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Water quality in the Tibetan Plateau: Major ions and trace elements in rivers of the “Water Tower of Asia”

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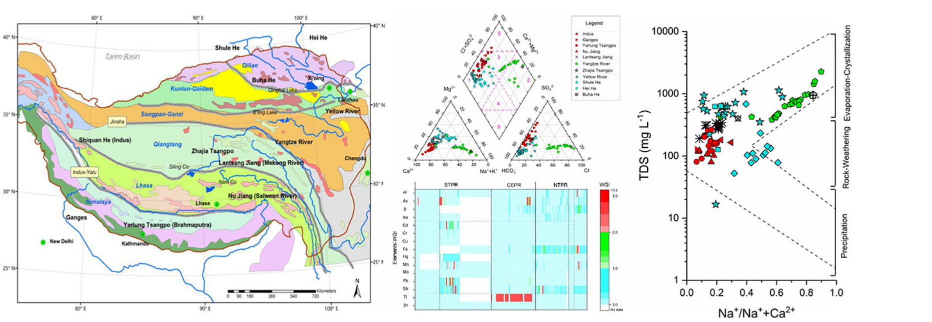
HIGHLIGHTS

- Natural processes dominate the water chemistry in rivers of the Tibetan Plateau.
- Human activities have certain impacts on the water quality in the Tibetan rivers.
- Waters in parts of the rivers of the Tibetan Plateau are not safe for drinking.

GRAPHICAL ABSTRACT



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ABSTRACT

As the “Water Tower of Asia”, rivers originating from the Tibetan Plateau provide water resources for more than one billion residents in both its local and surrounding areas. With respect to the essential role that this region plays in terms of water resources in Asia, we provide an overview of the mechanisms governing the water quality, including the major ions and trace elements release, in eleven rivers of the Tibetan Plateau. Overall, the rivers running on the Tibetan Plateau reflect an alkaline aquatic environment, with an average pH of 8.5; and the total dissolved solids (TDS, ~339 mg L^{-1}) are much higher than the global average value. Over 80% of the water ionic budget in the rivers of the plateau is comprised of Ca^{2+}, Mg^{2+}, HCO_3^- and SO_4^{2-}. The main mechanisms that control the river water chemistry on the Tibetan Plateau are natural processes and present a visible spatial heterogeneity. For instance, in rivers of the southern Tibetan Plateau, the water quality is mainly controlled by the rock-weathering, while rivers of the central and northern Tibetan Plateau are also largely affected by evaporation-crystallization processes. In general, most of the rivers on the Tibetan Plateau are uncontaminated and still in a pristine condition. However, it should be noted that due to the natural process such as rock-weathering and groundwater leaching, and anthropogenic activities such as urbanization and mining operations, the concentrations of several toxic elements (e.g., As, Cd, Pb, Mn, Hg and Tl) in some of the basins are higher than

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the China national standard (GB) and the World Health Organization (WHO) guidelines for drinking water. With increasing anthropogenic activities on the plateau and changes in the river basins, it is necessary to conduct the long-term monitoring of the river water chemistry of this climate-sensitive and eco-fragile region.

1. Introduction

The Tibetan Plateau is the largest elevated plateau in Central and East Asia (Yao et al., 2012). It extends approximately 2500 km from east to west and 1000 km from north to south, covering an area of almost 2% of the Earth's land surface (Zhang et al., 2002). With an average elevation exceeding 4000 m above sea level (a.s.l.), the Tibetan Plateau has a peculiarly cold climate for its latitude (26°N–40°N) and has developed the largest glacial ice volume in the middle-latitude region of the Earth (Xu et al., 2008; Yao et al., 2012). Because of its high elevation and storage of a huge amount of solid water, the Tibetan Plateau serves as the "Water Tower of Asia", which feeds several large rivers (e.g., the Yarlung Tsangpo, the Yellow River, the Yangtze River) in Asia (Huang et al., 2008; Jiang and Huang, 2004). There are >1.4 billion people living in China, Pakistan, Nepal, Bangladesh, Vietnam, Thailand and India who depend on the waters originating from this region (Immerzeel et al., 2010); hence, the water chemistry in the Tibetan Plateau is an important issue for the residents in both its local and surrounding areas.

Chemical substances transported by rivers have been studied using geochemical budgets for more than one hundred years (Forel, 1892). The most abundant materials dissolved in rivers are ions that originate from terrestrial and atmospheric systems, which are mainly calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), chloride (Cl^-) and nitrate (NO_3^-) (Meybeck and Ragu, 1995). The ionic chemistry of rivers can provide essential information about both the processes affecting the continental surface (e.g., rock weathering, atmospheric precipitation, evaporation-crystallization) and the amount of natural material carried by river water bodies (Gibbs, 1970; Meybeck, 1982). In addition to studying dissolved elements such as lead (Pb), cadmium (Cd) and mercury (Hg), scientists can also investigate the influences of anthropogenic activities on the water chemistry in rivers (Huang et al., 2009; Meybeck and Helmer, 1989; Novotny and Olem, 1994).

Due the essential role that the Tibetan Plateau plays in terms of water resources in Asia, intensive efforts have been dedicated to studying the chemical compositions of its water in recent decades. It has been revealed that the contents of dissolved salts in the major rivers of the Tibetan Plateau were relatively high compared to those of waters from other parts of the world (Huang et al., 2009; Jiang et al., 2015; Pant et al., 2018; Qu et al., 2017; Zhang et al., 2015). Due to the anthropogenic impacts (i.e., mining activities) occurring on the southern plateau, some pollution has been identified in the Yarlung Tsangpo basin (Huang et al., 2010; Huang et al., 2009; Qu et al., 2017). Additionally, groundwater and sediment leaching have also affected the water quality in the rivers of the central and southern plateau (Huang et al., 2011; Jiang et al., 2009; Li et al., 2009). Most previous studies have focused on the large rivers in the eastern and southern plateau, which exhibit large runoff and flow transnationally. However, few studies have focused on the inland rivers in the arid northern and western plateau, despite the crucial role that they play in the livelihood of local residents. Considering that the rivers on the Tibetan Plateau are the headwaters of rivers that provide water for more than one billion people in High Asia and its surrounding areas, we have conducted a series of field trips over the past five years and compiled a dataset of the water chemical compositions in eleven main rivers, including those running on the remote plateau. This study will provide an overview of the mechanisms of water quality, including the major ions and trace element release, in the rivers of the Tibetan Plateau. Moreover, the potential risks for decreased water quality are addressed to provide a caution of the water quality of this essential water source region of Asia.

2. Materials and methods

2.1. Geology of the major river catchments

In this study, the water major ions and trace element transport in eleven rivers on the Tibetan Plateau were investigated (Fig. 1, Table 1). Most of these rivers originate from mountain glaciers and serve as the "Water Tower of Asia" in the uplifted region of the Tibetan Plateau. On a geological time scale, the Tibetan Plateau has formed six major east-west blocks (Yin and Harrison, 2000). These blocks include the Himalaya Block and Lhasa Block, which are located in the southern Tibetan Plateau; the Qiangtang Block, which is developed in the central region and extends from west to east in the plateau; and the Songpan-Ganzi Block, Kunlun-Qaidam Block and Qilian Block, which are located in the northern Tibetan Plateau (Fig. 1). The large rivers (e.g., the Indus, Yarlung Tsangpo and Yangtze rivers) on the Tibetan Plateau are usually developed along the sutures between the tectonic blocks forming the plateau. For example, the Indus and Yarlung Tsangpo rivers run along the Indus-Yalu suture between the Himalaya Block and the Lhasa Block, while the Yangtze River was developed along the Jinsha suture between the Lhasa Block and the Qiangtang Block. Different blocks exhibit different terranes reflecting the tectonic formation of the plateau, and the rivers of the Tibetan Plateau run over different bedrock (Fig. 1). Generally, the water chemistry of rivers in remote areas is largely dominated by the bedrock within the catchments. Due to the geological differences between the catchments, we group the eleven rivers into three river systems: 1) the South Tibetan Plateau River system (STPR), which includes the Indus, Ganges, Yarlung Tsangpo, Nujiang and Lantsang Jiang rivers, which run on the Himalaya Block and the Lhasa Block; 2) the Central and East Plateau River system (CEPR), which includes the Yangtze and Zhajia Tsangpo rivers, which run on the Qiangtang Block; and 3) the North Tibetan Plateau River system (NTPR), which includes the Yellow, Shule He, Hei He and Buha He rivers, which run on the blocks of the northern plateau. The selected rivers drain an area that is larger than half of the plateau (Fig. 1).

2.2. Data preparation

Because water chemistry can change rapidly due to natural and anthropogenic factors, the data collected in this study were obtained during the *Go-West Campaign* (Economy, 2002) in the year 2000 and afterwards (Table 1). A data set from over one hundred sampling sites (112 for ions and 134 for elements) was compiled from the eleven rivers on the Tibetan Plateau, and detailed data are listed in Tables S1 and S2.

The general parameters of water quality (e.g., water temperature, pH, EC, TDS, ORP and turbidity) in this study were measured with a Wagtech CP1000 portable water testing kit (Potalab®+, Palintest Ltd., England) during the sampling work in the field. The accuracy of the probes/sensors for water temperature is ±0.5 °C; that for pH is ±0.01; that for TDS is ±1% Full Scale +1 digit. Due to the major role that they play in the area's water resources, the rivers of the Tibetan Plateau were investigated for their water chemistry. Water samples were collected against the river current at a depth of approximately 10 cm; they were then filtered by polypropylene membrane (0.2 μm) and stored in polypropylene bottles (15 mL). The samples for elemental