa, R.B. and Y. Murayama (2008). Spatial structure of land use dynamics in Kathmandu Valley. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XXXVII (B8), 11-16.

Thapa, R.B. and Y. Murayama (2010). Drivers of urban growth in the Kathmandu Valley, Nepal: Examining the efficacy of the analytic hierarchy process. *Applied Geography*, **30:** 70-83.

Tourbier, J.T. (1994). Open space through stormwater management: Helping to structure growth on the urban fringe. *Journal of Soil Water Conservation*, **49:** 14-22.

Tsai, L.J., Yu, K.C. and S.T. Ho (2007). Cadmium distribution in sediment profiles of the six main rivers in southern Taiwan. *Journal of Hazardous Materials*, **148:** 630-639.

Turekian, K.K. and K.H. Wedepohl (1961). Distribution of the elements in some major units of the Earth's crust. *Geological Society of America Bulletin*, **72:** 175-192.

Tyagi, S., Sharma, B., Singh, P. and R. Dobhal (2013). Water quality assessment in terms of water quality index. *American Journal of Water Resources*, **1(3):** 34-38.

USEPA (1997). Volunteer stream monitoring: A Methods Manual (EPA 841-B-97-003). United States Environmental Protection Agency. Retrieved August 30, 2010, from http://water.epa.gov/type/rsl/monitoring/upload/2002_08_13_volunteer_stream_stream.pdf.

vanLoon, G.W. and S.J. Duffy (2005). Environmental Chemistry: A Global Perspective. Second ed. Oxford University Press, New York.

Vega, M., Pardo, R., Barrado, E. and L. Deban (1998). Assessment of seasonal and polluting effects on the quality of river water by exploratory data analysis. *Water Research*, **32(12):** 3581-3592.

Viers, J., Dupre, B. and J. Gaillardet (2009). Chemical composition of suspended sediments in world rivers: New insights from a new database. *Science of the Total Environment*, **407:** 853-868.

Wang, S., He, Q., Ai, H., Wang, Z. and Q. Zhang (2013). Pollutant concentrations and pollution loads in stormwater runoff from different land uses in Chongqing. *Journal of Environmental Science*, **25(3):** 502-510.

Yang, Z., Wang, Y., Sen, Z., Niu, J. and Z. Tang (2009). Distribution and speciation of heavy metals in sediments from the mainstream, tributaries, and lakes of the Yangtze River catchment of Wuhan, China. *Journal of Hazardous Materials*, **166:** 1186-1194.

Yadav, S.K. (2010). Heavy metals toxicity in plants: An overview on the role of glutathione and phytochelatins in heavy metal stress tolerance of plants. *South African Journal of Botany*, **76(2):** 167-179.

Zhang, C., Yu, Z., Zeng, G., Jiang, M., Yang, Z., Cui, F., Zhu, M., Shen, L. and L. Hu (2014). Effects of sediment geochemical properties on heavy metal bioavailability. *Environment International*, **73:** 270-281.