Water quality and health risk assessment in the Gandaki river basin, central Himalaya, Nepal

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Abstract: Public health is at threat due to chemical contaminants in drinking water which may have direct health concerns. The suitability of water for health is primarily governed by the mineral constituents present in the water. The present study was carried out to evaluate the water quality and associated health risks in the Gandaki River Basin (GRB) in Central Himalaya, Nepal considering hydrochemical variables such as total dissolved solids (TDS); major cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}); major anions (Cl^{-}, NO_3^{-}, SO_4^{2-}, and HCO_3^{-}) and trace metals (As, Cu, Mn, Ni, Pb, Zn, Ba, Cr, Li and Sr) in spatiotemporal levels. Water Quality Index (WQI), Health Risk Assessment (HRA) and Cancer Index (CI) were analyzed to evaluate the overall quality of water in the GRB. The results revealed that all the examined variables were within the National Guidelines recommended for the domestic uses. Moreover, the results revealed that concentrations of TDS, major ions and the trace metals showed significant seasonality and the WQI values were found to be 36.38, 23.77 and 30.36 in pre-monsoon, monsoon and post-monsoon, respectively indicating better water quality in the monsoon season. Additionally, CI analysis of the selected trace metals such as As, Cr and Pb indicated relatively low cancer risk in the river water during all the seasons. The hazard quotient (HQ) dermal values of all the elements were < 1, signifying the little or no adverse effects via *a* dermal path, while HQ ingestion values of Ba, Li, Sr and Zn were found to be >1 during all the seasons indicating their possible threat via ingestion path. This study provides a useful database and suggests regular assessment and, also appropriate policy formulations for safeguarding the water bodies in the Himalayas.

Keywords: Drinking water quality; Health risk assessment; Cancer index; Gandaki river Basin.

1.Introduction

Water is an essential component and contributes many mWater is an essential component and contributes many mineral nutrients for the existence of life and also good health of the environment[1,2]. It sustains the ecological processes, protects public health, and supports the economy. These processes are directly connected with the quality of the aquatic ecosystems. The utility of water depends on the level of chemical concentrations which regulate the quality of water bodies i.e., suitable for irrigation, drinking, fishing, recreation, industrial as well as cultural and spiritual needs[3]. Water sources are vulnerable to pollutants depending on geological conditions and agricultural, industrial, and other anthropogenic activities[4]. If water quality is not maintained, the commercial and recreational value of the water resources will be diminished. Thus, the measurements of water quality can be used to evaluate the overall quality of the riverine systems and to determine whether the water is suitable for a healthy environment and can be used or not for the desired purposes.

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Quality of the water bodies is closely linked to the surrounding environment, recharging capacity, ion exchange, lithology, climate, oxidation-reduction reactions, interactions with bedrock, and aquifer genesis including the potential impacts of global climate change, particularly in the glacial-fed Himalayan river basins[5–9]. In addition, the rivers frequently act as conduits for the contaminants by collecting and carrying wastewater from the sub-catchments having different land use/covers. The climatic conditions, weathering processes, and evaporites can also have a major impact on their quality, particularly in the arid/semi-arid, and fragile regions of the river basins[10]. The anthropogenic activities include domestic water use, intensive agriculture, urban and industrial use, recreation, etc. along with the alteration in the natural conditions such as dams, and diversion affects the quality of the flowing stream[1,11].

Generally, quality of water in the rivers is free from the contamination in the headwaters. In the mid- and downstream segments, they carry pollutants and get contaminated due to different anthropogenic and natural processes and thus can be characterized by a complex mechanism. Accumulation of trace metals (TMs) along with pollutants in the surface water through multiple sources pose a negative impact on humans and the environment health. Some of these elements accumulate in the adipose tissues of humans that severely affect the body, like circulatory, nervous and immune systems. Potentially toxic trace metals such as lead (Pb), chromium (Cr), zinc (Zn), arsenic (As), and cadmium (Cd) are carcinogenic, which may affect the liver, kidney, nervous, blood and digestive systems of human[12]. The element Cu is also harmful to the digestive system, liver, and brain if the concentration is beyond the guideline values[13,14].

In the Himalayan region, the chemical characterization, source identification, and health risk assessment (HRA) of the surface water are limited, except for a few studies on the Tibetan Plateau[7,15–18]. The study carried out on mercury (Hg) contamination and other TMs have highlighted the fact of limited studies in the southern slope of the central Himalaya[19,20]. Assessment of drinking water quality is a timely requirement amid emerging public health complications in this context where accessibility of safe water is at risk[21].

The Gandaki River Basin (GRB) has one of the highest anthropogenic disturbances in the watershed areas in Nepal, primarily due to agricultural runoff, fisheries, municipal wastes, boating and water supply. The earlier studies focused on the chemical characterization of the major ions and the TMs in terms of spatiotemporal variations revealing the major controlling mechanisms in the overall basin[1,22]. However, there are very limited in-depth investigations regarding the drinking water and health risk perspectives until to this date. The comparative study of two tributaries of the GRB namely Kaligandaki and Seti river indicates the suitability of water for irrigation and domestic purposes[23]. Thus, the major objective of this research is to evaluate the water quality and associated health risks focusing on water quality, health, and cancer indices to improve public health interventions. This study provides information on the water quality and health risk assessment in the GRB during the current state of rapid urbanization and socioeconomic development.

2. Materials and methods

2.1. Study Area

The Gandaki River is one of the first order perennial rivers originated in the Himalaya and carry snow-fed flows with significant discharge, even in the dry season. It is located in the central Himalaya, Nepal between longitudes 82.88°E to 85.81°E and latitudes 27.32°N to 29.33°N (Figure 1). The river is trans-boundary in nature, lying north-south in the central Himalayan region. The GRB has one of the largest discharges among all the river basins in Nepal[24]. The headwater of the river lies on the southern edge of the Tibetan Plateau (TP), and it passes through Nepal before entering India. The elevation of the basin ranges from 8,100 m in the north to 89 m in the south covering 32,104 km^2 area cover in Nepal[25]. The basin is characterized by complex lithology, and substantial climatic and ecological variations and a sharp contrast exists in between upstream and downstream segments along the elevation gradient.

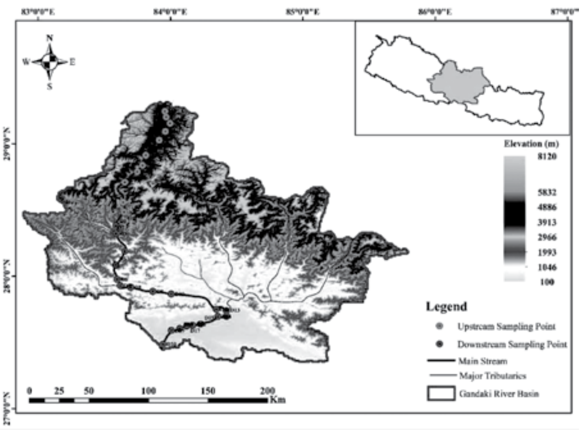

Figure 1. Location map showing the sampling points in the Gandaki River Basin (GRB), Central Himalaya, Nepal.

2.2. Analytical methods

In this study, a total 19 hydrochemical variables such as total dissolved solids (TDS); major cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+); major anions (Cl^-, NO_3^-, SO_4^{2-}, and HCO_3^-) and trace metals (As, Cu, Mn, Ni, Pb, Zn, Ba, Cr, Li and Sr) in GRB were used for the water quality and health risk assessment. Details of the sampling methods, data on variables and analytical procedures have been discussed and presented elsewhere[1,22]. Two segments of the GRB i.e., upstream (US) and downstream (DS) (**Figure 1**) have been selected for this assessment. Assessment includes the following water quality and health risk analyses:

2.2.1. Water quality index (WQI)

The WQI has been widely used in recent years for quality assessment of the surface water[26,27]. To assess the WQI of river water, it was calculated using TDS, major ions and trace metals (TMs). The weight of each parameter (Wi) was assigned according to the relative significance of different water quality variables in the overall quality of drinking water[28]. The WQI was calculated using the following equation[27]:

$$WQI = \sum_{i=1}^{n} Wi \times \left(\frac{Ci}{Si}\right) \times 100 \quad \text{.................... (1)}$$

Where, the relative weightage (W_i) of each parameter was calculated as:

$$Wi = wi / \sum_{i=1}^{n} wi \quad \text{..................... (2)}$$

Here,

wi is the weight of each parameter,

∑wi is the sum of the weightings of all parameters,

Ci, is the concentration of each variable in the water sample, and Si, is the guideline value limit as given in World Health Organization Guidelines for Drinking Water[29] for each water quality variables. The WQI and type of water are classified into five different categories i.e., excellent water (WQI < 50), good water (WQI = 50-100), poor water (WQI = 100-200), very poor water (WQI = 200-300), and water unsuitable for drinking purposes (WQI > 300)[30–32].

2.2.2. Health risk assessment (HRA)

The chemical variables including TMs enter into the human body through several paths such as direct ingestion, inhalation through the mouth and nose, and dermal absorption. Particularly, in case of TMs, oral and dermal intake play a most important role. For instance, other pathways are negligible in comparison with the direct intake of arsenic through eating and drinking. On average, human being consumes 2 L water daily for a healthy body. For average daily dose ingestion (ADD_i) (mg/kg/day) and average daily dose dermal (ADD_d) (mg/kg/day) through drinking water intake the following equation can be used[33]. The exposure dose for these two main pathways was calculated using the following equations:

$$ADDi = \frac{C \times IR \times EF \times ED}{BW \times AT} \quad \text{...................... (3)}$$

$$ADDd = \frac{C \times SA \times Kp \times ET \times EF \times ED \times CF}{BW \times AT} \quad \text{...... (4)}$$

Where C, is the average concentration of water quality variables (mgL^{-1}), IR is the ingestion rate (2 L Day^{-1} in this study), EF is the exposure frequency (365 days $year^{-1}$), ED is the exposure duration (assumed 67 years), BW is the average body weight (72 kg), AT is the average lifetime (24,455 days). Similarly, SA = exposed skin area (17,000 cm^2), Kp is the skin permeability coefficient in water, i.e., Kp = 0.001 (cm/h), ET = exposure time spent in bathing and shower (0.6 h/day), and CF = unit conversion factor, for water (0.001 L/cm^3). These values were obtained and confirmed by the US Environmental Protection Agency[33,34].

2.2.3. Hazard quotient (HQ) and hazard index (HI)

HQ was calculated to evaluate the non-carcinogenic risk of the water quality variables, i.e. TMs for inhabitants in the basin. The HQ is defined as the chronic daily intake of the chemical element divided by the corresponding reference dose (RfD), which is calculated using the following equation. HQ values ≤ 1 indicates the risk of the elements poisoning can be neglected, and > 1 indicates the potential risks to the consuming population[35].

$$HQ = \frac{ADD}{RfD} \quad \text{...................... (5)}$$

Where, TMs toxicity reference dose (RfD) is 0.0003 mg/kg-day. To evaluate the total potential non-carcinogenic risks posed by more than one pathway, the HI is applied for assessing the general tendency for the non-carcinogenic effects and is calculated as follows:

$$HI = HQ_{ingestion} + HQ_{dermal} \quad \text{..................... (6)}$$

2.2.4. Cancer risk (CR)

TMs in water could impose both non-carcinogenic and carcinogenic risks to the consuming population. The range of acceptable carcinogenic risks[36] is 10^{-6} to 10^{-4}. The carcinogenic or cancer risk is defined as the probability that the people will develop cancer during their lifetime exposure to chemicals under specific scenarios[37].

The CR of As, Pb, and Cr is calculated using the following equations:

$CRi = ADD_i/CSF$ …………………. (7)

$CRd = ADD^d/CSF$ ……………….. (8)

And the cancer index (CI) was calculated as

CI = CR ingestion + CR dermal … (9)

Here, the colony-stimulating factor (CSF) is the carcinogenic factor (1.5 mg/kg/day as obtained from US Environmental Protection Agency).

Results and Discussion

*3.1. Water quality assessmen*t

The analysis was conducted with 19 variables namely TDS, Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, NO_3^-, SO_4^{2-}, HCO_3^-, As, Cu, Mn, Ni, Pb, Zn, Ba, Cr, Li and Sr, at spatiotemporal levels and the mean values of these variables were obtained from published literature[1,22]. From the analysis, WQI lies in the excellent category in most of the sampling sites, however, in some of the locations the WQI values exceeded 50 (Figure 2 and Table 1). During pre-monsoon, the WQI is relatively very high in the upstream segments of the GRB than other seasons. In all the sampling seasons the WQI was > 25.00 in the upstream segment while it was < 25.00 in the downstream segment (Table 1). The major cause behind this could be due to the elevated concentrations of TDS and major ions in the lee-ward side of the Himalaya, which mainly contributed from geogenic sources. Based on the WQI, better water quality was found in the monsoon season as compared to the pre-and post-monsoon. Specifically, the poorest water quality was found at the Chusang area of Mustang district (upstream segment) during the pre-monsoon season (Figure 2). It could be due to the semi-arid environment with dominant evaporites in the river [1].

Results showed that the geogenic control in the upstream region and mixed control of both geogenic and anthropogenic activities in the downstream region that regulate the water quality of the GRB. Meanwhile, the grand average value of WQI indicated that the overall water quality is in the excellent category for domestic consumption.

Table 1. Water quality index of upstream and downstream segments of the Gandaki River Basin (GRB) with respect to TDS, major ions and trace metals (TMs), Central Himalaya Nepal.

Major Segments	WQI		
	Pre-monsoon (PreM)	Monsoon (Mon)	Post-monsoon (PoM)
Upstream	52.61	29.96	38.26
Downstream	20.16	17.58	22.46
Average	36.38	23.77	30.36

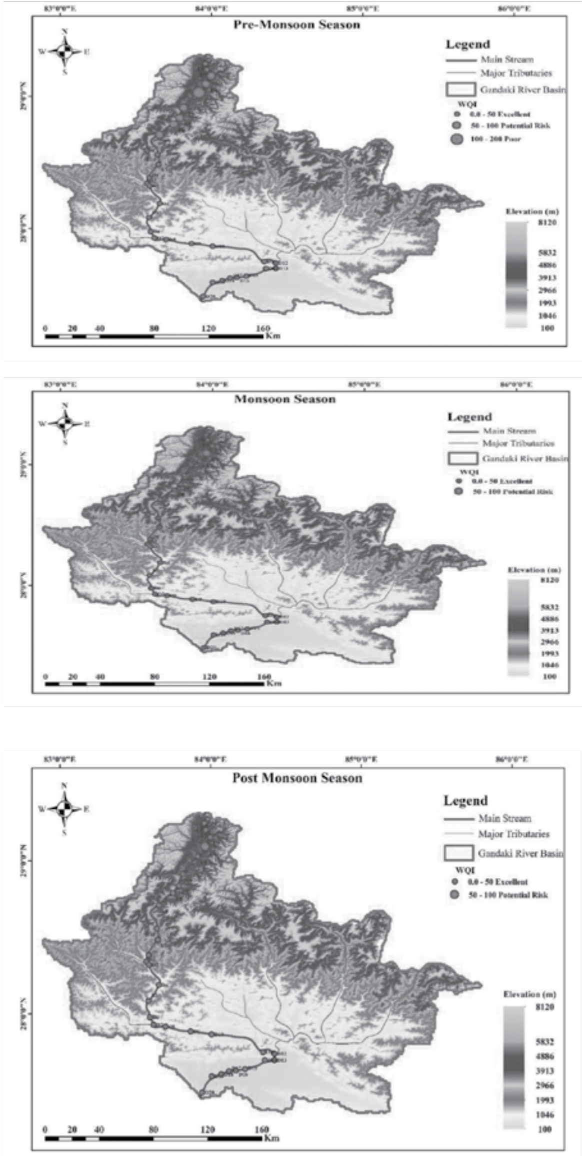

Figure 2: Spatiotemporal analysis of the high-risk areas from the suitability perspectives for drinking water in the Gandaki River Basin (GRB), Central Himalaya.

3.2. Health risk assessment (HRA)

Average concentration of the TMs was applied to evaluate the risk level for local residents. Age and exposure levels are one of the main factors that might contribute to the potential health risk 38. HRA is the process of gathering information for the potential public health risk posed by the chemical variables including TMs. The HRA of the TMs was evaluated for ingestion and dermal exposure (Figure 3 and Table 2). In addition, we studied the hazard quotient (HQ) and hazard index (HI) for As, Ba, Cr, Cu, Li, Mn, Ni, Pb, Sr and Zn.

The analysis showed that there was relatively no risk of five elements i.e., As, Cr, Cu, Ni and Pb in both the up- and down streams of the GRB. The element Ba had shown the risk in all seasons in both the segments while two elements i.e. Li and Sr showed relatively high risk in the upstream segments but low risk in the downstream segment. Moreover, Mn exhibited high risk only in the upstream in all the seasons while Zn has no risk in upstream during pre-monsoon and high risk in monsoon and post monsoon in both segments. It signifies that Ba, Li and Sr are mainly contributed from the geogenic sources whereas Zn has both geogenic and anthropogenic sources. Generally, the concentration of chemical variables is diluted during monsoon due to heavy rainfall particularly in the Himalaya but the results of this study are not consistent with the aforementioned statement particularly for the TMs. Importantly, TMs such as Ba, Li, Sr and Zn were major contributors to the chronic exposures to inhabitants, while other elements such as As, Cr, Cu, Ni, and Pb were found least participants via both oral and dermal paths (Table 2). All elements have HQ_{dermal} < 1, signifying little adverse effects via dermal path [21]. In contrast, $HQ_{ingestion}$ of some of the elements as Ba, Li, Sr and Zn were found > 1 during all three seasons (Table 2). This result demonstrated that these elements are comparatively more hazardous in the river via the ingestion path. Meanwhile, Zn was also enriched indicating anthropogenic origin particularly in the downstream region (Table 2). Elements such as As have been known to cause potentially carcinogenic effects in human beings such as cancers of the lung, liver, bladder, and skin [39]. Thus, rigorous efforts are required to ensure the safety of consumers and sustainable development of the aquatic ecosystem by removal of As contamination in drinking water in the GRB.

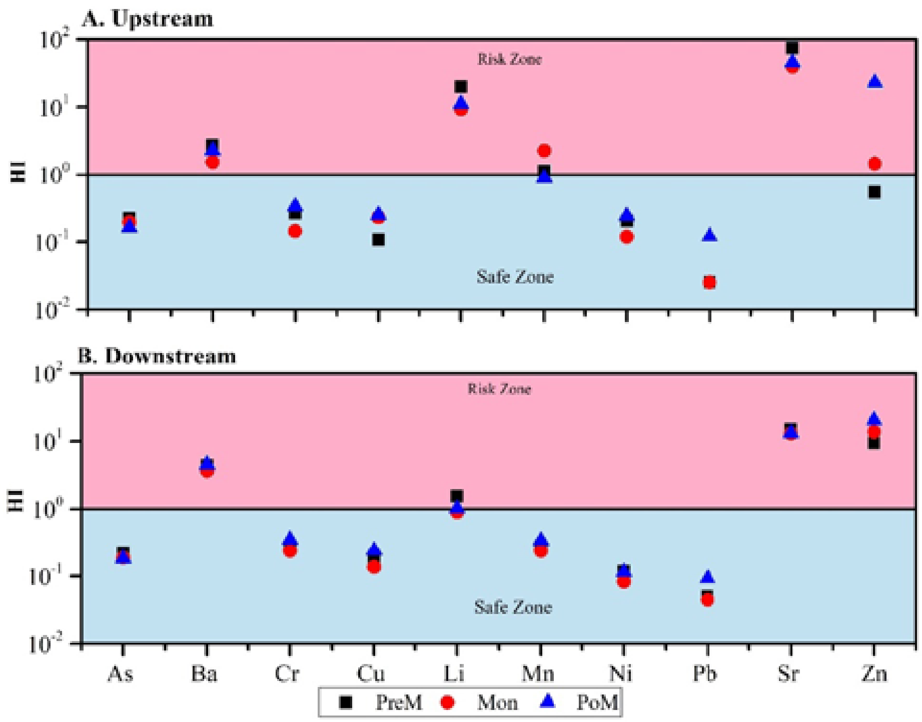

Figure. 3: Graphical representation of Health Risk Index (HRI) during the pre-monsoon, monsoon and post-monsoon in Gandaki River Basin (GRB), Nepal.

Table 2: Health risk assessment during the pre-monsoon, monsoon and post-monsoon seasons of the Gandaki River Basin (GRB), Nepal.

TMs	HQ ingestion			HQ dermal			HI		
	PreM	Mon	PoM	PreM	Mon	PoM	PreM	Mon	PoM
Upstream									
As	0.2214	0.1927	0.1621	0.0011	0.0010	0.0008	0.2225	0.1937	0.1629
Ba	2.7548	1.5404	2.2676	0.0140	0.0079	0.0116	2.7689	1.5483	2.2792
Cr	0.2631	0.1427	0.3316	0.0013	0.0007	0.0017	0.2644	0.1434	0.3333
Cu	0.1065	0.2288	0.2473	0.0005	0.0012	0.0013	0.1071	0.2300	0.2486
Li	19.854	9.2195	11.068	0.1012	0.0470	0.0564	19.956	9.2665	11.125
Mn	1.1264	2.2528	0.8809	0.0057	0.0115	0.0045	1.1321	2.2643	0.8854
Ni	0.2029	0.1186	0.2399	0.0010	0.0006	0.0012	0.2039	0.1192	0.2411
Pb	0.0250	0.0250	0.1204	0.0001	0.0001	0.0006	0.0251	0.0251	0.1210
Sr	74.412	39.135	45.150	0.3793	0.1995	0.2302	74.791	39.335	45.380

Zn	0.5419	1.4543	22.808	0.0028	0.0074	0.1163	0.5447	1.4617	22.925
Downstream									
As	0.2223	0.1862	0.1806	0.0011	0.0009	0.0009	0.2234	0.1871	0.1816
Ba	4.3981	3.5996	4.4926	0.0224	0.0184	0.0229	4.4205	3.6180	4.5155
Cr	0.2760	0.2371	0.3492	0.0014	0.0012	0.0018	0.2774	0.2383	0.3510
Cu	0.1760	0.1352	0.2390	0.0009	0.0007	0.0012	0.1769	0.1359	0.2402
Li	1.5469	0.8976	1.0087	0.0079	0.0046	0.0051	1.5548	0.9022	1.0139
Mn	0.2788	0.2362	0.3409	0.0014	0.0012	0.0017	0.2802	0.2374	0.3426
Ni	0.1167	0.0824	0.1139	0.0006	0.0004	0.0006	0.1173	0.0829	0.1145
Pb	0.0500	0.0445	0.0917	0.0003	0.0002	0.0005	0.0503	0.0447	0.0922
Sr	14.890	12.830	13.042	0.0759	0.0654	0.0665	14.966	12.896	13.109
Zn	9.3325	13.668	20.305	0.0476	0.0697	0.1035	9.3801	13.7373	20.408

3.3. Cancer Index (CI)

Carcinogenic risk of As, Cr and Pb through the oral intake of water based on the three seasons dataset were analyzed and presented (Figure 4 and Table 3). It has been reported that the target risk of 1×10^{-4} of the aforementioned elements via the ingestion of water over a long lifetime could increase the probability of cancer [36].

In the river water, the As has a moderate risk (Figure 4) comparing to the Cr and Pb. Precisely, comparing on the seasonal basis, As has relatively high risk in pre-monsoon than other seasons. On contrary to that Cr and Pb have relatively more risk during the post monsoon seasons in both segments (Figure 4). The CI is dependent on input factors such as exposure condition, duration of exposure and temporal variation in the toxicant concentration. Comparatively higher values of CI for Cr, As, and Pb in the downstream than the upstream segment of the river indicate that anthropogenic activities are dominated in the downstream segment of the GRB. A high concentration of Cr may cause toxic effects such as liver, kidney problems and genotoxic symptoms to the residing people in the area[21]. Similarly, a high concentration of As may cause adverse carcinogenic health effects like cancers of liver, lung, bladder, kidney, and skin, including hypertension, neuropathy, diabetes, skin lesions, and cardiovascular and cerebrovascular diseases[12]. Moreover, excess amount of Pb may cause chronic health risks, including headache, irritability, abdominal pain, nerve damage, kidney damage, blood pressure, lung cancer, stomach cancer and gliomas and children are relatively more susceptible to Pb toxicity[12,13,14]. As there was high risk of As, Pb and Cr in our study, special attention should be paid to these elements in the downstream segments particularly for health risk of children.

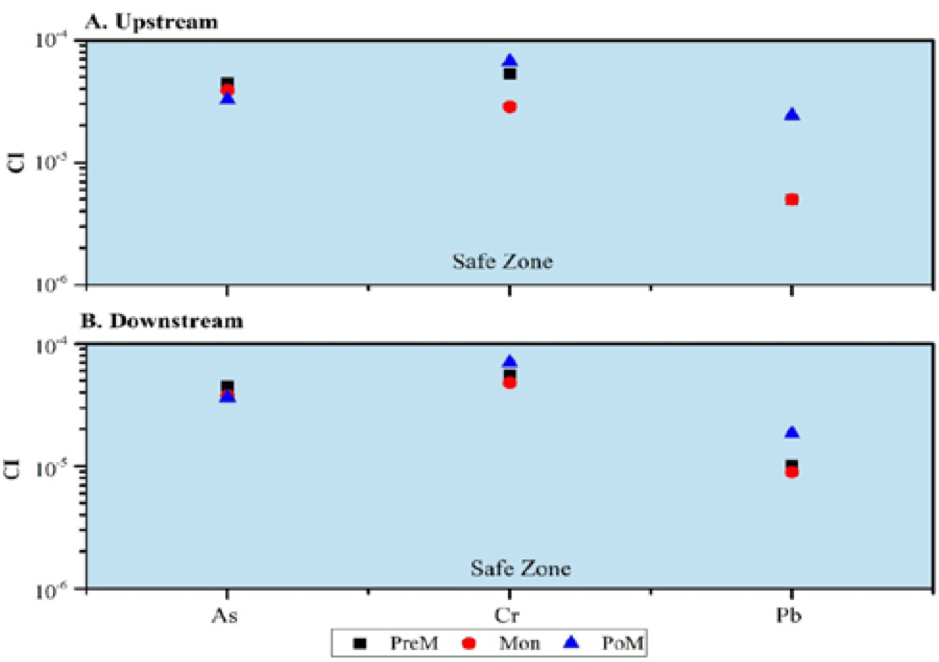

Figure 4: Graphical representation of Cancer Index (CI) during the pre-monsoon, monsoon and post-monsoon seasons of the Gandaki River Basin (GRB), Nepal .

Table 3: Cancer Index (CI) during the pre-monsoon, monsoon and post-monsoon seasons of the Gandaki River Basin (GRB), Nepal.

TMs	$CR_{ingestion}$			CR_{dermal}			CI		
	PreM	Mon	PoM	PreM	Mon	PoM	PreM	Mon	PoM
Upstream									
As	4.43×10^{-5}	3.85×10^{-5}	3.24×10^{-5}	2.26×10^{-7}	9.82×10^{-4}	1.65×10^{-7}	4.45×10^{-5}	3.87×10^{-5}	3.26×10^{-5}
Cr	5.26×10^{-5}	2.85×10^{-5}	6.63×10^{-5}	2.68×10^{-7}	7.27×10^{-4}	3.38×10^{-7}	5.29×10^{-5}	2.87×10^{-5}	6.67×10^{-5}
Pb	5.00×10^{-6}	5.00×10^{-6}	2.41×10^{-5}	2.55×10^{-8}	1.28×10^{-4}	1.23×10^{-7}	5.03×10^{-6}	5.03×10^{-6}	2.42×10^{-5}
Downstream									
As	4.45×10^{-5}	3.72×10^{-5}	3.61×10^{-5}	2.27×10^{-7}	9.49×10^{-4}	1.84×10^{-7}	4.47×10^{-5}	3.74×10^{-5}	3.63×10^{-5}
Cr	5.52×10^{-5}	4.74×10^{-5}	6.98×10^{-5}	2.81×10^{-7}	1.84×10^{-2}	3.56×10^{-7}	5.55×10^{-5}	4.77×10^{-5}	7.02×10^{-5}
Pb	1.00×10^{-5}	8.89×10^{-6}	1.83×10^{-5}	5.10×10^{-8}	1.21×10^{-3}	9.35×10^{-8}	1.01×10^{-5}	8.94×10^{-6}	1.84×10^{-5}

4. Conclusion and future perspectives

This study provides the detailed insights on water quality status and associated health risks during pre-monsoon, monsoon and post monsoon seasons in the Gandaki River Basin (GRB), Central Himalaya, Nepal. Geogenic contribution, water flow seasonality and anthropogenic activities have a predominant role in the regulation of water quality of upstream and downstream segments of the basin. Concentrations of observed variables in the surface water of the GRB demonstrated great seasonality. The average water quality index results during pre-monsoon, monsoon and post-monsoon seasons were found to be 36.38, 23.77 and 30.36, respectively, indicating better water quality during the monsoon in the basin. Health Risk Assessment of the river water revealed that Ba, Li, Sr and Zn were major contributors to chronic exposures to the inhabitants, while other elements such as As, Cr, Cu, Ni, and Pb were found to be the least contributors via oral and dermal paths. All elements were < 1 hazard quotient (HQ_{dermal}) signifying little or no adverse effects via the dermal path. In contrast, the $HQ_{ingestion}$ of Ba, Li, Sr and Zn were found to be > 1 during all the three study seasons. The findings demonstrated that these elements were relatively more hazardous pollutants in the river water via the ingestion path. Zn was also enriched indicating anthropogenic origin, especially in the downstream reason. Moreover, the cancer index level of As, Cr and Pb were found in the order of Cr > As > Pb with CI level $<1\times10^{-6}$, indicating that the elements were within the tolerance limit in river water during all the three seasons. Overall, the water quality in the GRB is found to be safe and pose minimal health risk to the human population, however, increasing anthropogenic activities particularly in the downstream region may cause potential threats in the future. Furthermore, this study could be used as a reference for further research as this paper provides the first health risk assessment focusing on TDS, major ions and trace metals for the Himalayan river in Nepal.

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References

1. Pant, R.R., Zhang, F. Rehman, F.U., Wang, G., Ye. M.,Zeng. C., Tang H. 2018. Spatiotemporal variations of hdrogeochemistry and its controlling factors in the Gandaki River Basin, Central Himalaya Nepal. *Science of Total Environment*. **622:**770–782.
2. Qu, B., Zhang. Y., Kang. S., Sillanpää. M. 2019. Water quality in the Tibetan Plateau: Major ions and trace elements in rivers of the "Water Tower of Asia." *Science of Total Environment*. **649**:571-581.
3. Rehman-Qaisar, F.U., Zhang, F., Pant, R.R., Wang, G., Khan, S,, Zeng, C. 2018. Spatial variation, source identification, and quality assessment of surface water geochemical composition in the Indus River Basin, Pakistan. *Environmental Science and Pollution Research*. **25**:12749-12763.
4. Pal, K.B., Pant, R.R., Rimal, B., Mishra, A.D. 2019. Comparative assessment of water quality in the Bagmati river basin , Nepal. *ZOO-Journal*. **5**:68-78.
5. Nepali, K,B., Pant, R.R., Pradhanang, S. 2014. Impacts of climate change on the livelihoods of local people: A case from Jethal V.D.C., Sindhupal-Chowk District. *International Journal of Interdisciplinary Studies.* **2**:147-158.
6. Subedi, R., Bhuju, D., Bhatta, G., Pant, R. 2018. Climate variability and livelihood of rural farmers in Chisapani, Ramechhap, Nepal. *Nepal Journal of Environmental Science*. **6**:47-59.
7. Zhang, F., Qaiser, F.R., Zeng, C., Pant, R.R., Wang, G., Zhang, H., Chen, D. 2019. Meltwater hydrochemistry at four glacial

catchments in the headwater of Indus River. *Environmental Science and Pollution Research*. 26, 23645-23660.

8. Bishwakarma, K., Wang, G. xing., Zhang, F., Adhikari, S., Karki, K., Ghimire, A. 2022. Hydrochemical characterization and irrigation suitability of the Ganges Brahmaputra River System : review and assessment. *Journal of mountain science*. **19**:388-402.

9. Pant, R.R., Qaiser, F.R., Wang, G., Adhikari, S., Bishwakarma, K., Baral, U., Rimal, B., Bhatta, Y.R., Rijal, K. 2021. Hydrochemical appraisal and solute acquisitions in Seti River Basin, Central Himalaya, Nepal. *Environmental Monitoring and Assessment.* **193**:1-21.

10. Xiao, J., Jin, ZDD., Ding, H., Wang, J., Zhang, F. 2012. Geochemistry and solute sources of surface waters of the Tarim River Basin in the extreme arid region, NW Tibetan Plateau. *Journal of Asian Earth Sciences.* **54**:162-173

11. Pant, R.R., Bishwakarma, K., Qaiser, F.R., Pathak, L., Jayaswal, G., Sapkota, B., Pal, K.B., Thapa, L.B., Koirala, M., Rijal, K., Maskey, R. 2021. Imprints of COVID-19 lockdown on the surface water quality of Bagmati river basin. *Nepal. Journal of Environmental Management*. **289**:1-13.

12. Li, S., Zhang, Q. 2010. Spatial characterization of dissolved trace elements and heavy metals in the upper Han River (China) using multivariate statistical techniques. *Journal of Hazardous Materials*. **176**:579-588.

13. Peng, F., Xie, F., Muzik, O. 2018. Alteration of copper fluxes in brain aging: A longitudinal study in Rodent using 64CuCl2-PET/CT. *Aging and Disease*. **9**:109-118.

14. Pant, R.R., Bishwakarma, K., Basnet, B.B., Pal, K.B., Karki, L., Dhital, Y.P., Bhatta, Y.R., Pant, B.R., Thapa, L.B. 2021. Distribution and risk appraisal of dissolved trace elements in Begnas Lake and Rupa Lake, Gandaki Province, Nepal. *SN Applied Science.* **3**:1-13.

15. Jin, Z., You, C.F., Yu, J. 2009. Toward a geochemical mass balance of major elements in Lake Qinghai, NE Tibetan Plateau: A significant role of atmospheric deposition. *Applied Geochemistry.* **24**:1901-1907.

16. Jin, Z., You, C.F., Yu, T.L., Wang, B.S. 2010. Sources and flux of trace elements in river water collected from the Lake Qinghai catchment, NE Tibetan Plateau. *Applied Geochemistry.* **25**:1536-1546.

17. Wang, X., Yang, H., Gong, P., Zhao, X., Wu, G., Turner, S., Yao, T. 2010. One century sedimentary records of polycyclic aromatic hydrocarbons, mercury and trace elements in the Qinghai Lake, Tibetan Plateau. *Environtal Pollution*. **158**: 3065-3070.

18. Yuan, H., Liu, E., Shen, J., Zhou, H., Geng, Q., An, S. 2014. Characteristics and origins of heavy metals in sediments from Ximen Co Lake during summer monsoon season, a deep lake on the eastern Tibetan Plateau. *Journal of Geochemical Exploration.* **136**:76-83.

19. Sharma, C.M., Kang, S., Sillanpää, M., Li, Q., Zhang, Q., Huang, J., Tripathee, L., Sharma, S., Paudyal, R. 2015. Mercury and selected trace elements from a remote (gosainkunda) and an urban (Phewa) Lake Waters of Nepal. *Water Air Soil Pollution*. **226:**1-11.

20. Sun, X., Zhang, Q., Li, M., Kandel, K., Rawat, B., Pandey, A., Guo, J., Kang, S., Pant, R.R., Cong, Z., Zhang, F. 2020. Mercury variation and export in trans-Himalayan rivers : Insights from field observations in the Koshi River. S*cience of Total Environment*. 738.

21. Iqbal, J., Shah, M.H. 2013. Health risk assessment of metals in surface water from freshwater source lakes, Pakistan. *Human and Ecological Risk Assessment*. **19**:1530-1543.

22. Pant, R.R., Zhang, F., Rehman, F.F.U., Koirala, M., Rijal, K., Maskey, R. 2020. Spatiotemporal characterization of dissolved trace elements in the Gandaki River, Central Himalaya Nepal. *Journal of Hazardous Materials*. **389**: 121913

23. Pant, R.R., Zhang, F., Qaiser, F.R., Maskey, R. 2018. Contrasting characteristics of water quality in Kali and Seti rivers, central Himalaya , Gandaki Province, Nepal. In: Bhandari, BB, Shahi LB, Pandey P and Sada R. [Eds.], International Lake Conference: Sustainable Utilization of Lake Resources, Pokhara, 11-13 May. Kathmandu: *National Lake Conservation Development Committee (NLCDC).* 121-129.

24. Dahal, P., Shrestha, N.S., Shrestha, M.L., Krakauer, N.Y., Panthi, J., Pradhanang, S.M., Jha, A., Lakhankar, T. 2016. Drought risk assessment in central Nepal : temporal and spatial analysis. *Natural Hazards*. **80**:1913-1932.

25. Panthi, J., Dahal, P., Shrestha, M.L., Aryal, S., Krakauer, N.Y., Pradhanang, S.M., Lakhankar, T., Jha, A.K., Sharma, M., Karki, R. 2015. Spatial and temporal variability of rainfall in the Gandaki River Basin of Nepal Himalaya. *Climate*. **3**:210-226.

26. Meng, Q., Zhang, J., Zhang, Z., Wu, T. 2016. Geochemistry of dissolved trace elements and heavy metals in the Dan River Drainage (China): distribution, sources, and water quality assessment. *Environmental Science and Pollution Research.* **23**:8091-8103.

27. Tripathee, L., Kang, S., Sharma, C.M., Rupakheti, D., Paudyal, R., Huang, J., Sillanpää, M. 2016. Preliminary health risk assessment of potentially toxic metals in surface water of the Himalayan rivers, Nepal. *Bulletin of Environmental Contamination Toxicology*. **97**:855-862.

28. Xiao, J., Jin, Z., Wang, J. 2014. Geochemistry of trace elements and water quality assessment of natural water within the Tarim River Basin in the extreme arid region, NW China. *Journal of Geochemical Exploration*. **136**:118-126.

29. WHO. 2011. Guidelines for Drinking-water Quality. World Health Organization (available in http://www.who.int).

30. Sahu, P., Sikdar, P.K. 2008. Hydrochemical framework of the aquifer in and around East Kolkata Wetlands, West Bengal, India. *Environ Geology.* **55**:823-835.

31. Misaghi, F., Delgosha, F., Razzaghmanesh, M., Myers, B. 2017. Introducing a water quality index for assessing water for irrigation purposes: A case study of the Ghezel Ozan River. *Science of Total Environment.* **589**:107-116.

32. Vasanthavigar, M., Srinivasamoorthy, K., Vijayaragavan, K., Ganthi, R., Chidambaram, S., Anandhan, P., Manivannan, R., Vasudevan, S. 2010. Application of water quality index for groundwater quality assessment: Thirumanimuttar sub-basin, Tamilnadu, India. *Environ Monitoring and Assessment.* **171**:595-609.

33. USEPA. 2004. Risk assessment guidance for superfund. Volume I. Human health evaluation manual. Part E. Supplemental guidance for dermal risk assessment. *US Environmental Protection Agency, USA*.

34. Rupakheti, D., Tripathee, L., Kang, S., Sharma, C.M., Paudyal, R., Sillanpää, M. 2017. Assessment of water quality and health risks for toxic trace elements in urban Phewa and remote Gosainkunda lakes, Nepal. *Human Ecological Risk Assessment.* **23**:959-973.

35. Khan, S., Cao, Q., Zheng, Y.M., Huang, Y.Z., Zhu, Y.G. 2008. Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. *Environmental Pollution.* **152**:686-692.

36. Li, S., Zhang ,Q. 2010. Risk assessment and seasonal variations of dissolved trace elements and heavy metals in the Upper Han River, China. *Journal of Hazardous Materials*. 181:1051-1058.

37. Chen, S.C., Liao, C.M. 2006. Health risk assessment on human exposed to environmental polycyclic aromatic hydrocarbons pollution sources. *Science of Total Environment.* **366**:112-123.

38. Wu, B., Zhao, D.Y., Jia, H.Y., Zhang, Y., Zhang, X.X., Cheng, S.P. 2009. Preliminary risk assessment of trace metal pollution in surface water from Yangtze River in Nanjing section, China. *Bulletin of Environmental Contamination and Toxicology.* **82**:405-409.

39. Bhattacharjee, P., Banerjee, M., Giri, A.K. 2013. Role of genomic instability in arsenic-induced carcinogenicity. A review. *Environment International.* 53, 29-40.