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RESEARCH ARTICLE

Spatio-temporal variations in river water chemistry and hydrochemical facies of the Kathmandu valley river system, Nepal

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ABSTRACT

Understanding the hydrochemistry of river water is crucial for assessing hydrological processes, water-source contributions, and human impacts in rapidly urbanising basins. The Kathmandu Valley, a tectonic intermontane basin in central Nepal, have a dense river network, including major rivers such as the Bagmati, Bishnumati, Manahara, Dhobi, Hanumate, Godawari, Kodku, Nakhu, and Balkhu. Despite the importance of river systems for local water resources, spatial and temporal chemical investigations of these rivers remain limited.

In the current study, 80 sampling sites were selected from nine rivers during the wet (August 2017) and dry (February 2018) seasons. Total 160 water samples were collected, 80 samples from each season. Ions were analysed by ion chromatography. Chemical analysis showed a seasonal shift from Ca^{2+} dominance in the wet season to Na^{+} in the dry season, with significant temporal variation in most ions ($p < 0.01$). Strong correlations among ions indicated human influence, particularly increased NH_4^{+}-N and PO_4^{3-}-P levels during the dry season, except in Godawari Khola. Hydrochemical facies analysis revealed that river water was predominantly Ca-HCO_3^{-} type during the wet season, shifting to Na-K-HCO_3^{-} type in the dry season for northern rivers. Conversely, southern rivers largely maintained their original water type. The river systems of the valley were grouped into four clusters by Hierarchical Cluster Analysis (HCA) based on similarity of chemical concentrations. Hanumante Khola exhibited the highest chemical concentrations, indicating a heavily polluted river within the valley during the dry season.

Keywords: ***Water chemistry, hydrochemical facies, spatio-temporal variation, river water, Kathmandu valley***

INTRODUCTION

River water quality assessment is fundamental to sustainable water resources management, particularly in rapidly urbanizing basins where increasing anthropogenic pressures threaten both human and ecosystem health. Hydrochemical characteristics of river water reflect the integrated effects of natural hydrological processes such as precipitation, runoff, and water–rock interaction and human activities including domestic sewage discharge, industrial effluents, agricultural runoff, and solid waste disposal. Evaluating the spatio-temporal variation of river water chemistry is therefore essential for identifying pollution sources, understanding controlling processes, and supporting evidence-based water governance.

At the global level, the United Nations Sustainable Development Goal 6 (SDG 6: Clean Water and

Sanitation) emphasizes the need to improve water quality by reducing pollution, eliminating dumping, minimizing the release of hazardous chemicals, and substantially increasing wastewater treatment and reuse (Target 6.3). SDG 6 also highlights the protection and restoration of water-related ecosystems, including rivers, as a key component of sustainable development (Target 6.6). Achieving these targets requires reliable scientific data on river water quality, seasonal variability, and pollution hotspots, particularly in developing and rapidly urbanizing regions.

In Nepal, national commitments to SDG 6 are reflected in the Water Resources Policy (2020), National Water Plan, and National Environment Policy (2019), all of which prioritize river water quality monitoring, pollution control, and integrated river basin management. The Bagmati River Basin, which encompasses the Kathmandu Valley river system, has been identified as a high-priority basin under national river restoration and management programs due to its ecological, cultural, and socio-economic significance. The Bagmati River Basin Management Plan and associated river rehabilitation initiatives emphasize the need for scientific assessment of water quality, identification of pollution sources, and seasonal evaluation of chemical and nutrient loading to guide effective restoration and wastewater management strategies. However, the Kathmandu Valley hosts a dense river network including the Bagmati and its major tributaries Bishnumati, Manahara, Dhobi, Hanumante, Godawari, Kodku, Nakhu, and Balkhu rivers. It is very important to conduct such research in all tributaries and implement it to achieve SDG 6.

These rivers of the valley also serve as the primary surface water system and are closely connected to shallow groundwater resources (Bajracharya et al., 2018; Bajracharya et al., 2020; Prajapati et al., 2020; Malla et al., 2015; Gautam et al., 2013) and to urban water use. Previous studies have also documented chemical pollution in selected rivers or river reaches within the Kathmandu Valley (Devkota and Watanabe, 2005; Moog and Sharma, 2005; Kannel et al., 2007; Bhatt et al., 2013; Regmi and Mishra, 2016; Khadka et al., 2019; Adhikari et al., 2021; Acharya and Pant, 2021). However, basin-wide investigations that systematically examine spatial and seasonal variations in river water chemistry across the entire river network are still lacking. Such integrated assessments are required to identify pollution hotspots, assess temporal trends, and evaluate the effectiveness of ongoing and planned intervention measures.

In this context, the present study investigates the spatio-temporal variation of water chemistry in the Kathmandu Valley river system during wet and dry seasons. By integrating field measurements, laboratory analysis of major ions, and multivariate statistical techniques, this study aims to (i) characterize seasonal and spatial patterns of river water chemistry, (ii) identify dominant hydrochemical facies and controlling processes, (iii) assess anthropogenic influences and contamination sources.

STUDY AREA

Geology of the Kathmandu Valley

The Kathmandu Valley is underlain by the Kathmandu Complex, comprising the upper Phulchoki Group and the underlying Bhimphedi Group (Stöcklin & Bhattarai, 1977; Stöcklin, 1980). The northern and northeastern hills are dominated by gneiss and schist of the Bhimphedi Group, whereas the southern and western hills consist mainly of rocks of the lower Phulchoki Group.

The basin is filled with Plio–Pleistocene fluvial, fluvio-lacustrine, and fluvio-deltaic sediments (Yoshida & Igarashi, 1984; Sakai et al., 2008). Major sedimentary units include the Tokha, Thimi, Patan, Gokarna, and Chapagaon formations, along with the Lower Terrace Deposits, which are widely distributed along river corridors (Dhital, 2015) (Fig. 1). The Tokha Formation, exposed mainly in the northern basin, consists of silt and silty sand with gravel lenses. The central basin is occupied by the Thimi and Patan formations, composed of clay, peat, silt, sand, and gravel derived largely from the Shivapuri Range. The southern basin is characterized by the Gokarna Formation, consisting of laminated arkosic sand, silty clay, and peat, and the Chapagaon Terrace Deposits composed of limestone and metasandstone pebbles and cobbles. Lower Terrace Deposits along active channels consist mainly of micaceous sand, pebbles, and granules.

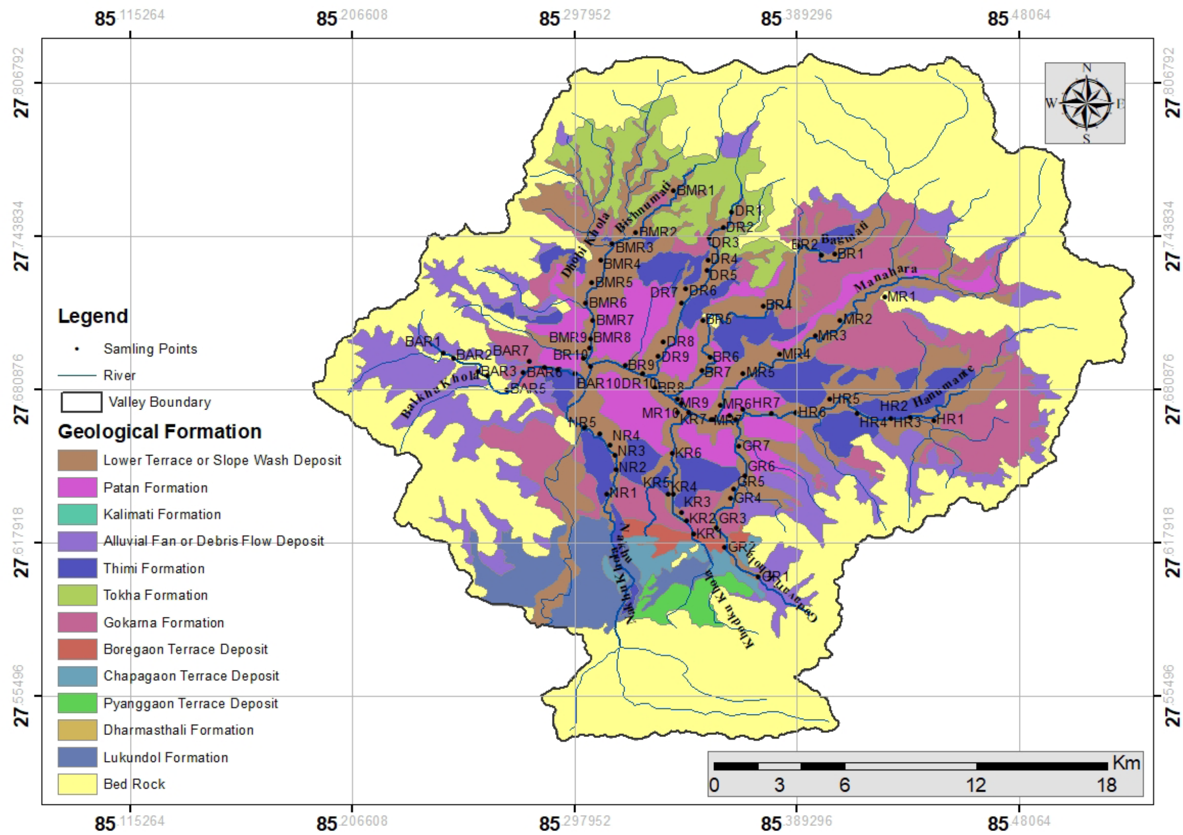

Fig. 1: Location of sampling point and geology of the Kathmandu valley (after Dhital 2015)

Fluvial Setting of the Kathmandu Valley

The Bagmati River is the principal drainage of the Kathmandu Valley, forming a centripetal drainage network with major tributaries including the Bishnumati, Manahara, Dhobi Khola, Hanumante, Godawari, Kodku, Nakhu, and Balkhu rivers. The Bagmati River is a 7th-order perennial stream extending approximately 51 km from the Nagarkot hills (Shrestha & Tamrakar, 2011). Its tributaries range from fifth- to sixth-order streams and vary in length, watershed area, and diverse channel patterns, including meandering and sinuous forms (Table 1). Most rivers show downstream fining of sediments from gravel and cobble to sand and silt.

Several tributaries exhibit severe environmental degradation due to human activities such as gravel extraction, direct sewage discharge, industrial effluents, channelization, road construction, and urban encroachment (Tamrakar, 2004; Pathak et al., 2015). As a result, tributaries have experienced morphological changes, pollution, bank erosion, flooding problems, and overall environmental degradation (Shrestha & Tamrakar, 2011; Maharjan & Tamrakar, 2011). In the Kathmandu Valley, variations in precipitation patterns significantly influence river slope and channel sinuosity. A decreasing trend in precipitation generally reduces discharge in perennial rivers, which in turn lowers channel slope and promotes increased sinuosity (Shrestha and Tamrakar, 2011).

Table 1: River order, type and major issues (Tamrakar, 2004; Bajracharya and Tamrakar, 2007; Maharjan and Tamrakar, 2010; Shrestha and Tamrakar, 2011; Tamrakar et al., 2013; Pandey, 2014; Karki and Tamrakar 2016; Lama and Tamrakar 2016)

River Name	Order	Length (km)	Watershed Area (km²)	Channel Type	Dominant Bed Material	Major Issues
Bishnumati River	6th	16.34	102.26	Low sinuosity, low gradient (steep headwaters)	Gravel to muddy gravel (fining downstream)	Severe pollution, morphological degradation
Dhobi Khola	5th	17.82	30.74	Modified/ channelized	Pebble to sand	Sewer discharge, reduced width, urban flooding
Manahara River	5th	25.24	74.26	Meandering	Cobble to sand	Bank erosion, channel shifting
Hanumante Khola	6th	18.3	97.05	Sinuous	Sand, silt and clay	Heavy sewage & industrial pollution
Godawari Khola	5th	16.08	46.65	Sinuous	Pebble to sand	Moderate human disturbance
Kodku River	5th	15.13	32.92	Sinuous	Coarse pebble to silt/clay	Urban and material extraction impacts
Nakhu Khola	5th	25.59	58.72	Meandering (low sinuosity)	Pebble upstream, sand downstream	Gravel quarrying, road construction, vegetation removal
Balkhu River	6th	16.44	43.95	Sinuous	Pebble to sand	Solid waste, sewage, chemical effluents

MATERIAL AND METHODS

Field Measurements and Water Sampling

River water samples were collected during two hydrological seasons: the wet season (August 2017) and the dry season (February 2018). A total of 80 sampling sites were selected in each season, comprising 10 sites from each river except Nakhu khola (Fig. 1). Total 160 samples were collected, including 80 samples from each season. Water samples were collected in pre-cleaned 100 mL polyethylene bottles, each rinsed three times with site water before sampling. All samples were stored at −4 °C and transported to the laboratory for subsequent chemical analyses.

During sampling, electrical conductivity (EC), dissolved oxygen (DO), pH, and water temperature were measured in situ at each location. In situ physicochemical parameters were measured using portable instruments: a DO meter (Mettler Toledo SG3-ELK, Greifensee, Switzerland) and a combined pH/EC meter (Mettler Toledo Duo, Greifensee, Switzerland).

Chemical Analyses

Chemical analyses were conducted at the laboratory of the Interdisciplinary Centre for River Basin Environment, University of Yamanashi (ICRE-UY), Japan. Before analysis, all water samples were filtered through 0.2 μm membrane filters. Major cations (Na^+, K^+, NH_4^+–N, Ca^{2+}, and Mg^{2+}) and anions (Cl^-, NO_3^-–N, PO_4^{3-}–P, and SO_4^{2-}) were quantified using ion chromatography (ICS-1100, Dionex, Waltham, MA, USA), with an analytical uncertainty of approximately ±5%. Bicarbonate (HCO_3^-) concentrations were determined by acid titration using 0.01 N sulfuric acid.

Statistical Analysis

Seasonal variations in chemical parameters were evaluated using paired *t*-tests at a 95% confidence level because corresponding sampling locations were sampled during both the wet and dry seasons. Thus, observations from the two seasons were treated as matched observations, and the analysis was based on the within-site seasonal differences. The number of paired observations was 80.

Because hydrochemical variables may exhibit skewed distributions and non-linear but monotonic relationships, Spearman's rank correlation coefficient (ρ) was used to evaluate associations among physicochemical parameters and major ions. Two-tailed significance tests were applied, with $p < 0.05$ and $p < 0.01$ considered statistically significant.

Hierarchical cluster analysis (HCA) was performed to identify spatial groupings of river sampling sites according to their hydrochemical characteristics. HCA was conducted using Ward's linkage method with squared Euclidean distance. The analysis was restricted to dry-season data because the dry season exhibited substantially higher concentrations of dissolved ions and stronger spatial contrasts than the wet season, providing clearer differentiation among sampling sites with different degrees of urban influence. Five variables EC, Na^+, NH_4^+–N, Cl^-, and HCO_3^- were selected because they represent complementary aspects of the observed dry-season hydrochemical conditions: EC reflects overall dissolved-ion mineralization, Na^+, NH_4^+–N, and Cl^- are sensitive to urban/domestic wastewater influence, and HCO_3^- represents a major component of the dissolved ionic composition. The objective of HCA was therefore to identify spatial differences in hydrochemical and pollution characteristics during the low-flow season rather than to classify the complete hydrochemical composition of the river system.

RESULTS

Spatio-temporal variation of in situ parameters

In situ parameters provide a direct indication of the quality and pollution status of river water. Water temperature, pH, dissolved oxygen (DO), electrical conductivity (EC), and nutrient-related ions (Na^+, Cl^-, nitrogen, and phosphorus compounds) are key factors controlling river water degradation.

River water temperatures across the Kathmandu Valley show comparable ranges during the wet (22–28 °C) and dry (12–18 °C) seasons, with minor site-specific deviations. River water exhibit slightly alkaline conditions in both seasons, with pH values ranging from 6.7 to 8.8 during the wet season and 6.8 to 8.5 in the dry season. Southern tributaries, including the Godawari, Kodku, Nakhu, and Balkhu rivers, recorded relatively higher pH values (>7.5) in both seasons.

Dissolved oxygen is a critical parameter for sustaining aquatic ecosystems, with a minimum concentration of 3 mg/L required for fisheries (US EPA, 1986). Upstream reaches of most rivers exhibit relatively high DO levels in both seasons, indicating favourable conditions for aquatic life. In contrast, downstream sections show critically low DO concentrations (<1 mg/L), particularly during the dry season, except in the Godawari Khola (Fig.2).

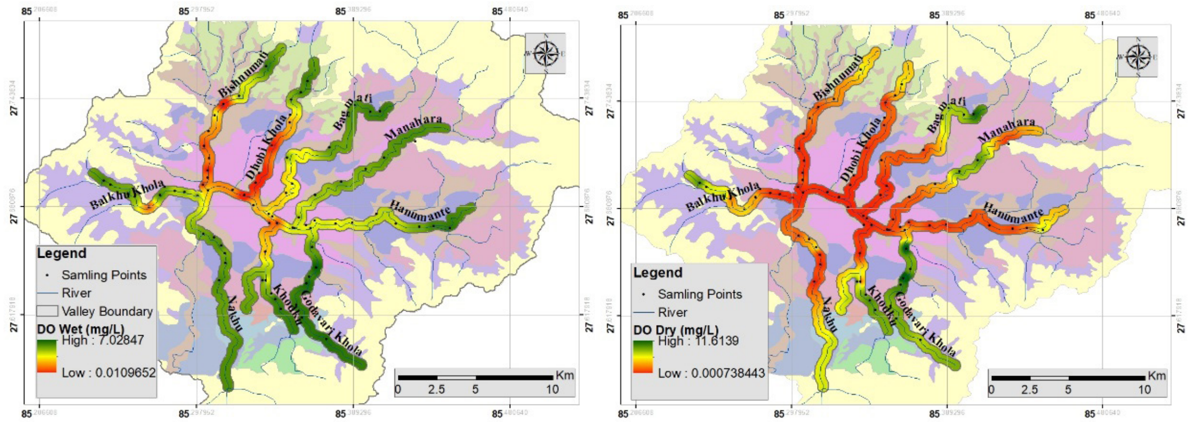

Fig. 2: Spatial variation of DO in a) wet and b) dry seasons

Electrical conductivity values are generally low during the wet season (41–892 µS/cm) but increase markedly during the dry season (118–2060 µS/cm). The magnitude of increase varied spatially, with upstream sections showing modest increases (1.5–3 times) and downstream sections exhibiting substantially higher increases (4 to >9 times). The Hanumante Khola recorded the highest EC values and seasonal increases, whereas the Godawari Khola showed consistently low EC values (Fig.3).

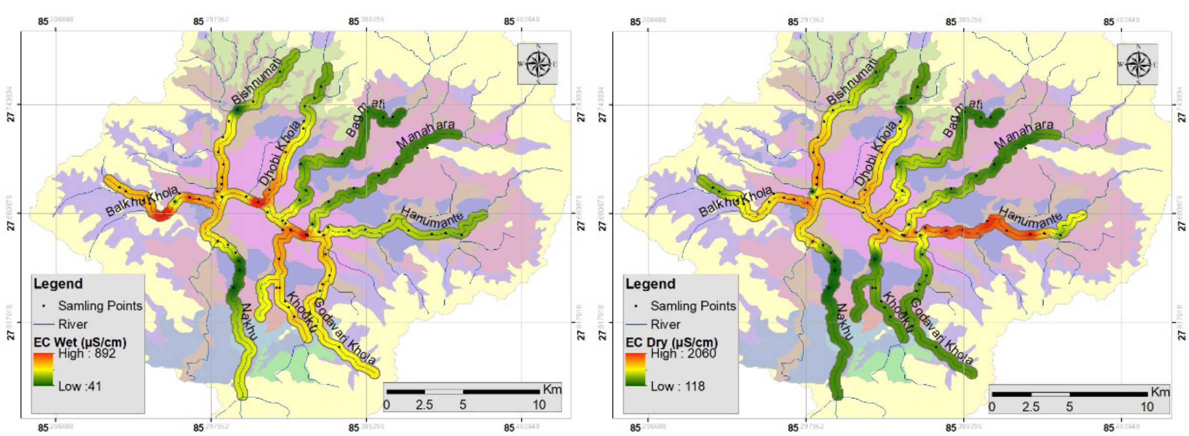

Fig. 3: Spatial variation of EC in a) wet and b) dry seasons

Spatio-temporal Variation of Chemical Parameters

The range of chemical concentrations spatially varies widely among tributaries of the Bagmati River in both seasons. Generally, water from the Kathmandu river system is characterized by Ca^{2+} and HCO_3^- dominance, with concentration ranges from 2.3 to 24 mg/L and 18.3 to 176.9 mg/L, respectively, during the wet season. The lowest values of both Ca^{2+} and HCO_3^- are recorded from the upstream section of the Bagmati River, while the highest values are measured from the downstream section of the Kodku Khola. Basically, southern tributaries like the Godawari, Kodku, and Nakhu Khola have lower chemical concentrations of Na^+, Cl^-, NH_4^+–N than the northern and eastern tributaries, including the Bishnumati, Dhobi, Manahara, and Hanumante Kholas, in both seasons. The PO_4^{3-}–P concentration is null in southern tributaries, while northern tributaries have a value range from 0.3 to 3 mg/L during the wet season (Fig.4).

Ion concentrations also vary widely within each river. Generally, concentrations increase in downstream sections of all rivers; however, the Godawari Khola exhibits comparatively low concentrations and minimal downstream enrichment (Fig.4). The concentrations of Na^+, Cl-, NH_4^+–N and PO_4^{3-}–P increase from 2 to 10 in the downstream urbanized sections. Similar downstream enrichment patterns in urbanized reaches have been reported in earlier studies (Kannel et al., 2007; Pathak et al., 2015).

Wide temporal variations are also observed across all chemical concentrations. Most chemical parameters show significant seasonal variation ($p < 0.01$), with higher concentrations recorded during the dry season, when Na^+ becomes the dominant cation. The Na^+ concentration increased from 1.6 to 22 mg/L (wet season) to 5.7 to 151.9 mg/L (dry season). At the same time, Ca^{2+} increased to 4.6 to 53.7 mg/L. Higher concentrations of Ca^{2+} and Na^+ are predominantly observed at the Hanumante and the Balkhu Kholas sampling sites.

Temporal variation is narrow in the Godawari Khola with the very lowest concentration, while very wide variation is noted from the Hanumante Khola, with extreme increments (>10 times) in almost all ion concentrations (Fig. 4). The rate of increment is generally high in the northern tributaries compared to the southern. PO_4^{3-}–P concentration is still null only in the Godawari Khola during the dry season, whereas other southern tributaries have a value range of 2.3 to 13.5 mg/L.

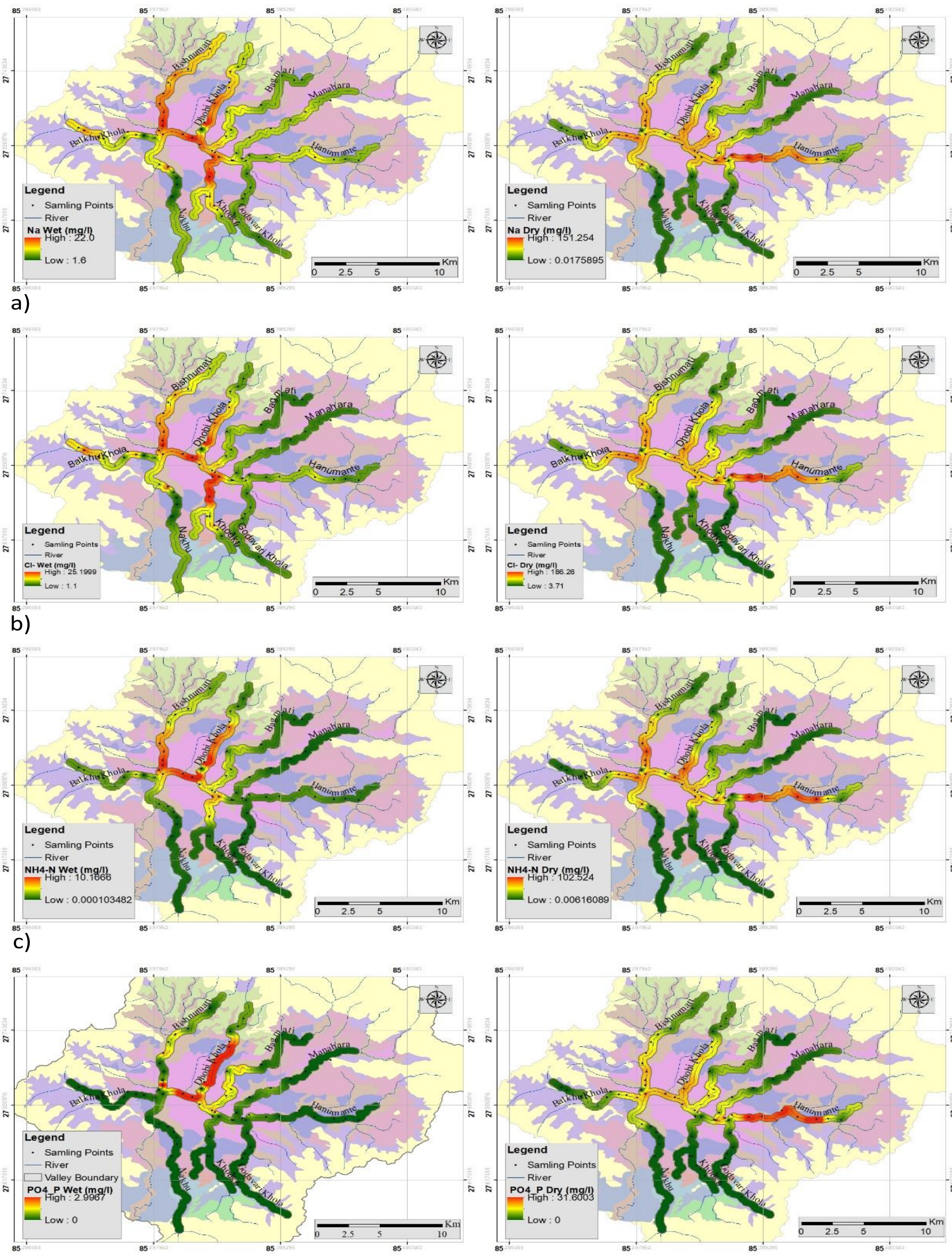

Fig. 4: Spatial variation of a) Na^{+}, b) Cl-, c) NH_4^{+}–N and d) PO_4^{3-}–P in wet and dry seasons

Hydrochemical Characteristics:

Hydrochemical conditions of the Kathmandu river system are determined by using a Piper Diagram. River waters are predominantly of the Ca–HCO_3 type during the wet season. This facies persists in southern tributaries (Godawari, Kodku, and Nakhu Kholas) during the dry season, with minor local deviations. In contrast, northern rivers show a seasonal shift to Na–K–HCO_3 type during the dry season (Fig. 5). The Ca–HCO_3 facies reflects recent recharge from rainfall and surface runoff, whereas the Na–K–HCO_3 type indicates enhanced mineral dissolution and mixing with anthropogenically influenced waters during low-flow conditions (Singh & Kumar, 2015; Al-Khatib & Al-Najar, 2011). The observed seasonal transition suggests increased contribution of water in rivers from untreated municipal and industrial discharges during the dry season (Zhu et al., 2019).

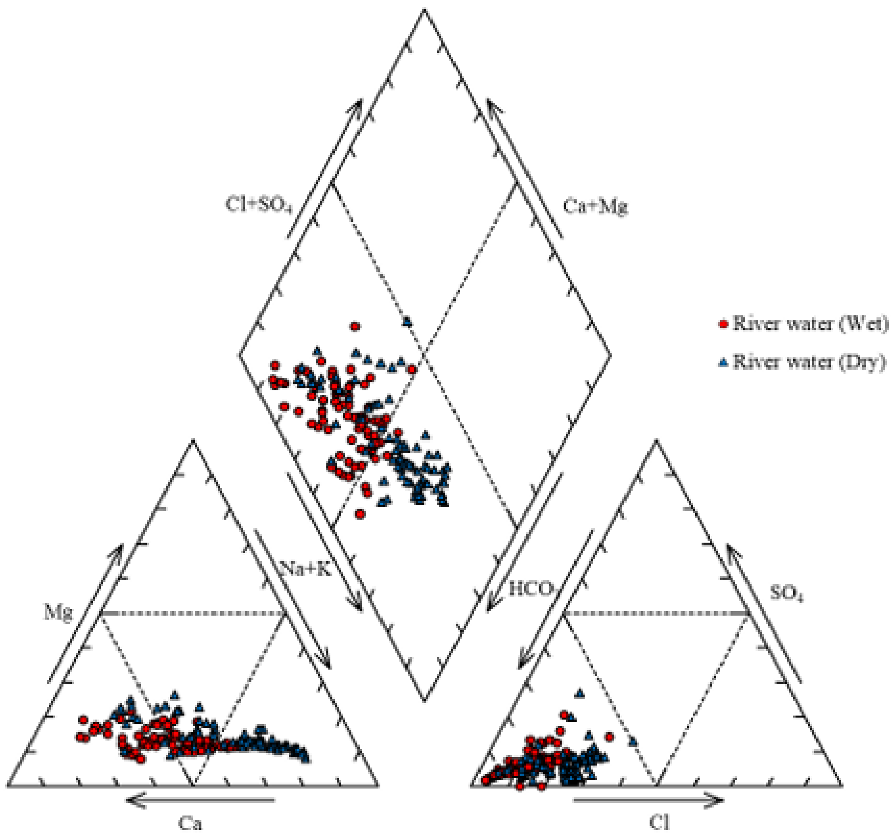

Fig. 5: Piper diagram of river water in the wet and dry seasons

DISCUSSION

Control on hydrochemistry of river water

Spearman's correlation is applied to determine tentative control on hydrochemistry of river water (Table 2). During both seasons, the correlation condition of chemical ions are similar (positive or negative) but the rate of correlation (-1 <ϱ> 1) is different. The dry-season correlation matrix exhibits much stronger relationships than the wet season, reflecting the concentration of dissolved constituents under low-flow conditions.

Table 2: Correlation coefficients among physicochemical parameters and major ions of Kathmandu Valley river water during the wet and dry seasons

River water wet season														
Parameters	DO	EC	Temp	pH	Na^+	NH_4^+-N	K^+	Mg^{2+}	Ca^{2+}	Cl^-	NO_3^- -N	PO_4^- -P	SO_4^{2-}	HCO_3^-
DO	1													
EC	-.470**	1												
Temp	-.414**	0.11	1.00											
pH	0.18	.278*	0.15	1										
Na^+	-.791**	.435**	.415**	0.00	1									
NH_4^+-N	-.833**	.476**	.360**	-0.04	.807**	1								
K^+	-.759**	.469**	.337**	0.02	.893**	.849**	1							
Mg^{2+}	-.349**	.529**	0.16	.317**	.644**	.363**	.563**	1						
Ca^{2+}	-.341**	.641**	0.14	.410**	.543**	.368**	.580**	.861**	1					
Cl^-	-.752**	.553**	.337**	0.10	.953**	.805**	.896**	.785**	.688**	1				
NO_3^- -N	.248*	0.07	-.225*	0.05	-0.05	-.282*	0.07	0.12	.305**	-0.04	1			
PO_4^- -P	-.903**	.541**	.402*	.434*	.831**	.906**	.877**	.751**	.743**	.900**	-.707**	1		
SO_4^{2-}	-.652**	.475**	.264*	0.04	.719**	.585**	.804**	.566**	.677**	.737**	.401**	.719**	1	
HCO_3^-	-.427**	.640**	.332**	.423**	.589**	.500**	.580**	.790**	.812**	.727**	0.09	.862**	.549**	1
River water dry season														
Parameters	DO	EC	Temp	pH	Na^+	NH_4^+-N	K^+	Mg^{2+}	Ca^{2+}	Cl^-	NO_3^- -N	PO_4^- -P	SO_4^{2-}	HCO_3^-
DO	1													
EC	-.773**	1												
Temp	-0.18	-0.05	1											
pH	.599**	-.496**	-0.16	1										
Na^+	-.813**	.941**	0.06	-.524**	1									
NH_4^+-N	-.750**	.894**	0.01	-.477**	.904**	1								
K^+	-.780**	.946**	-0.01	-.533**	.960**	.928**	1							
Mg^{2+}	-.699**	.904**	-0.05	-.354**	.885**	.797**	.859**	1						
Ca^{2+}	-.538**	.770**	-0.17	-.325**	.708**	.611**	.671**	.877**	1					
Cl^-	-.801**	.961**	0.01	-.492**	.987**	.907**	.966**	.918**	.746**	1				
NO_3^- -N	.419**	-0.16	-0.16	0.18	-0.20	-0.19	-0.14	-0.06	0.11	-0.17	1			
PO_4^- -P	-.664**	.888**	-0.10	-.351**	.830**	.867**	.910**	.729**	.459**	.831**	-0.06	1		
SO_4^{2-}	-.633**	.545**	0.17	-.358**	.651**	.653**	.635**	.398**	0.202	.614**	-.477**	.439**	1	
HCO_3^-	-.759**	.949**	-0.01	-.508**	.956**	.893**	.952**	.935**	.814**	.968**	-0.07	.820**	.494**	1
**. Correlation is significant at the 0.01 level (2-tailed).														
*. Correlation is significant at the 0.05 level (2-tailed).														

Generally, EC exhibited a significant positive correlation with all major dissolved ions. These relationships indicate that EC is primarily controlled by the concentration of dissolved ions and can be used as an indicator of mineralization and anthropogenic pollution (Ganiyu et al., 2018; Bhat et al., 2014). The increment in EC and strong positive correlation again indicate huge anthropogenic input during the dry season. In contrast, DO showed significant negative correlations with EC and most dissolved ions, particularly PO_4^{3-}–P, NH_4^+–N, Na^+, K^+, Cl^- and HCO_3^-. This suggests that increasing pollutant concentrations reduce oxygen availability, reflecting organic pollution and nutrient enrichment in urban river reaches.

There is also presence of a very strong positive correlation among Na^+, NH_4^+–N, K^+, Mg^{2+}, Cl^-, HCO_3^-, and PO_4^{3-}–P, indicating a common anthropogenic origin (Menció & Mas-Pla, 2008), most likely domestic sewage, municipal wastewater, and urban runoff (Pathak et al., 2015). The condition of river with higher solid and liquid untreated disposal on or near to river channel present in the urbanized sections (Fig. 6) also verify the present correlation condition. The stronger relationship in the dry season specify more concentrated because of reduced river discharge. Strong positive correlation between Ca^{2+}, Mg^{2+} and HCO_3^- suggest carbonate weathering, while strong relation of HCO_3^- with PO_4^{3-}–P and Cl^- (anthropogenic indicators) suggest that natural geochemical processes are increasingly modified by human activities during the dry season. Elevated phosphate levels and their strong negative correlation with DO indicate ongoing eutrophication processes in several rivers (Davie, 2003). Positive correlations between PO_4^{3-}–P and SO_4^{2-} further suggest inputs from agricultural fertilizers and pesticides used in river-adjacent cultivated areas (El Alfy & Merkel, 2004; Bhat et al., 2014; Zhong et al., 2018). Nitrate (NO_3^-–N) showed generally weak correlations with most parameters and a slight positive relationship with DO implying that nitrate is influenced by nitrification (Nienie et al., 2017), and localized agricultural inputs rather than municipal wastewater alone.

Fig. 6: Anthropogenic pollution at a) Hanumante Khola b) Bagmati River c) and d) Bishnumati River

Additionally, all these rivers flow through basement rock at the upstream section and then flow over fluvial-lacustrine deposits. The northern hills are mainly composed of gneiss and granite (Stocklin, 1980) and the debris deposited by triburaties and their riverbed are also dominated by gneiss and granite (Tamrakar, 2009). The dissolution of minerals from these rocks takes too long time to dissolve in river water. But the chemical concentration of water are drastically increased during the dry season, which cannot be possible to dissolve mineral from these rock within the duration between wet to dry seasons. At the meantime, the increased chemical ions such as Na^+, NH_4^+–N, Cl^- and PO_4^{3-}–P could not be the byproduct of basement rocks. Thus, it also clearly emphasize that the increased concentration in the dry season are mainly modified by anthropogenic influences.

On the other side, the hills of western and southern are dominantly composed of the Phulchoki Group including the Chandragiri Formation and Godawari Limestone. The positive correlation of Ca^{2+}, Mg^{2+} and HCO_3^- also signifies carbonate weathering from these formations. The overall correlation analysis and geological material present in the study areas demonstrates that the hydrochemistry of Kathmandu Valley River system is controlled by both natural geochemical processes and anthropogenic activities (especially in the dry season).

Polluted Zones in Kathmandu River System

As the chemical concentration drastically increased in the dry season, the Hierarchical Cluster Analysis (HCA) is carried out only for the dry season data using parameters EC, Na^+, NH_4^+–N, Cl^- and HCO_3^-. This analysis grouped spatially located river sites into clusters based on similar chemical ion concentrations.

HCA grouped river sampling sites into two major clusters (Fig. 7). Cluster A represents less polluted upstream and middle reaches, with relatively low EC and ion concentrations, while Cluster B comprises highly urbanized downstream sections with elevated concentrations of EC, Na^+, NH_4^+–N, Cl^-, and HCO_3^- (Table 3). The Hanumante Khola forms a distinct sub-cluster (B1) within Cluster B, exhibiting the highest concentration ranges and identifying it as one of the extremely polluted rivers in the Kathmandu Valley (Fig. 8). Separate grouping of upstream and middle reach sites from almost all rivers in Cluster A again emphasizes drastic spatial difference within each river. The clustering pattern clearly reflects the influence of urbanization, sewage discharge, and land-use intensity on river water chemistry.

The clustering of river sites and their chemical concentrations also indicates the importance of restoration and rehabilitation to improve river water quality and aquatic life survival. The basin management plan conducted only in one Bagmati river cannot improve the overall river system of the valley. Only collecting solid waste from the river bank is not sufficient work to improve the whole river system. Thus, to maintain the river system, it is very necessary to construct waste water treatment plant in different sections within each river so that direct disposal of untreated wastewater from municipal and industrial sources can be minimised.

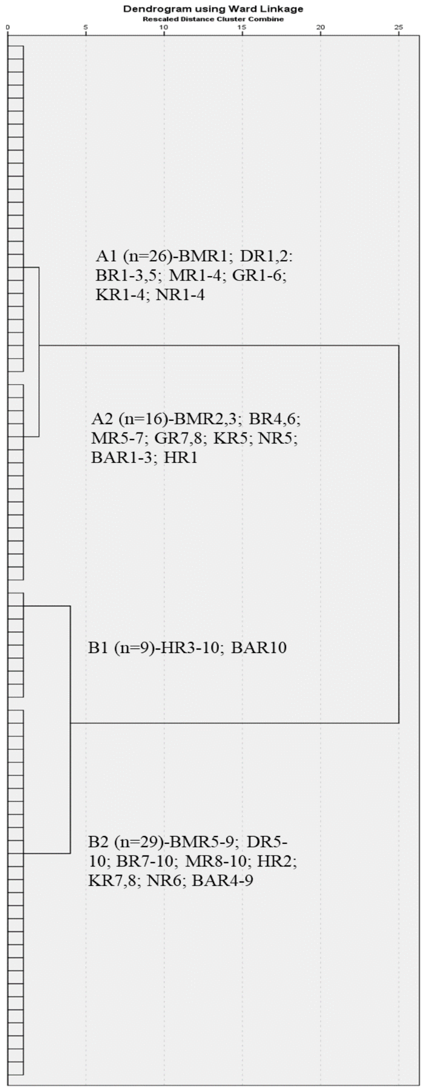

Fig. 7: Dendogram of HCA prepared from dry season data

Table 3: Value range of parameters of different clusters

Season	RW Cluster No.		Data range	EC µc/cm	Na^+ mg/l	NH_4-N_mg/l	Cl^- mg/l	HCO_3^- mg/l
Dry	Cluster A	A1 (n=26)	Min	118.5	5.7	0.0	3.7	48.8
			Max	439.0	30.3	11.5	34.3	158.6
		A2 (n=16)	Min	264.0	5.7	0.1	4.8	91.5
			Max	956.0	71.3	33.1	79.4	329.4
	Cluster B	B1 (n=9)	Min	1780.0	92.2	63.0	120.7	518.5
			Max	2060.0	151.9	102.9	186.3	884.5
		B2 (n= 29)	Min	1037.0	43.7	18.4	63.0	262.3
			Max	1644.0	108.2	83.6	132.3	634.4

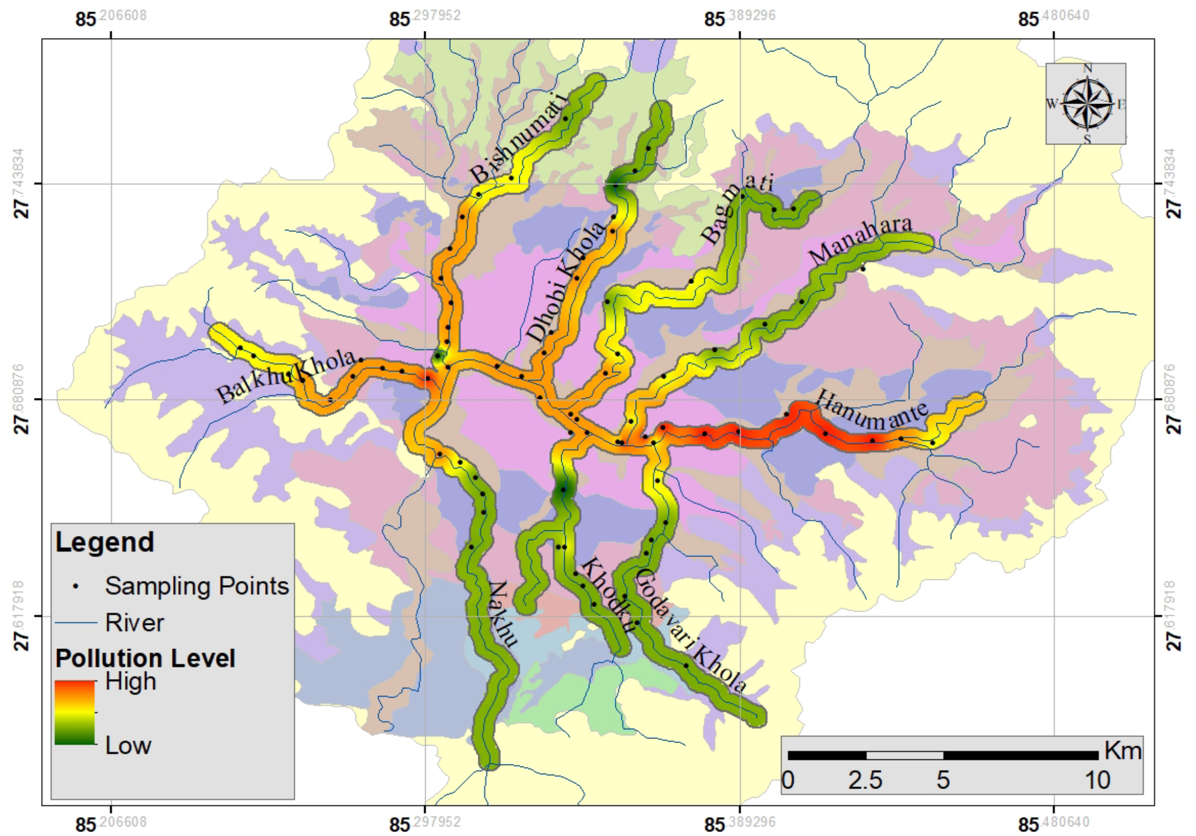

Fig. 8: Pollution level in the Kathmandu Valley river system

Importance of wastewater treatment and discharge control

The observed increase in EC, Na^+, NH_4^+–N, Cl^-, PO_4^{3-}–P and other dissolved constituents during the dry season indicates that untreated or inadequately treated wastewater is a major pressure on several river reaches. Therefore, wastewater should not be directly discharged into the Bagmati River and its tributaries without adequate treatment and compliance monitoring. A practical management approach is necessary to improve river water quality which may include source-level screening, primary sedimentation, biological treatment for reduction of organic matter, nutrient removal where necessary, and disinfection prior to final discharge.

Form this present research result, particular attention must be given to nitrogen and phosphorus removal because elevated NH_4^+–N and PO_4^{3-}–P were observed in several urbanized river reaches and were associated with reduced dissolved oxygen. Reduced DO (<3 mg/L) is not acceptable for aquatic ecosystems (US EPA, 1986). Thus, treatment facilities need to be designed according to the characteristics and loading of the wastewater rather than relying only on dilution by the receiving river.

It is also important to test final treated effluent before discharge, and discharge should be permitted only when the effluent complies with the applicable national standards. Nepal's Department of Environment already provides environmental laws, regulations, standards and treated-wastewater guidance, and its mandate includes pollution control and implementation/monitoring of environmental standards. These standards also prescribe tolerance limits for wastewater and industrial effluents discharged into inland surface waters. For example, the standard for wastewater discharged from a combined wastewater treatment plant specifies maximum concentrations of 60 mg/L for TDS, 50 mg/L for BOD_5 and 250 mg/L for COD, with pH maintained between 5.5 and 9.0.

For effective implementation in the Kathmandu Valley, local governments and relevant water and environmental authorities should establish routine monitoring points at wastewater treatment plant outlets and at upstream and downstream locations of receiving rivers. Effluent monitoring should include, at minimum, pH, EC, TSS, BOD_5, COD, NH_4^+–N, total nitrogen, phosphorus, and microbial indicators, with additional parameters such as metals and oil and grease monitored where relevant to the source. Treatment performance and compliance records need to be maintained and periodically reviewed. Where effluent does not meet the applicable standard, discharge should be stopped or diverted for further treatment rather than relying on dilution in the receiving river.

These measures will help to provide a practical framework for local institutions to reduce wastewater-derived pollution and progressively improve the water quality of the Kathmandu Valley river system.

Recommendations for Metropolitan Cities and Municipalities

The findings of this study have direct implications for metropolitan cities and municipalities responsible for urban wastewater and river management. The marked increase in EC and dissolved ions during the dry season, together with elevated NH_4^+–N, PO_4^{3-}–P and other pollution indicators in urbanized downstream reaches, indicates that wastewater management should be prioritized at the source. Based on the present research, followings are some recommendations for metropolitan cities/municipalities to maintain Kathmandu river systems:

Priority	**Action for metropolitan cities/municipalities**
Identify pollution sources	Map all sewage, industrial and institutional outfalls
Stop direct sewage discharge	Prioritize densely populated river corridors
Solid waste control	Prevent solid waste dumping into river channels
Wastewater treatment	Use treatment systems appropriate to wastewater quantity and characteristics
Effluent standards	Not allow treated wastewater to enter rivers unless it meets the applicable national standard, routine laboratory testing at treatment-plant outlets is nessesary
River monitoring	Establish permanent monitoring stations at upstream, middle and downstream
Pollution hotspot management	priority to highly polluted reaches such as Hanumante and other urban downstream sections, develop reach-specific pollution reduction plans
Inter-municipal coordination	Manage rivers as connected systems rather than municipal boundaries, joint river-basin committee involving Kathmandu Valley municipalities

These measures help metropolitan cities and municipalities to move from reactive river-cleaning activities toward preventive, source-based and evidence-based wastewater management.

CONCLUSION

The present study provides a comprehensive assessment of the spatial and temporal variation in river water chemistry across the Kathmandu Valley river system. River hydrochemistry exhibits distinct seasonal variability, with significantly higher concentrations of most dissolved ions during the dry season ($p < 0.01$), reflecting reduced river discharge. River waters are predominantly characterized by the $Ca–HCO_3$ hydrochemical facies during the wet season, indicating the influence of recent recharge and water–rock interaction. During the dry season, however, several northern tributaries shift to the $Na–K–HCO_3$ facies, demonstrating the increasing influence of anthropogenic inputs under low-flow conditions. These findings indicate that river hydrochemistry is controlled by the combined effects of geological conditions, seasonal hydrological processes, and human activities.

Correlation analysis further reveals strong positive relationships among EC, Na^+, NH_4^+–N, K^+, Cl^-, PO_4^{3-}–P, and HCO_3^-, whereas dissolved oxygen shows strong negative correlations with these parameters, indicating that domestic sewage, municipal wastewater, and urban runoff are the dominant sources of river pollution, particularly during the dry season. The positive correlations among Ca^{2+}, Mg^{2+}, and HCO_3^- confirm the contribution of carbonate weathering. While the stronger association between major ions and anthropogenic indicators demonstrates that natural hydrochemical processes are increasingly modified by urbanization.

Hierarchical Cluster Analysis effectively distinguished relatively less-polluted upstream and middle reaches from highly contaminated downstream urban reaches. The Hanumante Khola was identified as the most severely polluted river within the Kathmandu Valley, while the Godawari Khola consistently exhibited comparatively low ion concentrations and minimal seasonal variation, reflecting relatively limited anthropogenic disturbance. These spatial differences highlight the importance of catchment characteristics and land-use practices in controlling river water quality.

The results provide valuable baseline information for understanding hydrochemical evolution and identifying pollution hotspots within the Kathmandu Valley. The study emphasizes that restoring only the main Bagmati River is insufficient to improve the overall river system. Effective river restoration requires integrated basin-scale management, including expansion of wastewater treatment facilities, interception of untreated municipal and industrial discharges before they enter rivers, continuous hydrochemical monitoring, and coordinated management of all major tributaries. Such measures will contribute to improving river ecosystem health and support sustainable water-resource management in the Kathmandu Valley.

Future studies integrating hydrochemical, isotopic, and biological indicators over multiple hydrological years would further improve understanding of pollution sources, and the long-term impacts of urbanization on the Kathmandu Valley river system.

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AUTHORS CONTRIBUTION

Both authors made significant contributions to this study. The first author was primarily responsible for the conceptualization of the research, field investigation, data collection, analysis, and preparation of the original manuscript. The second author contributed to the interpretation of the results, scientific discussion, critical revision, and improvement of the manuscript. Both authors reviewed and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare that there are no financial, personal, or professional conflicts of interest that could have influenced the research, analysis, or conclusions presented in this study.

DATA AVAILABILITY STATEMENT

The data used and analyzed in this study are available from the corresponding author upon reasonable request through direct email communication.

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