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THEMATIC ISSUE

Water chemistry of the southern Tibetan Plateau: an assessment of the Yarlung Tsangpo river basin

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Abstract The Yarlung Tsangpo is the largest river draining the southern Tibetan Plateau along the Himalayan ranges. In this paper, the ions and elements in the water of the Yarlung Tsangpo were studied. In general, the water of the Yarlung Tsangpo had a fairly high buffering capacity (pH ~8.8) and oxidation environment (ORP ~190 mv). Total dissolved solids averaged approximately 157 mg L^{-1}, which is higher than that of the global mean level. Under the dominant rock weathering due to the abundant carbonates around the river basin, the ionic chemistry of the Yarlung Tsangpo was mainly composed of Ca^{2+} and HCO_3^-. In addition, with a large amount water discharged into the river, groundwater (e.g., numerous chloride-rich hot springs) is another potentially important source of ions that affect the water chemistry in the Yarlung Tsangpo basin. Although watercourses on the Tibetan Plateau can generally be considered pristine, concentrations of some toxic elements (i.e., Cd and Pb) were found to be higher than the WHO guideline for drinking water due to increasing influence from anthropogenic activities (e.g., tourism, mining operations and municipal wastewater discharge), which constitute a risk to human livelihoods in both local and surrounding regions.

Keywords Water chemistry · Ions · Elements · Yarlung Tsangpo · Tibetan Plateau

Introduction

The Tibetan Plateau covers an area of $\sim 2.6 \times 10^6$ km^2 and accounts for approximately two percent of the land surface of the earth (Zhang et al. 2002). With an average elevation of more than 4000 m above sea level (a.s.l.) and a total of ~100,000 km^2 glacial spread (Yao et al. 2012), the Tibetan Plateau is the source of quite a few large rivers in Asia (e.g., the Yarlung Tsangpo, the Yellow River and the Yangtze River). Glacial ice and snow meltwater are an important water source for the rivers on the Tibetan Plateau (Huang et al. 2008). With global warming, the accumulated ice and snow will undergo accelerated melting (Kang et al. 2010; IPCC 2013), which will lead to an increasing runoff of the rivers and affect the water chemistry on the plateau. Most studies so far have considered rivers on the Tibetan Plateau to be free from contamination and have a pristine aqua environment (Guan and Chen 1981; Huang et al. 2008, 2009; Li et al. 2009, 2011); however, with rapid development on the plateau in recent decades (Dreyer 2003), the regional river chemical budgets have been found

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to be affected by anthropogenic activities. For instance, with mineral deposit belts discovered on the Tibetan Plateau, some reaches of rivers in this fragile region have been claimed to be polluted by heavy metal such as Hg, Cd, Ni and Cu due to mining operations (Hu et al. 2004; Qu et al. 2007; Huang et al. 2010). Therefore, with changes in both climate and anthropogenic activities on the Tibetan Plateau, continuous studies are needed to investigate the water chemistry in this fragile water source area of Asia. In this work, we studied one of the largest and most populated river basins on the Tibetan Plateau, the Yarlung Tsangpo, to explore whether there are new characteristics in its water chemistry compositions with social–economic development and environmental change on the plateau.

The Yarlung Tsangpo, also known as the Brahmaputra in its lower reaches, drains the valley which is most heavily populated and affected intensively by anthropogenic activities on the Tibet Plateau. It provides water for millions of people in China, India and Bangladesh (Huang et al. 2011). Due to its crucial role as a regional water resource, several studies have been conducted to investigate the water quality in the Yarlung Tsangpo. It has been proposed that the major chemical constituents of the Yarlung Tsangpo are decisively influenced by natural processes such as intensive weathering and erosion in the basin (Hren et al. 2007; Immerzeel 2007; Huang et al. 2011). However, with the growing industrial and commercial development in the Yarlung Tsangpo valley in recent decades (Dreyer 2003), the chemical contents of the Yarlung Tsangpo River are likely to be affected by these anthropogenic activities. Therefore, despite providing the natural constituents that affect the water chemistry within the river basin, this study also investigated the possible effects of the human activities on the water compositions of the Yarlung Tsangpo.

Study area and methods

River catchment

The Yarlung Tsangpo ("Tsangpo" means "river" in Tibetan) is the largest river basin (~239,200 km^2) draining on the southern Tibetan Plateau, which has an average altitude over 4000 m a.s.l. (Guan and Chen 1980; Liu 1999). It originates from the Jemayangdrung glacier (~5500 m a.s.l.) and its uppermost headwaters run through sandy pastures inhabited by nomads. Further downstream, it bypasses major cities and towns and forms the fertile plains in the southern Tibet Valley. Alternating between wide open fluvial valleys and narrow gorges on the southern Tibetan Plateau, it makes a U-turn around the Eastern Syntaxis (Fig. 1) and forms the Yarlung Tsangpo Grand Canyon, the deepest gorge in the world. Then, it turns south and enters India and Bangladesh, finally flowing into the Bay of Bengal (Liu 1999; Huang et al. 2011). Generally, the lithological composition of the Ganges–Brahmaputra has been found to be 31.5% shales, 33.8% carbonate rocks and 18% shield rocks (Amiotte Suchet et al. 2003). On the plateau, the Yarlung Tsangpo (the upper reaches of the Brahmaputra) runs through a bedrock area with abundant of carbonate igneous and granite gneiss and evaporates in the high Himalayan region (Hu et al. 1982; Hren et al. 2007).

The Yarlung Tsangpo plays an important role in the regional water balance in the Himalaya area. Its annual runoff on the plateau was estimated to be 1.65×10^{11} m^3 and contributed ~10% of the water discharge at its estuary in the Bay of Bengal (Liu 1999; MWR 2004). Due to the climate and topographical conditions on the Tibetan Plateau, there is wide variation in both the temporal and spatial distribution of the runoff of the Yarlung Tsangpo. In summer, the Yarlung Tsangpo river basin is mainly controlled by the warm and moist India monsoon and more than 60% of the precipitation and over 70% of the annual discharge of the Yarlung Tsangpo take place during the period from June to September (Liu 1999; You et al. 2007). Meanwhile, because of the Himalaya rain shadow effect, the rainfall of the Yarlung Tsangpo catchment areas is also spatially uneven (Shi and Yang 1985). As a consequence, the discharge of the Yarlung Tsangpo varies greatly from its source areas ($<5.6 \times 10^9$ m^3 year^{-1}) to the southeast branch ($>6.1 \times 10^{10}$ m^3 year^{-1}) (Liu et al. 2007). It has been estimated that ~39% of the runoff of the Yarlung Tsangpo is due to precipitation (Liu 1999), while with a large number of geothermal springs and mineral-rich alpine lakes distributed over the Yarlung Tsangpo basin (Zheng 1989, 1997; Liao and Zhao 1999; Ji 2008), the groundwater contributes as much as ~36% to the runoff of the Yarlung Tsangpo, which is roughly equal to that of precipitation (Liu 1999). In addition, with 10,816 glaciers spreading over the Yarlung Tsangpo river basin, which account for approximately 28% of the glacial volume (4572 km^3) of the Tibetan Plateau (CDSTM 2006; Yao et al. 2010), melting water from the ice and snow contributes about 25% of the annual runoff of the Yarlung Tsangpo (Liu 1999).

Sampling and instrumental analysis

The main Yarlung Tsangpo channel is joined by quite a few of tributaries. Among them, the Doxung Tsangpo, the Nianchu River, the Lhasa River and the Nyang River are the major contributing tributaries, each drains an area larger than 10,000 km^2 (Liu 1999) (Fig. 1). Water samples from sixteen sites along the Yarlung Tsangpo and five of its major tributaries (Doxung Tsangpo, Xiabu Qu, Nianchu

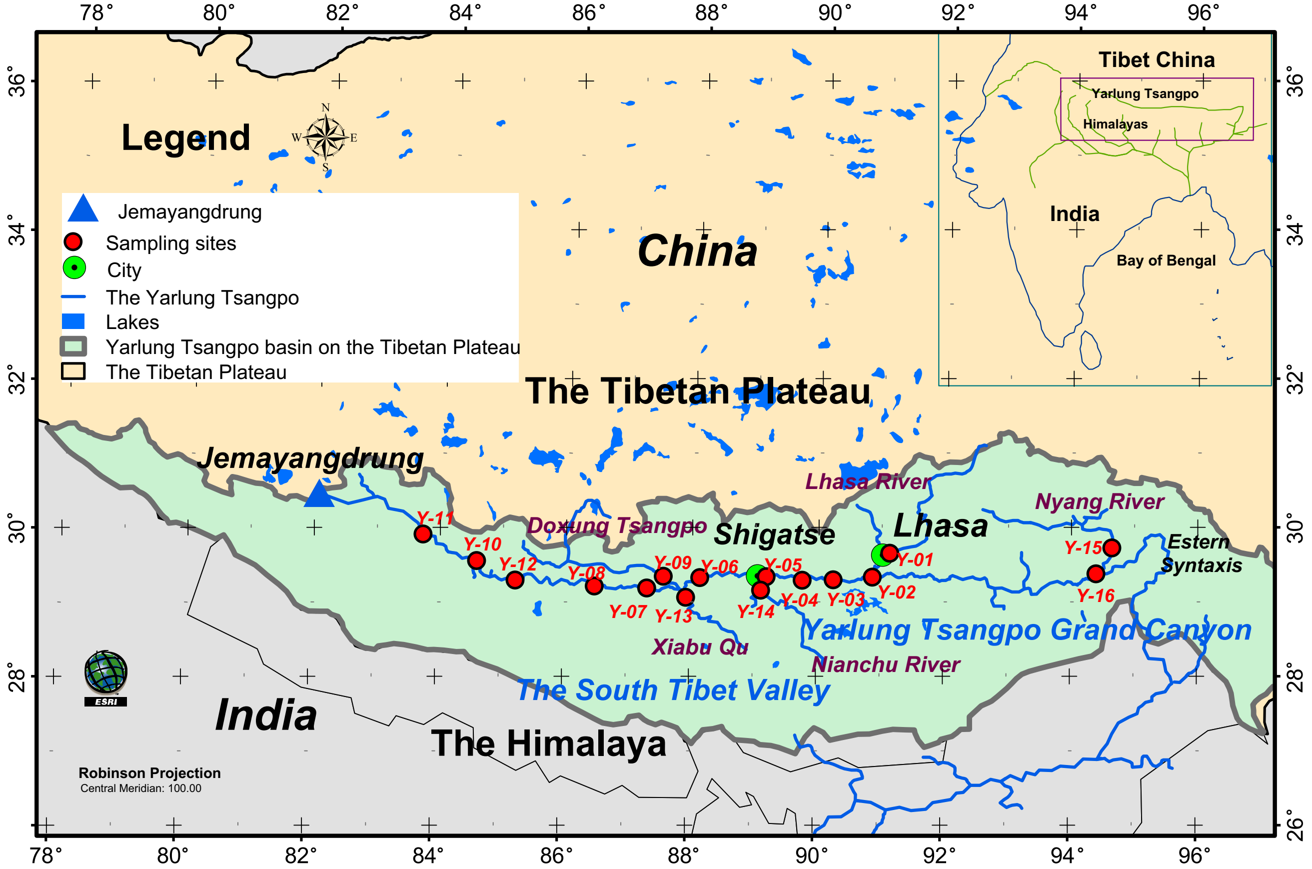

Fig. 1 The sampling sites in Yarlung Tsangpo catchments river basin

River, Lhasa River and Nyang River, Fig. 1) were collected in the summers of 2013 and 2014. General parameters of water quality such as water temperature and pH were measured in the field using portable water testing kits of Wagtech CP1000 in the course of the sampling work (Table 1). Waters were sampled at approximately 10 cm below the surface against the direction of the current, filtered by a 0.2-μm polypropylene membrane and stored in 15-ml polypropylene bottles. Four bottles of water were collected at each site, and the ions and elements in each were measured using two parallel samples. The samples for element measurement were acidified with ultrapure HNO_3^- ($pH < 2$) and stored in containers at 4 °C until laboratory analysis. Inductively coupled plasma-atomic emission spectrometers (ICP-AES) were used to measure the elements in the waters within 30 days of sample collection. The concentrations of cations (Na^+, NH_4^+, K^+, Mg^{2+} and Ca^{2+}) and anions (F^-, Cl^-, NO_3^- and SO_4^{2-}) in the water were detected using Dionex ICS 2000 and Dionex ICS 2500, respectively. HCO_3^- was determined by the other ions with the charge balance method, which has been proved to be reliable within 10% in rivers draining on the Tibetan Plateau (Galy and France-Lanord 1999; Wu et al. 2008). Sampling information (e.g., date and location) and general water quality parameters of the water in the Yarlung Tsangpo are listed in Table 1.

Results and discussion

Generally, the Yarlung Tsangpo has an alkaline aquatic environment with pH varying from 8.3 to 9.0 (average ~8.8, Table 1). The ORP of around 190 mv showed that the water in the Yarlung Tsangpo has an oxidizing aquatic environment. There exists a negative relationship between pH and ORP ($r \sim -0.45$), indicating that pH has a certain potential effect on the forms and distribution of the chemical composition such as metals in waters of the Yarlung Tsangpo (Gambrell et al. 1977). Due to the high soil erosion rate within the Yarlung Tsangpo catchment area (Huang et al. 2009), the average TDS of the whole river basin (157 mg L^{-1}) was higher than that of the world average (Table 2). The TDS of the Yarlung Tsangpo ranged widely from 66 to 265 mg L^{-1} (Table 1) as a result of different geology, meteorological and anthropogenic conditions within the river system. For example, with a more humid climate and significantly better vegetative cover (Yang et al. 2014), TDS in the Nyang River are much

Table 1 Sampling information and general water quality parameters measured by Wagtech CP1000

Location	Site no.	Date	Elevation (m a.s.l.)	Water temp (°C)	pH	ORP (mV)	EC (μs cm^{-1})	TDS* (mg L^{-1})	Turbidity (NTU)	Total alkalinity (mg L^{-1})
Yarlung Tsangpo	Y-02	08/25/2013	3547	23.1	8.6	200	241	164	360	390
	Y-03	08/26/2013	3632	18.8	9.0	188	209	156	310	360
	Y-04	08/26/2013	3725	18.7	8.8	199	249	157	>1000	>500
	Y-05	08/26/2013	3843	13.6	8.8	184	230	148	>1000	>500
	Y-06	08/27/2013	3885	14.3	8.8	195	226	171	>1000	>500
	Y-07	08/27/2013	3937	14.7	8.7	199	218	164	677	500
	Y-08	08/28/2013	3987	16.9	8.7	192	271	177	>1000	>500
	Y-10	08/29/2013	4556	15.6	9.0	188	209	153	88	120
	Y-11	08/29/2013	4565	15.1	8.9	186	179.8	120	110	150
	Y-12	08/30/2013	4438	15.7	8.8	193	279	161	115	155
	Y-16	08/21/2014	2932	15.2	8.8	177	298	134	841	>500
Lhasa River	Y-01	08/25/2013	3818	17.0	8.9	182	194	122	30	40
Doxung Tsangpo	Y-09	08/28/2013	4578	11.4	8.8	194	236	145	235	285
Xiabu Qu	Y-13	08/30/2013	3923	16.7	8.8	182	273	202	>1000	>500
Nianchu River	Y-14	08/30/2013	3809	14.2	8.8	183	400	265	>1000	>500
Nyang River	Y-15	08/20/2014	3412	15.9	8.3	196	165	66	56	47
Average				16.1	8.8	190	242	157		

ORP oxidation reduction potential, also known as Eh; *EC* electric conductance, *TDS* total dissolved solids

* TDS were calculated by the sum of ion concentrations

Table 2 Mean concentrations of major ion of the Yarlung Tsangpo and other main rivers on the Tibetan Plateau and the world (unit, mg L^{-1})

	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	NO_3^{-}	TDS
Yarlung Tsangpo River (mainstream)[a]	27.9	5.1	5.7	1	2.39	37.4	74.1	1.0	117.3
Yangtze River (upstream on the Tibetan Plateau)[b]	53.1	25.4	146.6	5.2	267.5	120.6	116.8	1.63	537.6
Yangtze River (midstream and downstream)[c, d]	36.5	9.7	14.7*	–	20.2	14.5	138.7	1.0	232.6
Nujiang (upstream of the Salween River)[e]	24	7	3	1	5	31	66	BD	141
Longchuanjiang (upstream of the Mekong River)[e]	49	14	12	1	14	69	138	BD	302
Asia average median[f]	16.5	4.8	7.0	1.6	5.8	9.0	65.0	0.2	104.7
Europe average median[f]	41.2	7.0	9.0	1.0	16.3	35.8	121.1	0.6	220.1
Africa average median[f]	4.4	2.4	4.2	2.3	2.7	2.3	33.8	0.1	27.6
North + Central America average median[f]	13.8	3.2	3.5	1.0	3.0	8.9	43.2	0.2	85.4
South America average median[f]	5.4	2.0	2.9	1.3	3.9	3.0	24.5	0.2	40.8
Oceania average median[f]	14.0	2.6	14.0	1.3	12.0	5.0	69.0	0.1	126.4
Global averages median[f]	14.2	4.0	5.4	1.2	5.5	8.9	52.0	0.2	96.9
Global discharge-weighted average[g]	13.4	3.3	5.2	1.3	5.8	8.4	51.9	–	99

* The sum of Na^{+} and K^{+}; *BD* below detection limit; – no report

[a] This study; [b] Qu et al. (2015); [c] Müller et al. (2008); [d] Chen et al. (2002); [e] Huang et al. (2009); [f] Meybeck and Ragu (2012); [g] Meybeck and Helmer (1989)

lower than those in the Xiabu Qu, the Nianchu River and the Lhasa River (Fig. 2c).

Ionic chemistry of the Yarlung Tsangpo basin

The major ions (Ca^{2+}, Na^{+}, K^{+}, Mg^{2+}, Cl^{-}, HCO_3^{-} and SO_4^{2-}) in the main stream of the Yarlung Tsangpo fluctuated, but generally there was a steady underlying trend from the source to the lower reaches (Fig. 2a, b). Ca^{2+}, $HCO_3^{-}$and SO_4^{2-} are the most abundant cations in the ions mass budget. With the precipitation and weathering supply, the evaporation along the drier upper reaches of the river basin significantly exceeds rainfall (ECLCT 2005), both of which could account for the high ion concentrations (e.g.,

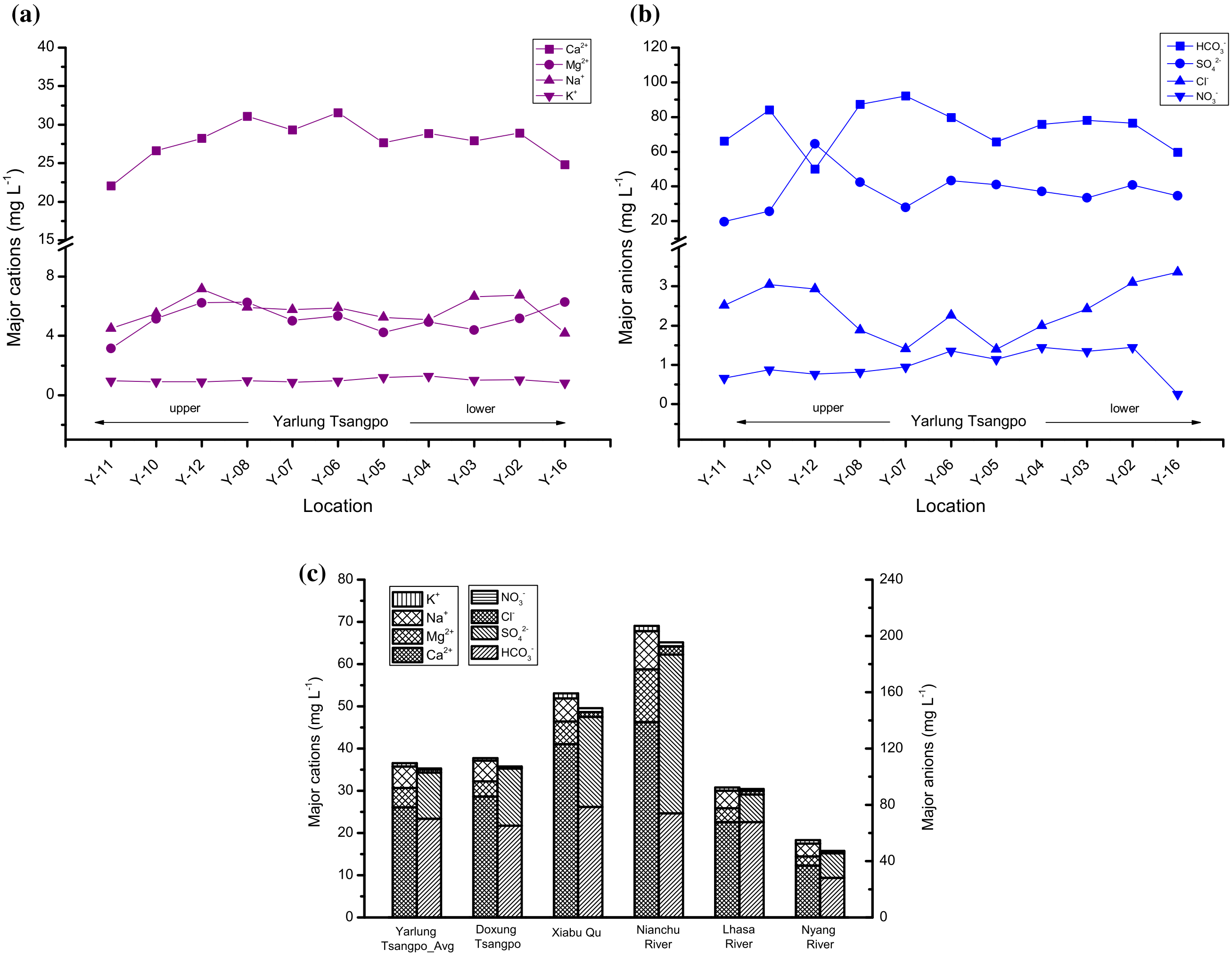

Fig. 2 **a** Spatial distribution of major cations concentrations of the main stream of the Yarlung Tsangpo; **b** spatial distribution of major anions of the main stream of the Yarlung Tsangpo; **c** average concentrations of major cations of the main stream of the Yarlung Tsangpo and its five major tributaries

Ca^{2+}, Na^{+}, Mg^{2+}, HCO_3^{-} and SO_4^{2-}) in the Yarlung Tsangpo. Concentrations of most ions in the Yarlung Tsangpo basin were higher than the world average (Table 2). For instance, the mean concentrations of Ca^{2+} and SO_4^{2-} in the main stream of Yarlung Tsangpo were, respectively, over two and four times higher than that of global average (Table 2). Concentrations of SO_4^{2-} in the Nianchu River, one of the major tributaries, were as high as 112.8 mg L^{-1}, which is ten times higher than that of the global mean level (Fig. 2c; Table 2). However, ions K^{+} and Cl^{-} in the water of the Yarlung Tsangpo had a lower concentration when compared with the world average (Table 2). Most studies so far have claimed that K^{+} in water of the global rivers is primarily due to leaching of silicate minerals, and in small amounts from other sources that often include one or more evaporate minerals, fertilizers, rainwater and the decay of land plants (Chaudhuri et al. 2007). It should be noted that there are only few fertilizers or decayed land plants on the Tibetan Plateau compared with most other river basins in the world; therefore, the concentration of K^{+} was relatively low in the Yarlung Tsangpo. It is widely accepted that the Cl^{-} in the surface waters of rivers contributed by the cyclic salts is expected to decrease with increasing distance from the sea (Stallard and Edmond 1981). With the major contribution of the rainfall during the monsoon season to the annual discharge of the Yarlung Tsangpo (Liu 1999), the water chemistry is inevitably affected by the precipitation, which is dominated by the Indian monsoon. However, as the roof of the world, the high-elevation Himalaya blocks most of the water vapor flux from the Indian Ocean to the Tibetan Plateau and reduces the precipitation in this area (Shi and Yang 1985). As a result, the concentration of Cl^{-} in the Yarlung Tsangpo was lower than in most other rivers in the world.

Besides cyclic salts transported by the atmosphere and deposited in rivers, solutes in river waters have multiple sources deriving from physical, chemical and biological processes in the drainage basin, such as weathering of carbonate, evaporates, silicate and sulfide minerals and anthropogenic input (Singh et al. 2005; Zhang et al. 2011). It has been proposed that the majority of the dissolved solids in the rivers of the Tibetan Plateau are derived from various evaporates, weathering and saline lakes (Singh et al. 2005). The water of the Yarlung Tsangpo exhibits good correlation between Cl^- and Na^+, Mg^{2+}, SO_4^{2-} in the analysis of the ions data, suggesting the influence of evaporates and brines from saltwater lakes. In addition, in the northern parts of the Yarlung Tsangpo river basin, there are numerous geothermal springs and mineral-rich alpine lakes distributed over the area (Zheng 1989; Liao and Zhao 1999). The groundwater contributes ~36% to the annual runoff of the Yarlung Tsangpo (Liu 1999). Therefore, along with the possible small portion source from the sea, groundwater and weathering of evaporate rocks likely play a crucial role in the ions of Cl^- in the Yarlung Tsangpo river basin.

Here, we used ternary plots to explore the major ionic composition characteristics of the Yarlung Tsangpo river basin (Fig. 3). The ternary anion diagram showed that the waters of the Yarlung Tsangpo contained a high HCO_3^- concentration clustering more toward the HCO_3^- apex, while in the cation plot the samples fall in the cluster close to the Ca^{2+} apex. According to the ternary cation diagram (Fig. 3), Ca^{2+} and HCO_3^- are the dominating ions in the waters of the Yarlung Tsangpo and accounting for approximately 64% of the total ionic budgets in the river basin. The Gibbs graph provided an assessment of the relative importance of major natural mechanisms controlling surface water chemistry, which includes atmospheric precipitation, evaporation, fractional crystallization and rock weathering (Gibbs 1970). The plot of TDS concentrations and $Cl^-/(Cl^- + HCO_3^-)$ and $Na^+/(Na^+ + Ca^{2+})$ weight ratios in this work revealed that the waters in the main stream of the Yarlung Tsangpo and its tributaries were characterized by the very low ratios of $Cl^-/(Cl^- + HCO_3^-)$ (<0.08) and $Na^+/(Na^+ + Ca^{2+})$ (<0.21) and a moderate TDS concentration (120 mg L^{-1}) (Fig. 4) (Gibbs 1970), indicating that the ionic chemistry in the Yarlung Tsangpo was typical of a river dominated by rock weathering. The major ionic chemistry in rivers can provide sights into the chemical weathering in the drainage basins, since the weathering of different bedrocks (e.g., silicates, carbonates and evaporates) yields different combinations of dissolved ions in solution. For instance, Ca^{2+} and Mg^{2+} in the Yarlung Tsangpo river basin have been proposed to originate mainly from the weathering of silicates, carbonates and evaporates, while Na^+ and K^+ are mainly due to the weathering of evaporates and silicates (Li and Zhang 2008; Huang et al. 2009). Furthermore, the molar ratio of Ca^{2+}/SO_4^{2-} was >2.5, indicating that H_2SO_4 did not replace H_2CO_3 as a source of protons for rock weathering.

Elements in the waters of the Yarlung Tsangpo river basin

In general, water chemistry compositions in rivers are to a large degree reflected by the bed rock and soil constituents in the catchment areas (Huang et al. 2009; Li et al. 2009). The Tibetan Plateau is the youngest and highest plateau in the world; soils on the plateau are in general weakly developed, while the chemical weathering and physical erosion are at a fairly high rate (Colin et al. 1999; Dalai et al. 2002; Singh et al. 2005). As discussed above, chemical weathering and physical erosion of the parent rock in the Yarlung Tsangpo river basin provided a significant contribution to the ionic chemical composition of its water. Thus, the mechanisms governing the elements of the waters in the Yarlung Tsangpo river basin were assessed by identifying interrelationships and identifying

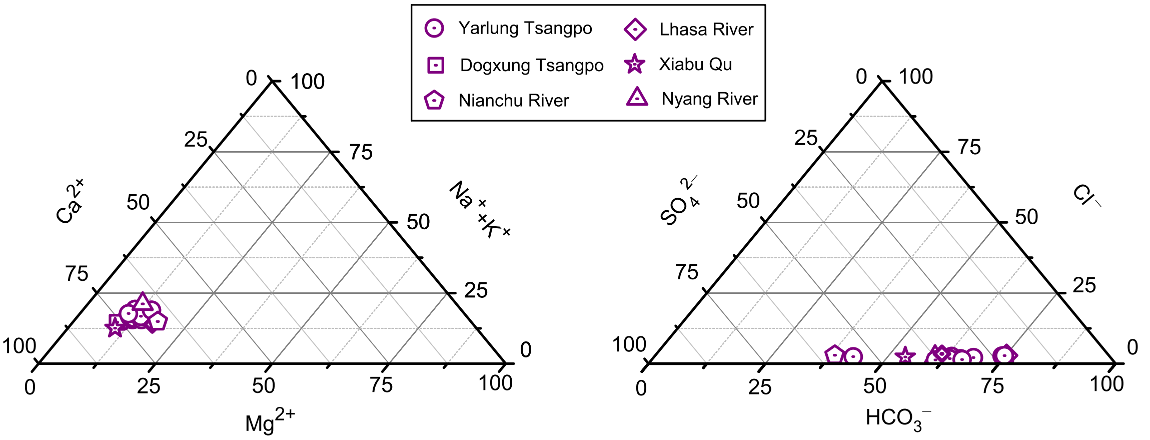

Fig. 3 Ternary plots of major cations (**a**) and anions (**b**) for water of the main stream of the Yarlung Tsangpo and its tributaries

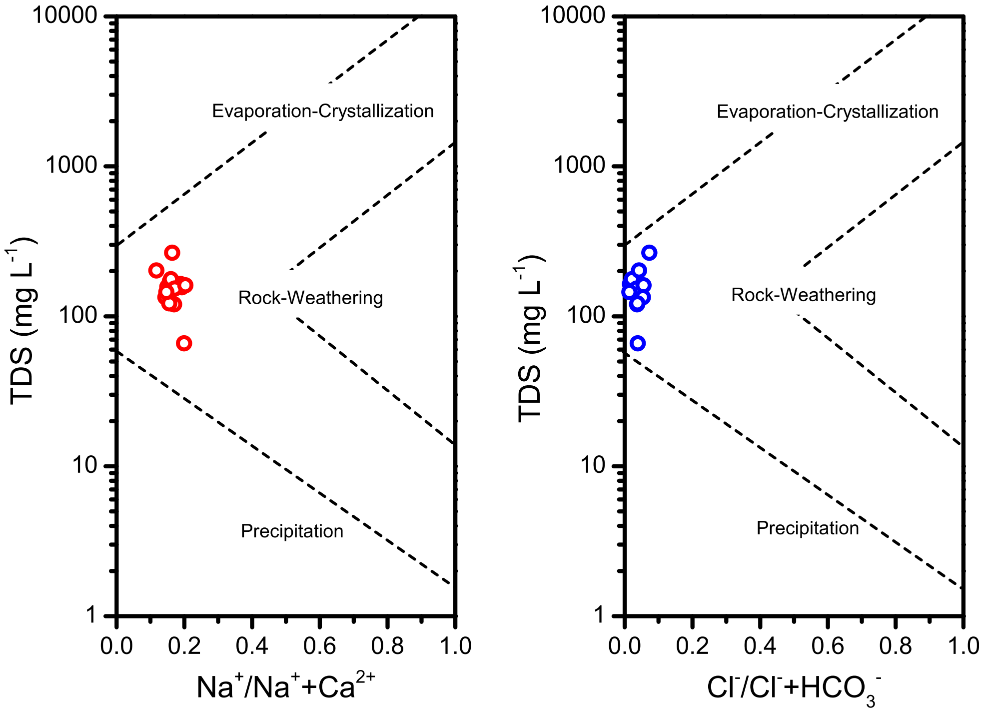

Fig. 4 Gibbs graph of major ion compositions in the Yarlung Tsangpo river basin

Table 3 Concentrations of elements in the Yarlung Tsangpo River and its tributaries (unit: μg L^{-1})

		Mn	Cr	Ni	Cu	Zn	Cd	Sb	Ba	Pb	U	Mo
Yarlung Tsangpo	Y-02	15.3	4.11	4.63	1.80	55.3	7.56	12.9	20.1	30.5	2.55	1.85
	Y-03	11.8	1.39	2.05	1.17	15.00	2.89	1.72	11.9	12.2	1.61	1.76
	Y-04	18.1	2.64	2.66	1.82	33.80	9.09	4.72	22.1	38.6	2.66	1.79
	Y-05	13.7	3.63	1.90	1.46	6.47	1.05	5.77	10.1	6.22	1.88	1.29
	Y-06	200	9.90	11.1	6.93	18.20	0.91	3.08	33.4	10.0	2.51	0.62
	Y-07	54.30	2.46	4.61	2.81	60.6	14.2	2.94	28.7	55.7	2.04	1.05
	Y-08	6.61	2.70	1.12	1.98	1.56	0.32	5.47	6.76	2.33	2.39	1.17
	Y-10	3.09	3.51	0.89	0.71	1.08	0.36	3.72	12.2	2.11	3.91	1.91
	Y-11	1.69	0.29	0.83	1.16	10.70	1.67	3.86	10.2	9.26	4.23	1.97
	Y-12	5.24	0.21	0.75	0.71	13.50	1.05	1.91	6.72	4.65	1.98	1.14
	Y-16	8.17	0.49	0.40	0.31	8.85	0.50	1.17	5.63	2.37	0.79	0.61
Average		30.7	2.8	2.8	1.9	20.5	3.6	4.3	15.3	15.8	2.4	1.4
Lhasa River	Y-01	19.4	3.49	0.85	3.08	2.16	0.24	4.08	12.1	1.63	2.27	1.77
Doxung Tsangpo	Y-09	24.3	1.06	1.96	1.34	6.91	0.88	2.54	21.3	4.68	2.20	1.61
Xiabu Qu	Y-13	265	12.0	11.9	7.43	26.6	0.23	1.85	20.8	5.06	0.67	0.11
Nianchu River	Y-14	3.19	3.13	1.22	0.65	8.34	0.64	18.4	11.1	3.36	2.35	0.73
Nyang River	Y-15	0.77	1.70	1.65	1.10	3.35	2.11	2.45	8.64	9.27	1.32	0.75

covariations of parameters using a correlation analysis. This analysis was based on the samples from sixteen sites yielding data for the complete set of eleven elements noted as health concerns by the World Health Organization (WHO 2011; Zhang et al. 2011) and the China national standard (GB) (MOH&SAC 2006) (Table 3). As these samples are not only from the main stream of the Yarlung Tsangpo, but also from its five separate tributaries, interdependencies within each stream are unavoidable and pose a limitation to the interpretation of the statistical results. Keeping this in mind, the correlation analysis could still provide a clarifying view of the parameter interrelationships. Despite considerable parameter variations among individual samples, we identified that there were good correlations among the ions (e.g., Ca^{2+}, Mg^{2+}, Cl^- and SO_4^{2-}) and elements (e.g., Mn, Cd, Ni, Cu and Pb),

Table 4 Correlation analysis of the ions and elements of health significance for drinking water

	TDS	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	Mn	Cr	Ni	Cu	Zn	Cd	Sb	Ba	Pb	U	Mo
TDS	1																			
Ca^{2+}	.814**	1																		
Mg^{2+}	.938**	.798**	1																	
Na^+	.728**	.776**	.815**	1																
K^+	.426	.575*	.471	.486	1															
HCO_3^-	.194	.574*	.298	.422	.315	1														
SO_4^{2-}	.921**	.856**	.891**	.810**	.514*	.121	1													
Cl^-	.734**	.640**	.810**	.636**	.435	.160	.723**	1												
NO_3^-	.546*	.809**	.572*	.579*	.699**	.346	.717**	.635**	1											
Mn	−.081	.276	−.048	.080	.126	.397	.023	−.181	.243	1										
Cr	.068	.440	−.001	.010	.220	.282	.190	.077	.511*	.764**	1									
Ni	.048	.418	−.016	.007	.226	.258	.180	.039	.497	.794**	.995**	1								
Cu	.026	.418	−.014	.079	.277	.330	.162	.024	.511*	.857**	.958**	.974**	1							
Zn	−.053	.352	−.096	−.047	.186	.336	.070	−.025	.475	.797**	.957**	.948**	.937**	1						
Cd	.008	.197	.013	.218	.253	.406	−.008	−.048	.205	.460	.238	.268	.429	.258	1					
Sb	−.159	−.046	−.095	.058	.149	.330	−.204	−.265	−.032	.276	−.084	−.046	.104	−.022	.877**	1				
Ba	−.205	−.136	−.220	.016	−.268	−.012	−.139	−.167	−.189	.370	.232	.205	.231	.342	.069	−.027	1			
Pb	−.117	.273	−.090	.074	.060	.479	−.026	−.215	.268	.879**	.616*	.646**	.744**	.666**	.638**	.522*	.301	1		
U	−.170	−.021	−.106	.051	.187	.352	−.199	−.273	.003	.359	−.003	.037	.188	.062	.892**	.994**	.004	.589*	1	
Mo	−.283	.061	−.203	−.043	.063	.399	−.200	−.062	.238	.619*	.484	.467	.551*	.682**	.249	.117	.602*	.627**	.182	1

$N = 16$

* Correlation at 0.05(two-tailed); ** Correlation at 0.01(two-tailed)

respectively (Table 4). However, the correlation between the ions and elements is not significant, indicating that, except for the natural processes, the mechanisms controlling the elements in the Yarlung Tsangpo river basin are not exactly the same as the ions.

Water quality assessment of the Yarlung Tsangpo river basin

Most studies so far have shown that the chemical compositions in the headwaters of the rivers on the Tibetan Plateau are controlled by natural processes such as rock weathering and soil erosion, and that the water chemistry of rivers on the Tibetan Plateau were widely considered to be pristine (MFA 2003; Huang et al. 2009). Although the waters in the Yarlung Tsangpo river basin were characterized by high alkalinity due to high concentrations of Ca^{2+} and HCO_3^-, the results of this study revealed that all ions were within the maximum desirable limits and most elements were under the WHO (WHO 2011) and GB (MOH&SAC 2006) guideline for drinking water (Table 5). Concentrations of Ag, Cd, Co, Cr, and Hg in Tibetan rivers were also identified in negligible levels as regards the established standard for drinking-water quality (MFA 2003; Huang et al. 2009). However, regional chemical compositions in the Tibetan rivers were proved to be affected by anthropogenic factors such as mining operations in the locality (Huang et al. 2010). With rapid development in commercial activities (e.g., tourism) taking place during recent decades in Tibet and a ~8,000,000 host population, most of which is concentrated within the major river basins of the Tibetan Plateau (Dreyer 2003; Hu

Table 5 Chemicals of health significance as described by the international guideline (WHO) and the China national guideline (GB) for drinking-water quality

Parameter	Unit	WHO[a]	Remark	GB5749[b]	Remark
pH			Optimum: 6.5–8	6.5–8.5	
TDS	$mg\ L^{-1}$	–	Optimum < 1200	1000	
Turbidity	NTU	5		–	
Antimony (Sb)	$mg\ L^{-1}$	0.02		0.005	
Barium (Ba)	$mg\ L^{-1}$	0.7		0.7	
Bicarbonate (HCO_3^-)	$mg\ L^{-1}$	–	Optimum < 600	–	
Cadmium (Cd)	$mg\ L^{-1}$	0.003		0.005	
Calcium (Ca^{2+})	$mg\ L^{-1}$	–	Optimum < 250	–	
Chlorine (Cl)	$mg\ L^{-1}$	5 (C)	For total chlorine	4	For total chlorine
Chromium (Cr)	$mg\ L^{-1}$	0.05(P)	For total chromium	0.05	For Cr(+6)
Copper (Cu)	$mg\ L^{-1}$	2		1	
Potassium (K)	$mg\ L^{-1}$	–	Optimum < 250	–	
Lead (Pb)	$mg\ L^{-1}$	0.01		0.01	
Magnesium (Mg^{2+})	$mg\ L^{-1}$	–	Optimum < 150	–	
Manganese (Mn)	$mg\ L^{-1}$	0.4(C)		0.1	
Molybdenum (Mo)	$mg\ L^{-1}$	0.07		0.07	
Nickel (Ni)	$mg\ L^{-1}$	0.02(P)		0.02	
Sodium (Na^+)	$mg\ L^{-1}$	–	Optimum < 200	200	
Sulfate (SO_4^{2-})	$mg\ L^{-1}$	–	Optimum < 500	250	
Uranium (U)	$mg\ L^{-1}$	0.03 (P)		–	
Zinc (Zn)	$mg\ L^{-1}$	–	Optimum < 3	1	

According to WHO drinking-water quality 4th edition (2011):

A Provisional guideline value because the calculated guideline value is below the achievable quantification level

C Concentrations of the substance at or below the health-based guideline value may affect the appearance, taste or odor of the water, leading to consumer complaints

D Provisional guideline value because disinfection is likely to result in the guideline value being exceeded

P Provisional guideline value because of uncertainties in the health database

T Provisional guideline value because calculated guideline value is below the level achievable through practical treatment methods, source protection, etc.

– No health-based guideline value is provided

[a] WHO (2011)

[b] MOH&SAC (2006)

et al. 2004; Qu et al. 2007; Huang et al. 2010; Zhang et al. 2010; NBS 2012), municipal wastewater can be another threat to the water quality in Tibetan rivers (Huang et al. 2009). For example, in this study, we found that concentrations of Cd and Pb at the points of Lhasa, Shigatse and Xietongmen County (Y-02, Y-04 and Y-07, respectively) were 1–3 times higher than the safety threshold value for drinking water. Lhasa, the capital city of the Tibetan Autonomous Region, and Shigatse are the two biggest cities in the Yarlung River basin that are home to about four million residents and attract more than ten million tourists every year (NBS 2012; Kun et al. 2013), and Xietongmen is an important mining city rich in Cu–Au and Pb–Zn ore in the Tibetan Autonomous Region (Huang et al. 2012; Tafti et al. 2014). Moreover, besides the local emissions, pollutants (e.g., Hg, Pb and PAHs) from the surrounding areas, such as India and the mainland of China may also reach the Tibetan Plateau with the monsoon (Cong et al. 2010; Wang et al. 2010; Zhang et al. 2012; Kang et al. 2016). Some of the pollutants are deposited in rivers and affect the water chemistry directly, while others accumulate in snow and ice and can be released into the rivers through glacier melting (Huang et al. 2014; Kang et al. 2016; Li et al. 2016a, b). Therefore, along with the natural processes that control the water chemistry, anthropogenic activities in both local and surrounding areas may also cause potential risks to the water quality in the Yarlung Tsangpo if no proper steps are taken in the future.

Conclusions

River water chemistry is highly variable and dependent on natural environment conditions such as basin lithology, hydrology and climate. This study provides an assessment of the ionic chemical water quality and pollutants in the Yarlung Tsangpo basin in the southern part of the Tibetan Plateau.

The waters of the Yarlung Tsangpo showed a fairly high buffering capacity with an average pH of 8.8 in the respective periods. TDS in the basin were mainly contributed by Ca^{2+} and HCO_3^- and fluctuated from 66 to 265 mg L^{-1} with an average of $\sim$157 mg L^{-1}, which was in a common level compared to other rivers in the world. The ORP of the water ranged from 177 to 200 mV, indicating an oxidizing aquatic environment in the waters of the Yarlung Tsangpo. The ionic characteristics of the river water chemistry of the Yarlung Tsangpo were mainly controlled by natural processes, e.g., weathering of carbonates, silicates and evaporates, and drainage from geothermal waters and saline lakes. In addition to various natural processes, this study revealed the impact of human activities such as mining, industry and the exponential growth of tourism on the plateau on the elements chemistry of the Yarlung Tsangpo river basin. Although the watercourses on the plateau can be generally considered pristine, high concentrations of toxic elements (i.e., Cd and Pb) were found in the basin, which showed that human activities on the plateau have an effect on the waters of the Yarlung Tsangpo. In addition, with the world's two most densely populated countries located adjacent to the Himalaya, long-range transported pollutants may affect the water quality along with the precipitation deposits in the rivers of the Tibetan Plateau. Furthermore, along with the global warming, the pollutants accumulated in the snow and ice will also be released into the rivers. In summary, both anthropogenic activities and climate change on the plateau will affect the water chemistry of the Yarlung Tsangpo and cause risks to human livelihoods in the river basin of the southern Tibetan Plateau Valley and even in India and Bangladesh further downstream. Therefore, with anthropogenic activities and climate change on the Tibetan plateau, long-term observations are needed for water chemistry studies on the rivers of the Tibetan Plateau in the future.

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