



## Review

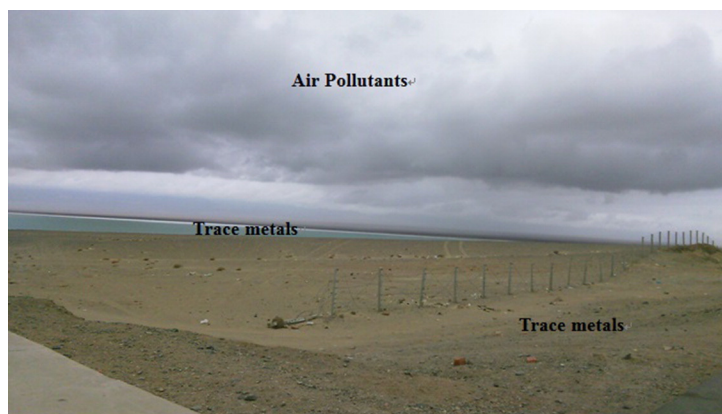
## Inorganic pollution around the Qinghai-Tibet Plateau: An overview of the current observations

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## HIGHLIGHTS

- Relatively high metal concentrations around the Qinghai-Tibet Plateau
- Non-negligible air pollution around the Qinghai-Tibet Plateau
- High soil heavy metal contamination degree of the Qinghai-Tibet Plateau
- High water heavy metal hazard index of the Qinghai-Tibet Plateau

## GRAPHICAL ABSTRACT



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## ABSTRACT

The Qinghai-Tibet Plateau is the highest geographical unit in the world. Thus, it serves an important role in evaluating long-term ecologic conditions and environmental status and changes over time. This study summarizes major and trace element concentrations in biota and in water and soil. It also pays attention to gaseous pollutant and particle concentrations in air around the Qinghai-Tibet Plateau. The degree of soil heavy metal contamination and the water heavy metal hazard index were respectively evaluated. The contamination degrees of two sampling areas around the Qinghai-Tibet Plateau reached extremely high levels with soil  $mC_d$  (modified degree of contamination) values exceeding 20. Surprisingly, over 54% of sampling areas showed moderate or more serious soil contamination degree ( $mC_d > 1.5$ ). Moreover, the hazard indexes of two important rivers were 1.56 and 7.59, reaching unacceptable level. The potential risk might be beyond our expectation. Therefore, it should be an urgent and top priority to identify and confirm possible pollution sources around the Qinghai-Tibet Plateau. Then, it is imperative to implement feasible and effective environmental quality control strategies.

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## 1. Introduction

The Qinghai-Tibet Plateau, known as the third polar and roof of the world, is a unique geographical unit to attract increasing attentions all over the world. The Qinghai-Tibet Plateau covers a total area of nearly  $3.0 \times 10^6 \text{ km}^2$  (about  $2.5 \times 10^6 \text{ km}^2$  in China) with an average altitude of over 4000 m. It serves as the source of several important rivers including: Yangtze, Lancang, Nujiang, Senge Tsangpo (also known as Shiquan River), Yarlung Zangbo (also called Brahmaputra River) and Tarim.

Major and trace elements, especially heavy metals, play important role in the environment. Heavy metals generally refer to metals or metalloids with a specific density of greater than  $5 \text{ g/cm}^3$  (Järup, 2003; Oves et al., 2012). Heavy metals exert a serious threat to human health and well-beings, living organisms, and local environment due to their bioaccumulation characteristics, persistence, and toxicity (Laskowski et al., 1995; Cheng, 2003; DeForest et al., 2007; Nabulo et al., 2010). Heavy metals naturally exist in the environment and enter the water, air, and soil by ways of natural and anthropogenic activities (Clark, 1981; Förstner, 1989; Valipour et al., 2012, 2013a, 2013b; Zukal et al., 2015). It is possible for heavy metals to travel long distances by bonding to particles in air.

Composed of solid and liquid particles suspended in the air (Kokhanovsky, 2008), atmospheric aerosols have aroused global attention due to their significant effects on climate, atmospheric chemistry and visibility, precipitation, clouds, and human health (Boucher et al., 2013). Gaseous pollutants are also important for air quality and human health (Cox, 2003) and deserve extensive study on the Qinghai-Tibet Plateau.

The Qinghai-Tibet Plateau is least disturbed by human activities in China. Thus, it is regarded as “the last pure land” with the least pollution in China. However, the observations obtained in recent years have provided different and thought-provoking facts. To the current state of knowledge, previous research paid more attention to concentrations of a few pollutants (metals, aerosol, etc.) in a certain media (biota, soil, water, or air) around one or several sites of the Qinghai-Tibet Plateau. The published results are diverse and fragmented to make it difficult to obtain the comprehensive information on contamination degree of the Qinghai-Tibet Plateau. Therefore, this study compiled the previously published data and evaluated the contamination degree of the Qinghai-Tibet Plateau, aiming at providing thorough insight for the inorganic pollution around the Qinghai-Tibet Plateau so as to provide the basis for environmental protection policies for this unique area.

## 2. Materials and methods

All concentration data were collected from the published research articles. The sampling sites were also marked in Fig. S1.

Due to the limitation of background/baseline data of air/aerosol metal contents and gaseous pollutant/particle concentrations, this study only evaluated the heavy metal contamination degree of soil/sediment and heavy metal hazard index of water.

The heavy metal contamination degree of soil/sediment was described as  $mC_d$  (modified degree of contamination), calculated using the following equation:

$$mC_d = \frac{\sum_{i=1}^n \frac{C_x^i}{C_b^i}}{n} \quad (1)$$

where  $C_x^i$  and  $C_b^i$  refer to the concentration of the  $i$ th pollutant in the contaminated soil/sediment (mg/kg) and the background concentration of the  $i$ th pollutant in the soil/sediment (mg/kg), respectively;  $n$  refers to the number of pollutants. More detailed information of this method were described by Hakanson (1980) and Abraham and Parker (2008). Background concentrations were determined from the reference (MEPC, 1990). This studied used maximal concentrations as  $C_x^i$  to obtain the possibly maximal contamination degree.

Water hazard index (HI) caused by heavy metals was calculated using the following equation (Park and Choi, 2013; Adamu et al., 2015):

$$HI = \sum_{i=1}^n \frac{C_i \times IR \times ED \times EF / (BW \times AT)}{RfD_i} \quad (2)$$

where  $C_i$  is the concentration of a pollutant in water (mg/L);  $IR$  is the ingestion rate ( $2 \text{ L/d}$ );  $ED$  is the exposure duration (30 years);  $EF$  is the exposure frequency ( $350 \text{ d/year}$ );  $BW$  is the body weight ( $60 \text{ kg}$ );  $AT$  is the average time ( $ED \times EF \text{ days}$ );  $RfD_i$  is the reference dose of the  $i$ th pollutant for non-carcinogen characterization. More detailed information refers to research articles written by Park and Choi (2013) and Adamu et al. (2015).

## 3. Results

### 3.1. Trace elements in biota of the Qinghai-Tibet Plateau

Due to bio-magnifications and bio-concentration effects, pollutants in the organisms attract more attentions from the researchers (Table 1). Yang et al. (2007) analyzed heavy metals in fish from two high mountain lakes (Nam Co Lake and Yamdro Lake) and Lhasa River in the Qinghai-Tibet Plateau. Heavy metals were relatively high in fish liver, eggs and gill, and generally low in brain and muscle. Maximal Cu and Zn concentrations reached  $2.0$  and  $6.9 \text{ mg/kg}$  (wet weight), respectively. Yang et al. (2007) speculated that the study on the metal pollution source or bioaccumulation mechanism by fish could obtain useful information from the correlations among metal concentrations in biota samples. Later then, the concentrations of total mercury ( $\text{Hg}_T$ )

**Table 1**Trace elements in the biota of the Qinghai-Tibet Plateau (mg/kg for the other elements and  $\mu\text{g/kg}$  for Hg).

Location	Period	Altitude (m)	species	n	Mn	Co	Ni	Cu	Zn	As	Se	Cs	Pb	Hg
Nam Co L. <sup>e</sup>	2005	4718	Fish	4	0.61	0.041	0.094	2.0	6.9	0.24	0.36	0.025	0.047	
Yamdro L. <sup>e</sup>	2005	4441	Fish	4	0.24	0.040	0.12	1.1	4.4	0.27	1.0	0.024	0.079	
Lhasa R. <sup>e</sup>	2005	3629	Fish	12	0.11–0.49	0.022–0.057	0.11–0.22	0.33–0.88	2.5–5.3	0.067–0.14	0.18–0.31	0.013–0.029	0.024–0.065	
Qinghai L. <sup>f</sup>	2007	3225	Fish	7										400 $\pm$ 94
Keluke L. <sup>f</sup>	2006	2813	Fish	3										243
Cuo Na L. <sup>f</sup>	2006	4595	Fish	3										1082
Nam Co L. <sup>f</sup>	2007	4718	Fish	10										609 $\pm$ 355
Yamdro <sup>f</sup>	2007	4441	Fish	17										1198 $\pm$ 438
Basum <sup>f</sup>	2007	3538	Fish	6										657 $\pm$ 180
Manasarovar <sup>f</sup>	2007	4588	Fish	7										764 $\pm$ 493
Palgon L. <sup>f</sup>	2007	4242	Fish	7										1132 $\pm$ 493
R. and L. <sup>d,g</sup>	2009, 2010	2720–4725	Fish	166										25.1–1218
Research farm <sup>h</sup>	2011	3050	Vetch seeds	12	12.74–21.78 <sup>c</sup>			3.37–8.77 <sup>c</sup>	30.01–48.16 <sup>c</sup>					
Hailuoguo G. <sup>i</sup>	2012	2960	Moss	>23 <sup>b</sup>									20.0–62.1	
Gongga Mt. <sup>j</sup>	2013	~3000	Moss	54									17.44 $\pm$ 6.86	
Gongga Mt. <sup>j</sup>	2013	2200	Plants1	90									~6.67–60 <sup>a</sup>	
Gongga Mt. <sup>j</sup>	2013	2780	Plants2	80									~3.56–45 <sup>a</sup>	
Gongga Mt. <sup>j</sup>	2013	3200	Plants3	63									~1.82–53.33	
Gongga Mt. <sup>j</sup>	2013	3800	Plants4	20									~0.97–21	

Note: Plants1 refers to *Abies fabri* and *Quercus aliena*; plants2 refers to *Abies fabri* and *Picea brachytyla*; plants3 refers to *Abies fabri* and *Rhododendron*; plants4 refers to *Rhododendron*; L. refers to lake; R. refers to river; G. refers to glacier; Mt. refers to Mountain.

<sup>a</sup> Refers to estimated average value based on figures of the reference.

<sup>b</sup> Refers to values estimated from *Samples collection and preparation* of the reference.

<sup>c</sup> Refers to average value.

<sup>d</sup> Refers to rivers (Bomi, Bayi, Nyang, Lulang, Lhasa, Dazhuka, and Rongbu) and lakes (Basong Tso, Ranwu, Bangong Tso, Lang Tso, Yamdrok Tso, and Nam Co).

<sup>e</sup> Yang et al. (2007).

<sup>f</sup> Yang et al. (2011).

<sup>g</sup> Q. Zhang et al. (2014).

<sup>h</sup> Mao et al. (2015).

<sup>i</sup> Bing et al. (2014).

<sup>j</sup> Luo et al. (2015).

and methyl mercury (MeHg) in the fish samples collected from 8 lakes of the Qinghai-Tibet Plateau were reported (Yang et al., 2011), respectively in the range of 243–2384 µg/kg dw (dry weight) and 131–1610 µg/kg dw. Furthermore, the strong correlation between Hg<sub>T</sub> and MeHg showed that the mercury methylation mainly occurred in situ. Q. Zhang et al. (2014) investigated the concentrations of Hg in 166 wild fish samples of 13 species collected from 13 rivers and lakes across the southern Qinghai-Tibet Plateau. The average Hg<sub>T</sub> and MeHg concentrations in the axial muscle of fish were 100.5 µg/kg ww (wet weight) and 90.7 µg/kg ww, respectively. The Hg concentrations in fish were related with the limited available environmental Hg data and special geochemical characteristics in the region. They also found that pelagic fish possessed higher Hg concentrations while zooplankton and benthic amphipods showed higher percentages of MeHg, giving some insights on geochemical/biological control for Hg bioaccumulation in fish and Hg biomagnifications in aquatic food web of the remote high-altitude area.

Bing et al. (2014) investigated the Pb concentrations and its isotope composition (<sup>208</sup>Pb, <sup>207</sup>Pb and <sup>206</sup>Pb) in mosses from the Hailuoguo Glacier foreland in the eastern Tibetan Plateau. Pb concentrations in the mosses ranged from 20.0 to 62.1 mg/kg. The ratio ranges of <sup>206</sup>Pb/<sup>207</sup>Pb and <sup>208</sup>Pb/<sup>206</sup>Pb were 1.165–1.175 and 2.104–2.111, respectively. The results suggested that the long-distance atmospheric transport could make anthropogenic Pb reach the remote high mountains such as the Qinghai-Tibet Plateau. Luo et al. (2015) analyzed Pb concentrations of 307 plant samples in four typical ecosystems of the Gongga Mountain. The average Pb concentration of the aboveground parts of plant was 3.60 mg/kg. They confirmed Pb input into the Qinghai-Tibet Plateau through long-distance transport and atmospheric deposition. The mining activities and anthropogenic activities including tourism were speculated as the main pollution source of Pb.

Mao et al. (2015) analyzed contents of heavy metals (Mn, Cu, and Zn) in vetch seeds harvested from a research farm on the Qinghai-Tibet Plateau. Maximal Zn concentration reached over 48 mg/kg, serving as dominant pollutant. They concluded that common vetch seeds could be alternative dietary food source for necessary mineral elements if considering potential toxic effect by excessive intake.

### 3.2. Major and trace elements in environmental media of the Qinghai-Tibet Plateau

Major and trace elements in environmental media have been widely studied due to relatively easy pre-treatment and reliable test methods. The detailed information on major and trace elements distribution around the Qinghai-Tibet Plateau was shown in Table S1.

Soils and sediments were extensively studied for exploring major and trace element distribution and contents. Li et al. (2009) analyzed major and trace elements in total 54 soil samples collected from the western Qinghai-Tibet Plateau (the Lhasa block to the south and the Qiangtang block to the north). The percentage of median concentrations for Na, Mg, Al, K, and Ca were 0.82%, 2.03%, 7.39%, 2.47% and 5.52% in the <20 mm fractions. The concentrations of most elements in the <20 mm fractions were higher than those in the bulk samples. Rare earth elements (REEs) concentrations of <20 mm fractions ranged from 144.4 to 274.5 mg/kg, with average of 191.26 mg/kg. The unusual and highly characteristic REE compositions could be regarded as effective index to identify dust aerosol. Sheng et al. (2012) analyzed heavy metals and total organic carbon in soils. The average concentrations of Mn and Cr were 617.36 and 155.54 mg/kg, respectively, serving as dominant heavy metals. Natural average As concentration in plateau soils was 19.27 mg/kg, showing high background value. They also pointed out that some metals such as Hg, Cd, and Pb possessed elevated concentrations partly due to anthropogenic sources while soil parent materials mainly caused relatively high concentrations of others including Cr and Ni. Some research paid more attention to the effects of traffic on the heavy metal enrichment in soils. H. Zhang et al. (2012) found the topsoil (0–10 cm depth) at Delingha was mostly contaminated by heavy

metals, with Cd and Zn having the highest concentrations. The results showed significant effect of railway transport on the concentrations of Zn, Cd, and Pb. Soil trace metal contents at 4 depths (5, 10, 20, and 30 cm) along the Delhi-Ulan section of the Qinghai-Tibet railway were also studied (H. Zhang et al., 2013). The mean concentrations of Rb and Pb were 97.31 and 19.21 mg/kg, respectively, higher than those in continental crust (90 and 12.5 mg/kg). The concentrations of Zn, Cd, and Pb at the embankment were more than seven times greater than those in continental crust. The concentrations of Pb, Cd, and Zn in soil were mainly influenced by railway operations that only weakly affected on soils less than vertical 10 cm from the surface and horizontal 5 m from the bottom of the embankment according to statistical analysis. Heavy metals in the topsoil of four sites along the Qinghai-Tibet highway were also studied (Zhang et al., 2015). The results showed the content of most of heavy metals in roadside soils decreased exponentially with the distance from the road. Cd caught more attention due to the highest contamination factor (1.46). Transportation activities and regional differences including wind and terrain were regarded as important contributors for metal enrichment in soils. Bing et al. (2014) investigated Pb concentrations and its isotope composition in soil profiles from the Hailuoguo Glacier foreland of the eastern Qinghai-Tibet Plateau. The ratios of <sup>206</sup>Pb/<sup>207</sup>Pb and <sup>208</sup>Pb/<sup>206</sup>Pb in the horizon O, A, and C were in the range of 1.160–1.180/2.092–2.120, 1.171–1.209/2.042–2.108, and 1.183–1.206/2.070–2.130, respectively. They concluded that the recently atmospheric deposition mainly influenced the enrichment of Pb in the O and A horizons of soil layers, while the local soil parent materials mainly contributed to the relatively high concentrations of Pb in the C horizon of soils. Furthermore, they speculated that Pb accumulation in the remote high mountains of the eastern Qinghai-Tibet Plateau might be mainly caused by the long distance atmospheric transport. P. Wang et al. (2015) observed deficit of Cu & Zn and an enrichment of Pb in the soils from the Qinghai Lake catchment. They pointed out that elements in soils mainly originated from natural sources according to soil geochemical patterns, cluster analysis, and principal component analysis, while some human activities also influenced elements in virgin topsoils. Luo et al. (2015) analyzed Pb concentrations in soil samples from four typical ecosystems of the Gongga Mountain. The results showed Pb concentrations in different soil layers followed the order of O > A > C, with the value of 20–80.4 mg/kg. They concluded that the mountain rainfall mode as well as increasing vehicles and tourists affected the Pb distribution in the study area. Yang et al. (2010) collected sediment cores along three areas of north to south transect on the Plateau to investigate the history of atmospheric Hg pollution and its spatial variations. The estimated mean post-2000 atmospheric pollution Hg accumulation rates for the sampling sites ranged from 5.1 to 7.9 µg/(m<sup>2</sup> year). They speculated that the economic activities occurred in Asia (mainly including China and India) could contribute to Hg pollution in the Qinghai-Tibet Plateau. Wu et al. (2011) investigated the vertical profiles of <sup>239+240</sup>Pu and <sup>137</sup>Cs activities and <sup>240</sup>Pu/<sup>239</sup>Pu isotopic ratios for three sediment cores of the Qinghai Lake from the Qinghai-Tibetan Plateau. The average inventory of 47.7 ± 18.7 MBq/km<sup>2</sup> for <sup>239+240</sup>Pu activity in the Qinghai Lake was comparable to the average value of global fallout. The mean inventory of 1112.0 MBq/km<sup>2</sup> for <sup>137</sup>Cs was slightly lower than that of global fallout. The mixing of local sources including anthropogenic activities and global fallout source contributed to Pu input and distribution.

Major and trace element concentrations in water and precipitation were also reported. Huang et al. (2008) collected water samples from four major Asian rivers in the Qinghai-Tibet Plateau to investigate major and trace element concentrations. The results showed that the concentrations of Cu, Zn, Ag, Cd, and Cr were generally low while Mg were rather high in Tibetan rivers and Al and Fe (>1 mg/L) were in relatively high concentrations. Pb pollution was identified at several sites of the Salween and Ni pollution was determined at a few locations of the Yangtze River. However, the origin of these elements was not clearly known. Huang et al. (2009) also reported major ions and trace elements

in the headwaters of four major Asian rivers. The concentrations of dissolved salts in these rivers were relatively high. Geological variation, climate changes, and land-use changes seemed to strongly affect the spatial distribution in chemical composition and properties. C. Li et al. (2015) collected surface water samples from 38 lakes in the Tibetan Plateau. Hg in Tibetan lake waters widely ranged from  $<1$  to 40.3 ng/L, exhibiting an increasing trend along transect from the southeast to northwest. The total Hg concentrations strongly correlated with salinity and salinity-related environmental variables including total dissolved solids (TDS) and some of the major ions such as  $\text{Na}^+$ ,  $\text{K}^+$ , and  $\text{Cl}^-$ . Cong et al. (2010a) collected precipitation samples from the Nam Co station of the Qinghai-Tibet plateau. Zn showed the highest maximal concentration among the heavy metals. The backward trajectory analysis was performed to indicate that anthropogenic activities more significantly affected the element inputs during the summer monsoon season. Huang et al. (2012a) reported the volume-weighted mean (VWM) concentrations and wet deposition fluxes of  $\text{Hg}_\text{T}$  and MeHg in precipitation from Tibetan Plateau were 4.8 ng/L and 1.75 mg/( $\text{m}^2$  year), 0.031 ng/L and 0.01 mg/( $\text{m}^2$  year), respectively. They found that 83% of the  $\text{Hg}_\text{T}$  wet deposition fluxes came during the monsoon season and the precipitation amount was the governing factor to affect  $\text{Hg}_\text{T}$  wet deposition flux. Y. Zhang et al. (2012) collected precipitation samples from the Nam Co Station in the central Plateau. The results showed  $\text{Ca}^{2+}$  and  $\text{HCO}_3^-$  were dominant cation and anion in precipitation, 27.46% and 30.84% of the total ions respectively.  $\text{HCO}_3^-$  had the highest flux (98.66 eq/ $\text{hm}^2$ ), while  $\text{NO}_3^-$  flux was the lowest among anions. The ionic deposition fluxes were mainly from the natural crustal dust and influenced by precipitation amount. Major ion concentrations showed a clear seasonal variation with high values during the non-monsoon seasons and low values during the monsoon seasons.

Due to high altitude of the Qinghai-Tibet plateau, many high remote mountains exist there to possess unique environmental media (snowpit and ice core). Therefore, some researchers studied the major and trace element concentrations in snowpit, ice core, and surface snow. Lee et al. (2008) investigated trace metal concentrations in snowpit samples collected from the East Rongbuk glacier. Concentrations of Mn ranged from 102 to 6884 ng/kg, serving as the dominant element in snowpit. The relationship between enrichment factors of each element and Al concentrations suggested that anthropogenic activities mainly contributed to trace element inputs during both non-monsoon and monsoon seasons. Liu et al. (2011) reported the concentrations of trace metals in snowpit from Gyabrag glacier ranged from 0.5 (Sb) to 4598 (Mn) ng/kg. Mn was the dominant element in the snowpit. The crustal enrichment factor analysis showed that rock and soil dust was possibly important source for V, Mn, Co, Ni, Rb, Sr, and Th while anthropogenic inputs mainly contributed to enrichment of trace elements including Cu, Zn, As, Cd, Sn, Sb, Tl, Pb, Bi, and U. Huang et al. (2012b) investigated the seasonal variations, speciation, and sources of Hg in 63 snowpit samples collected from the southern Qinghai-Tibet Plateau.  $\text{Hg}_\text{T}$  concentrations in snowpit samples collected in 2008 and 2011 ranged from  $<1$  to 38.2 and  $<1$  to 20.8 ng/L, separately. Back trajectory analysis suggested that the majority of air mass from the arid regions of northwestern India could arrive at the Zhadang Glacier and these regions provided the main source for Hg deposited in snowpit. Huang et al. (2013) collected samples from a 210 cm snowpit at Zhadang glacier of the Mt. Nyainqêntanglha region. Significant differences in the concentrations for measured elements occurred with the ratio of  $M_{\text{non-monsoon}}/M_{\text{monsoon}}$  ranging from 2 for Zn to 12 for Mn. The results illustrated that high altitude atmosphere on the southern Plateau might be more sensitive to variations in the anthropogenic emissions than that in the central Himalayas. Trace element deposition in the snowpacks at the Laohugou (LHG) and the Tanggula (TGL) glacier basins in the northern Plateau was studied by Dong et al. (2015), while Kaspari et al. (2009) and Hong et al. (2009) respectively investigated the concentrations of trace metals in ice core from Mt. Qomolangma. Dong et al. (2015) found that most of heavy metals originated from anthropogenic sources

and some other elements were mainly from crustal sources. Kaspari et al. (2009) reported that atmospheric trace metal concentrations widely increased with regionally varied enrichment according to comparison of trace metal concentrations in different ice cores. Hong et al. (2009) concluded that natural sources (mainly from mineral dust) dominated the atmospheric cycles of As, Mo, Sn during the 700 years prior to the 20th century and anthropogenic emissions of these elements (largely from stationary fossil fuel combustion and nonferrous metals production) contributed to the pronounced increases of both concentrations and crustal enrichment factors since the 1970s. They speculated that the increased concentrations of metals were attributed to anthropogenic emissions mainly including stationary fossil fuel combustion and nonferrous metals production. Zhang et al. (2008) analyzed the trace metal concentrations in surface snow from the Mt. Qomolangma. Trace metal concentrations ranged from 139 (V) to 1,852,000 (Ca) ng/kg. Moreover, no clear trends for relationship between element variations and elevation were observed because of surface snow distribution caused by strong winds during spring. Huang et al. (2012c) analyzed total Hg in surface snow samples collected from high-elevation glaciers in the Tibetan Plateau. The highest Hg concentrations were observed at the Mt. Muztagata (8.56 ng/L), and the lowest concentrations occurred at the Mt. Nyainqêntanglha (0.90 ng/L). Furthermore, the altitude effect was found on four high-elevation glaciers to indicate that atmospheric Hg was cold-trapped, implying important sink role of the glaciers over the Qinghai-Tibet Plateau for global Hg cycling.

Recently, major and trace element contents in aerosol and particles of the Qinghai-Tibet Plateau were attracting more attentions. Wen et al. (2001) investigated metal concentrations in aerosols of Waliguan. Besides Al, Ca, and Fe, Zn showed maximal concentrations ranging from 9.5 to 26.3 ng/ $\text{m}^3$ . The results showed that natural sources accounted for more than 70% of contribution to element contents in aerosols. Zhang et al. (2009) analyzed Pb concentrations in aerosol samples collected from the Mount Qomolangma, with three Pb peaks located at  $<0.25$   $\mu\text{m}$ , 0.5–1  $\mu\text{m}$ , and 4–8  $\mu\text{m}$  in diameters. The slight air pollution with Pb over the Qinghai-Tibet Plateau were observed with the support of high enrichment factor values for fine and coarse particles of atmospheric Pb (413.2 and 62.6, respectively). Cong et al. (2007) reported that concentrations of elements in aerosols ranged from 82 (K) to 550 (Si) ng/ $\text{m}^3$  and Si, Ca, Fe, Al, K, and S were the main components of aerosols. They speculated that south Asia might be the source of trace metal pollutants in total suspended particles (TSP) around Nam Co according to the backward air mass trajectory analysis. Cong et al. (2010b) reported that the average elemental concentrations in aerosols from the Mt. Qomolangma ranged from 0.31 ng/ $\text{m}^3$  (Cu) to 451 ng/ $\text{m}^3$  (Ca). High aerosol enrichment factors for Cu, Cr, Pb, Ni, V, and Zn indicated the effects of long-distance transport on element enrichment. Yang et al. (2009) reported metal concentrations in  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$  of the Gongga Mountain. Na, Mg, Al, Ca, Fe, and K served as the major components in  $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ . Furthermore, several heavy metals including Ni, Cu, As, Zn, Tl, Ag, and Pb mainly originated from atmospherically long-distance transport. Concentrations of Pb and Zn reached relatively high levels. Cong et al. (2011) and Li et al. (2012) respectively investigated trace metals bound to fine particulate from Lhasa and the southern Tibetan Plateau. Cong et al. (2011) reported that the average trace element concentrations in  $\text{PM}_{10}$  ranged from 0.27 (Sc) to 1640 (Ca) ng/ $\text{m}^3$ . The ratios of indoor average trace metal concentrations to outdoor were in the range of 69–291 (Li et al., 2012). Moreover, enrichment factors of most trace metals for indoor air and outdoor air possessed the similar values, indicating that outdoor air quality might be influenced by contaminants emitted from local tents. N. Zhang et al. (2013) analyzed sixteen elements in  $\text{PM}_{2.5}$  and TSP samples collected at Lijiang of the southeastern Tibetan Plateau. Ca was the most abundant element in both  $\text{PM}_{2.5}$  and TSP samples. Elements including Cu, Zn, S, Br and Sb showed strong enrichment in  $\text{PM}_{2.5}$  and TSP samples. The enrichment factors and  $\text{PM}_{2.5}$ /TSP ratios of these elements indicated different

sources. Furthermore, wind field analysis and back trajectories indicated aerosol transport from northwestern China during the dust-storm season affected Al, Si, Ca, Ti, Cr, Mn and Fe whereas S, K, Ni, Br and Pb enriched during westerly transport from south Asia. N. Zhang et al. (2014) also analyzed metals and metalloids in PM<sub>2.5</sub> and TSP samples collected from Qinghai Lake in northeastern Tibetan Plateau. Ion concentrations ranged from 0.06 (Mg<sup>2+</sup>) to 4.45 (SO<sub>4</sub><sup>2-</sup>) µg/m<sup>3</sup> for PM<sub>2.5</sub> and from 0.13 (K<sup>+</sup>) to 5.04 (SO<sub>4</sub><sup>2-</sup>) µg/m<sup>3</sup> for TSP. Backward trajectory analysis and correlation analysis indicated that the concentrations of organic carbons, sulfate, As, Pb, and Zn were influenced by long-range transport of pollutants from eastern China.

### 3.3. Air pollution of the Qinghai-Tibet Plateau

Research results on gaseous pollutants and particles in air around the Qinghai-Tibet Plateau were listed in Table 2. Tobo et al. (2007) used a balloon-borne optical particle counter to measure vertical profiles of aerosols (radii ≥ 0.15 µm) at Lhasa, China in 1999. The observed aerosols could be divided into two groups; the coarse (r ≥ 0.6 µm) and fine (r = 0.15–0.6 µm) particles. The results showed that deep convection triggered high number concentrations over the Plateau. Cong et al. (2010b) found that the particles were clustered into eight groups with aluminosilicates/silica (55%) serving as dominant group. Moreover, backward trajectory analysis suggested that the northwestern part of India might account for the atmospheric aerosol in the central Himalayas. Engling et al. (2011) investigated aerosol concentrations in Tengchong. PM<sub>2.5</sub> and PM<sub>10</sub> were in the range of 10–85 and 9–96 µg/m<sup>3</sup>, respectively. The maximum hourly mass concentrations of PM<sub>2.5</sub> and PM<sub>10</sub> reached 107 and 117 µg/m<sup>3</sup>, respectively. Biomass-burning smoke exerted important contributions to high values of K<sup>+</sup> against organic carbon. Cong et al. (2011) reported the annual average concentration of PM<sub>10</sub> in Lhasa was 51.8 µg/m<sup>3</sup>. PM<sub>10</sub> concentrations indicated distinct seasonal patterns, with lower values in summer and higher values in winter. N. Zhang et al. (2013) reported TSP and PM<sub>2.5</sub> concentrations

of Lijiang City, ranging from 6 to 24 and from 3 to 9 µg/m<sup>3</sup>, respectively. The developing tourism and urban expansion might contribute to slight anthropogenic pollutant emissions in Lijiang. N. Zhang et al. (2014) reported mass average concentrations of PM<sub>2.5</sub> and TSP at the Qinghai Lake were 21.27 and 41.47 µg/m<sup>3</sup>, respectively. EC concentrations were 0.33 ± 0.17 µg/m<sup>3</sup> and 0.47 ± 0.28 µg/m<sup>3</sup> whereas OC concentrations were 1.49 ± 0.63 µg/m<sup>3</sup> and 2.30 ± 0.95 µg/m<sup>3</sup> in PM<sub>2.5</sub> and TSP, respectively. Most of the ECs were related to biomass burning emissions. SO<sub>4</sub><sup>2-</sup> and Ca<sup>2+</sup> were dominant anion and cation in both PM<sub>2.5</sub> and TSP, respectively. Backward trajectories and correlation analysis showed that the concentrations of SO<sub>4</sub><sup>2-</sup>, OCs, As, Pb, and Zn, were affected by the long-distance transport from eastern China. X. Wang et al. (2015) reported TSP concentrations in Lulang of TP, with value of 4.1–46.7 µg/m<sup>3</sup>. TSP concentrations exhibited seasonal patterns with lower levels in summer seasons and higher values in the winter-spring season. Duo et al. (2015) investigated the composition and major sources of aerosol particles in Lhasa City of Tibetan Plateau. During the sampling period, the average concentrations of both PM<sub>2.5</sub> and PM<sub>10</sub> were 25.7 and 57.2 µg/m<sup>3</sup>, respectively. The particles could be classified into 8 different categories based on energy dispersive spectroscopy (EDS) analysis. It was speculated that local sources such as mineral dust, the celebration ceremony, and religious ritual produced a large quantity of anthropogenic controlled the pollution during the sampling according to the meteorological parameters and back trajectory analysis.

Shen et al. (2014) continuously monitored surface O<sub>3</sub> at a high altitude site of the Qinghai Lake in the Northeast Tibetan Plateau. Annually mean O<sub>3</sub> concentrations was 41.0 ppbv. Daily average O<sub>3</sub> concentrations were in the range of 21.8–65.3 ppbv. The experimental and back-trajectory analysis supported the hypothesis that stratospheric O<sub>3</sub> and long range transport might be the main sources of O<sub>3</sub> in this area. Q.Y. Wang et al. (2015) measured surface O<sub>3</sub>, nitrogen oxides (NO<sub>x</sub> = NO + NO<sub>2</sub>), carbon monoxide (CO), and dew point at Qinghai Lake. The average O<sub>3</sub> mixing ratio was 41 ppb in October 2010 and 57 ppb in October 2011. The increased O<sub>3</sub> mixing ratios were observed in the

**Table 2**  
Gaseous pollutant and particle distribution in the Qinghai-Tibet Plateau.

Location	Date	Altitude (m)	Samples	n	Aerosol	O <sub>3</sub>	VOC	NO	NO <sub>2</sub>	SO <sub>2</sub>	CO	TSP	PM <sub>2.5</sub>	PM <sub>10</sub>
Lulang <sup>e</sup>	2008–2011	NM	Air <sup>d</sup>	NM								4.1–46.7		
Qinghai L. <sup>f</sup>	2010–2011	3200	Air <sup>b</sup>	NM		44.5–65.3	63.8–344.6	0.001–1.5	0.03–2.4					
Qinghai L. <sup>g</sup>	2010,2011	3200	Air <sup>c</sup>	NM		22–77		0.5–7			34–634			
Lhasa <sup>h</sup>	1999	3650	Aerosol <sup>a</sup>	NM	0.7–0.8									
Tengchong <sup>i</sup>	2004	1960	Aerosol <sup>d</sup>	52									10–85	9–96
Mt. Q <sup>j</sup>	2005	6520	Aerosol <sup>d</sup>	NM								2.02–6.34		
Lhasa <sup>k</sup>	2013	3667	Aerosol <sup>c</sup>	43		72.10 ± 17.33			19.95 ± 10.85	8.29 ± 3.37	1109.04 ± 306.54	25.7 ± 21.7	57.2 ± 46.7	51.8 ± 42.5
Lhasa <sup>l</sup>	2007–2008	3650	PM <sub>10</sub> <sup>d</sup>	59										
Lijiang <sup>m</sup>	2009	NM	TSP <sup>d</sup> and PM <sub>2.5</sub> <sup>d</sup>	49								6–24	3–9	
Qinghai L. <sup>n</sup>	2010	3200	TSP <sup>d</sup> and PM <sub>2.5</sub> <sup>d</sup>	36								41.47 ± 20.25	21.27 ± 10.70	

Note: L. refers to lake; Mt. Q refers to Mountain Qomolangma; NM means not mentioned.

<sup>a</sup> Concentration unit refers to particles/cm<sup>3</sup>.

<sup>b</sup> Concentration unit refers to ppbv.

<sup>c</sup> Concentration unit refers to ppb.

<sup>d</sup> Concentration unit refers to µg/m<sup>3</sup>.

<sup>e</sup> X. Wang et al. (2015).

<sup>f</sup> Shen et al. (2014).

<sup>g</sup> Q.Y. Wang et al. (2015).

<sup>h</sup> Tobo et al. (2007).

<sup>i</sup> Engling et al. (2011).

<sup>j</sup> Cong et al. (2010b).

<sup>k</sup> Duo et al. (2015).

<sup>l</sup> Cong et al. (2011).

<sup>m</sup> N. Zhang et al. (2013).

<sup>n</sup> N. Zhang et al. (2014).

afternoon possibly due to in situ photochemical production process and low O<sub>3</sub> mixing ratios occurred in the morning. Y. Li et al. (2015) investigated seasonal changes of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes in different types of alpine grassland in Tibetan Plateau. The lowest CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes were observed in alpine deserts, and the highest fluxes occurred in alpine steppe. Soil physical and chemical properties including temperature, water content, pH, clay content, and NO<sub>3</sub><sup>-</sup> N contributed to the variation of CO<sub>2</sub> and N<sub>2</sub>O flux.

#### 4. Discussion

Based on the limited data, soil/sediment contamination degree and water hazard index caused by heavy metals were calculated (Table 3). Surprisingly, the maximum and minimal  $mC_d$  values were 24.69 and 0.94, respectively. Even for the minimal  $mC_d$  value, the soil contamination degree reached a level deserving attention. Soil samples collected from the whole Qinghai-Tibet Plateau and area along the Delhi-Ulan railway section possessed extremely high contamination degrees, both  $mC_d$  values exceeding 20. Hg, Cd, As, Cr, and Ni mainly contributed to the soil  $mC_d$  of whole Qinghai-Tibet Plateau. Zn, Cd, and Pb accounted for the main soil  $mC_d$  of area along Delhi-Ulan railway section. The percent of  $mC_d$  greater than 1.5 (moderate contamination degree or more serious contamination) exceeded 54% among all sampling areas. In summary, the Qinghai-Tibet Plateau could be divided into two sub-regions according to soil pollution caused by heavy metal. Qinghai region possessed relatively serious soil pollution due to relatively frequent anthropogenic activities including mining, tourism, and transportation. Tibet region showed relatively light pollution that mainly was caused by pollutants transported from long-distance regions such as India and eastern China.

Water hazard index mainly targeted at several rivers originating from the Qinghai-Tibet Plateau and waterbodies along southeast-northwest section of plateau. An astonished result showed that hazard indexes of two important rivers were respectively 1.56 and 7.59, already

reaching unacceptable risk level. Relatively high Pb concentration mainly caused high HI. Although contamination degree and risk analysis caused by heavy metal in other environmental media were not performed due to scarce background values and evaluation method, the soil contamination degree and water HI analysis still provided us different facts to re-consider the environmental quality of the Third Pole. The potential risk might be beyond our expectation.

As fragile ecological system, the Qinghai-Tibet Plateau has been paid high attention from the government and been performed various protection practices. However, different pollution sources and pathways possibly brought pollutants for this area. Local mineral exploitation has most likely resulted in significant contribution to the heavy metal pollution in the plateau. The Qinghai-Tibet Plateau, especially the Qinghai Province, is rich in mineral resources (Lin et al., 2007). The anthropogenic exploitation activities inevitably occurred in this area due to remarkable economic benefits (Lin et al., 2007).

Another important pollution driver is monsoon atmospheric transport from the surrounding areas such as Indian sub-continent (Cong et al., 2007). Meanwhile, road transportation including highway and railway also played important role in soil heavy metal pollution along the traffic lines (H. Zhang et al., 2013; Zhang et al., 2015). On the other side, some religious culture, especially Tibetan Buddhism, might cause slight pollution in remote and non-industrial areas of the Qinghai-Tibet Plateau due to wide usage of pigments including vermilion although further research work on the relationship between religious activities and heavy metal pollution is needed.

#### 5. Conclusions

This study summarized the inorganic pollution including major and trace elements in biota & environmental media and gaseous pollutants & particles in the air of Qinghai-Tibet Plateau by collecting data from the published research articles. Soil contamination degree and water hazard index caused by heavy metals were respectively calculated.

**Table 3**  
Soil/sediment heavy metal contamination degree and heavy metal hazard quotient of water body around the Qinghai-Tibet Plateau.

Location	Date	Altitude (m)	Sample	$mC_d$	Note	HI	Note
A <sup>a</sup>	2007	NM	Soil	0.94	Nil to very low degree of contamination		
TP <sup>b</sup>	2007–2009	NM	Surface soil	20.23	Extremely high degree of contamination		
DURS <sup>c</sup>	2008	NM	Topsoil	24.69	Extremely high degree of contamination		
Qinghai L <sup>d</sup>	2010	3194	Topsoil	1.03	Nil to very low degree of contamination		
Gongga Mt. <sup>e,f</sup>	2012, 2013	2850–2960	Soil	2.43	Moderate degree of contamination		
Haergai <sup>g</sup>	NM	3240	Soil	1.57	Moderate degree of contamination		
Tianjun <sup>g</sup>	NM	3420	Soil	1.44	Nil to very low degree of contamination		
Delingha <sup>g</sup>	NM	2910	Soil	1.28	Nil to very low degree of contamination		
Golmud <sup>h</sup>	NM	3302	Soil	1.05	Nil to very low degree of contamination		
Tuotuohe <sup>h</sup>	NM	4567	Soil	2.30	Moderate degree of contamination		
Nagqu <sup>h</sup>	NM	4539	Soil	2.10	Moderate degree of contamination		
Damxung <sup>h</sup>	NM	4489	Soil	1.34	Nil to very low degree of contamination		
9 lakes <sup>i</sup>	2006, 2007	2813–4652	Sediment core	3.35	Moderate degree of contamination		
Salween <sup>j</sup>	2006	NM	Water			7.59	Unacceptable risk
Mekong <sup>j</sup>	2006	NM	Water			0.28	Acceptable risk
Yangtze <sup>j</sup>	2006	NM	Water			0.50	Acceptable risk
Yarlung Tsangpo <sup>j</sup>	2006	5200	Water			1.56	Unacceptable risk
SE-NW <sup>k</sup>	2010, 2011	3469–5145	Water			0.004	Acceptable risk

Note: A refers to Area between Lhasa and Qiangtang; TP refers to Qinghai-Tibet Plateau; DURS refers to Delhi-Ulan railway section; SE-NW refers to southeast-northwest transect of Qinghai-Tibet Plateau; Mt. means mountain; Mt. Q refers to Mountain Qomolangma; 9 lakes refer to Keluke Lake, Gaihai Lake, Qinghai Lake, Cuo Na Lake, Cuo E Lake, Nam Co Lake, Cuolong Co Lake, Peku Co Lake, and Kemen Co Lake;  $mC_d$  means modified degree of contamination; NM means not mentioned.

<sup>a</sup> Li et al. (2009).

<sup>b</sup> Sheng et al. (2012).

<sup>c</sup> H. Zhang et al. (2013).

<sup>d</sup> P. Wang et al. (2015).

<sup>e</sup> Bing et al. (2014).

<sup>f</sup> Luo et al. (2015).

<sup>g</sup> H. Zhang et al. (2012).

<sup>h</sup> Zhang et al. (2015).

<sup>i</sup> Yang et al. (2010).

<sup>j</sup> Huang et al. (2008).

<sup>k</sup> C. Li et al. (2015).

More than 50% of the Qinghai-Tibet Plateau sampling areas exerted moderate or more serious soil contamination degree based on calculated  $mC_d$  values whereas two important rivers possessed high water hazard index to exert unacceptable risk. The results showed the thought-provokingly situation and potential contamination around the Qinghai-Tibet Plateau. Therefore, it is urgent to explore and confirm the possible pollution source for potential contamination around the Qinghai-Tibet Plateau so as to propose the feasible and effective environmental quality control strategies. On the other side, research on the background/baseline data of air/aerosol metal contents and gaseous pollutant/particle concentrations around the Qinghai-Tibet Plateau are relatively scarce, bringing the difficulty for evaluating the air quality of this important area. Thus, the extensive air sampling and analysis are recommended for future studies.

## Conflict of interest

The authors declare that they do not have any conflict of interest.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.scitotenv.2016.01.136>.

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