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Spatiotemporal variations of hydrogeochemistry and its controlling factors in the Gandaki River Basin, Central Himalaya Nepal

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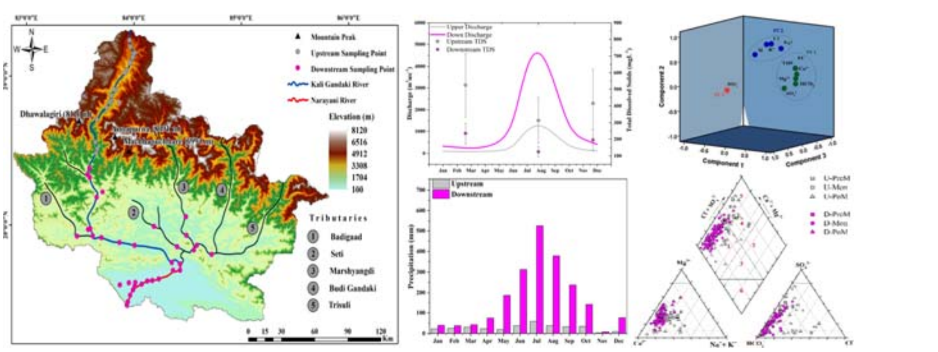
HIGHLIGHTS

- Strong spatiotemporal variation of geochemistry is observed in the Gandaki River.
- Hydrogeochemistry is controlled by climatic, geogenic and anthropogenic factors.
- Water facies are prevailed with Ca-HCO_3 (83%), Ca-Mg-Cl (13%) and Ca-Cl (4%).
- Water quality at a few locations poses safety concern for drinking and irrigation.

GRAPHICAL ABSTRACT



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ABSTRACT

The characterization and assessment of water quality in the head water region of Himalaya is necessary, given the immense importance of this region in sustaining livelihoods of people and maintaining ecological balance. A total of 165 water samples were collected from 55 sites during pre-monsoon, monsoon and post-monsoon seasons in 2016 from the Gandaki River Basin of the Central Himalaya, Nepal. The pH, EC values and TDS concentrations were measured in-situ and the concentrations of major ions (Ca^{2+}, Mg^{2+}, K^+, Na^+, Cl^-, SO_4^{2-}, NO_3^-) and Si were analyzed in laboratory. Correlation matrices, paired *t*-test, cluster analysis, principal component analysis (PCA), the Piper, Gibbs, and Mixing plots, and saturation index were applied to the measurements for evaluating spatiotemporal variation of the major ions. The results reveal mildly alkaline pH values and the following pattern of average ionic dominance: $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ for cations and $HCO_3^- > SO_4^{2-} > Cl^- > NO_3^-$ for anions. The results of PCA, Gibbs plot and the ionic relationships displayed the predominance of geogenic weathering processes in areas with carbonate dominant lithology. This conclusion is supported by geochemically different water facies identified in the Piper plot as Ca-HCO_3 (83.03%), mixed Ca-Mg-Cl (12.73.0%) and Ca-Cl (4.24%). Pronounced spatiotemporal heterogeneity demonstrates the influence of climatic, geogenic and anthropogenic conditions. For instance, the Ca^{2+}-SO_4^{2-}, Mg^{2+}-SO_4^{2-} and Na^+-Cl^- pairs exhibit strong positive correlation with each

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other in the upstream region, whereas relatively weak correlation in the downstream region, likely indicating the influence of evapo-crystallization processes in the upstream region. Analyses of the suitability of the water supply for drinking and irrigation reveal that the river has mostly retained its natural water quality but poses safety concern at a few locations. Knowledge obtained through this study can contribute to the sustainable management of water quality in the climatically and lithologically distinct segments of the Himalayan river basins.

1. Introduction

The quality of surface water, influenced by various natural and anthropogenic factors, is one of the most sensitive issues worldwide (Diamantini et al., 2018; López-Moreno et al., 2011; Singh et al., 2014; Sun et al., 2010). The chemistry of natural surface water is controlled primarily by atmospheric precipitation, chemical weathering and evapo-crystallization processes (Gibbs, 1970; Jiang et al., 2015), and secondarily by tributaries, ground water discharge, and anthropogenic interferences (Thomas et al., 2015). The study of geochemical properties of surface water has broad implications for securing water quality, as it provides an insight to understand the chemical composition and characteristics and recommend appropriate conservation measures (Şener et al., 2017; Vrebos et al., 2017). The Himalayan Rivers draining from the alpine segments of semiarid/arid region require a special understanding in terms of ionic concentrations, sediment loads, and the relevant geochemical processes (Lioubimtseva and Henebry, 2009; Xiao et al., 2012). The quality and quantity of the surface water fed by high altitude glaciers are affected by various natural and anthropogenic activities and particularly by the impacts of global climate change, across the Himalaya and Tibetan Plateau. These changes may have serious implications on livelihoods and ecosystems at local and regional levels, and thus, water and environmental sustainability requires thoughtful attention (Barnett et al., 2005; Yao et al., 2012; Zhang et al., 2012).

Catchment characteristics, such as climate, geology, land use etc., have profound impacts on hydrochemistry and water availability for human beings. For instance, the primary source of riverine Ca^{2+}, Mg^{2+}, and HCO_3^- in the hydrosphere is from the geospheric minerals with the interactions of atmospheric CO_2, whereas Na^+, Cl^-, NO_3^-, and SO_4^{2-} have multiple sources from geosphere, atmosphere, biosphere and anthroposphere (Haidary et al., 2013; Huang et al., 2009). Considering the key role of hydrochemical attributes in river water quality for the economic and ecological stability, the chemical signatures and the factors controlling the hydrochemistry of the world's major rivers have been well documented in the past decade, particularly the Amazon River (Stallard and Edmond, 1983), Ganges-Brahmaputra River (Sarin et al., 1989), Yellow River (Zhang et al., 1995), Nile River (Dekov et al., 1997), Indus River (Ahmad et al., 1998), Mississippi River (Sharif et al., 2008), Mekong River (Huang et al., 2009), Tigris River (Varol et al., 2013) and Yangtze River (Huang et al., 2009; Jiang et al., 2015). These studies have not only addressed the various sources and controlling mechanisms of hydrogeochemistry in the large river basins but also provided a remarkable information on the rates and patterns of dissolved chemicals cycle in the continent-river-ocean system.

The Himalayan ranges extending approximately 2400 km represent a lifeline that secures the water needs of humans and ecosystems, especially in the Central Himalayan region of Nepal (Paudyal et al., 2016a). Some past studies reported on specific geochemical parameters from particular segments of these Himalayan basins, such as the Seti, Koshi, Bagmati and Gandaki Rivers and to some extent highlighted the natural and anthropogenic interferences influencing the quality of water in the Himalaya (English et al., 2000; Galy and France-Lanord, 1999; Paudyal et al., 2016a; Quade et al., 2003).

The Gandaki River Basin (GRB) contains three of the world's 14 mountains peaks with the elevation over 8000 m namely Dhaulagiri, Manaslu and Annapurna (Panthi et al., 2015) (Fig.1). The main river and its tributaries draining from these Himalayas are not only the major source of drinking water and agricultural use in Nepal but also one of the major tributaries of the Ganges River System which is used by thousands of people for various purposes, e.g., domestic use, irrigation, hydropower, industrial and even ritual practices (Paudyal et al., 2016a; Singh et al., 2014; Tripathee et al., 2016). Therefore, water quality of the GRB is a matter of great concern and it is important to understand the hydrogeochemistry and major weathering processes in the basin. Recent hydrochemical studies conducted in the GRB with limited samples suggest the urgent need of comprehensive and systematic assessment of water quality in the basin (Tripathee et al., 2016; Trower, 2009).

Thus, the present study is carried out to fill the above gap with major objective to analyze the spatiotemporal variations of hydrogeochemistry and its controlling factors from two climatically and lithologically distinct segments of the GRB in the Central Himalaya, Nepal.

2. Materials and methods

2.1. Study area

The GRB, one of the three major glacier-fed river basins in Nepal, is located in the Central Himalaya and between longitudes 82.88° to 85.81°E and latitudes 27.32° to 29.33°N (Fig. 1). The GRB has one of the largest discharges among all the river basins in Nepal (Aryal, 2011). The headwater of the river lies on the southern edge of the Tibetan Plateau and flows from Nepal to India. The elevation of the GRB ranges from about 89 m in the south to >8100 m in the north, and the basin area is about 32,104 km^2 in Nepal (Dahal et al., 2016).

The Kali Gandaki is the main tributary of the GRB, which plunges its way down through the deep gorge between two peaks above 8000 m, Dhaulagiri and Annapurna. It is then joined by its major tributaries, the Trisuli, Marsyandi, Budhi Gandaki and Seti Gandaki Rivers (Bajracharya et al., 2011). The mean air temperature and annual discharge of the GRB are 17.7 °C and 1753 $m^3 s^{-1}$, respectively. Besides, >80% of the annual precipitation is concentrated during the monsoon season from June to September (Aryal, 2011; Panthi et al., 2015).

The GRB 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 (Panthi et al., 2015).The upstream segment (leeward side) of the river basin is located in the Trans-Himalayan zone between the Tibetan Plateau and the High Himalayas and experiences semi-arid climatic conditions with markedly low annual precipitation (mean ~163 mm) whereas the downstream region lies on the windward side of the Himalayas and experiences a humid, sub-tropical to temperate climate with high annual precipitation (mean ~2667 mm) (Manandhar et al., 2012; Panthi et al., 2015). The temperature and discharge also vary greatly in space and time in both segments of the basin. For instance, the minimum recorded air temperature in the upstream segment is −25 °C, while the maximum air temperature in the downstream segment reaches up to 35 °C (Paudel and Andersen, 2011; Tripathee et al., 2014). The distinct mean monthly precipitation and discharge together with the TDS concentrations obtained in this study in the two contrasting segments of the basin are shown in Fig. 1b–c.

From north to south, the Gandaki River and its tributaries drain through four major litho-tectonic units (Fig. A1) (Amatya and Jnawali,