Environmental hazards associated with mining activities in Bolivian Poopó Lake

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Abstract

Hydrographically the Bolivian Poopó Lake is located in a basin where the main tributary river is Desaguadero over a dozen other lower flow rivers and they are polluted by abandoned and current mining activities and they are carry heavy metals and solids into the Poopó lake and consequently will be polluted this important Lake.

In the present paper deals the environmental hazards associated with mining activities and for that objective to determine the environmental quality of the Poopó Lake and its tributary rivers, based physical-chemical analysis of superficial water and sediment samples.

The results of the research show that the Poopó Lake water quality is highly saline, the concentration of solids dissolved or in suspension, as well As, Pb, Cd, Zn and other heavy metals concentrations is highly above the permissible limits.

Desaguadero River contributed in Poopó Lake pollution by 70% As, 64% Pb, 4.27% Zn and 2.18% Cd. Other important pollution contributors are Antequera River by 57% Zn, 32.9% Cd and 0.66% Pb, and Huanuni River by 61.2% Cd, 2.23% Pb and 34.3% Zn. Vinto foundry, Kori Kollo mine and mainly San José mine polluted of Poopó Lake by arsenic and lead trough Desaguadero river. Bolivar and Huanuni mines polluted of Poopó Lake by cadmium and zinc trough Antequera and Huanuni rivers.

Additionally the mining activities will be polluted the Poopó Lake by dissolved and suspended solids transport trough by Desaguadero, Antequera and Huanuni rivers.

Key words: Lake, mining, environmental, pollution, heavy metal, dissolved suspended solids.

Peligros ambientales en el Lago Poopó relacionados con la actividad minera

Resumen

Hidrográficamente, el lago boliviano Poopó se encuentra situado en una cuenca donde el tributario principal es el río Desaguadero, sobre una docena de otros ríos de menor caudal, que se encuentran contaminados por la actividad minera actual y minas abandonadas, y transportan metales pesados y material sólido hacia el Lago Poopó, con la consiguiente contaminación de este importante lago.

En el presente trabajo, se relacionaron los peligros ambientales con las actividades mineras con el objetivo de determinar la calidad ambiental del Lago Poopó y sus ríos tributarios, basados en el análisis físico-químico del agua superficial y muestras de sedimento.

Los resultados de la investigación muestran que la calidad del agua del lago Poopó es altamente salina, la concentración de sólidos disueltos o en suspensión, así como la de Pb, Cd, Zn y otros metales pesados, está muy por encima de los límites permisibles.

El río Desaguadero contribuye en la contaminación del lago Poopó con 70% As, 64% Pb, 4.27% Zn y 2.18% Cd, del total de estos metales pesados presentes. Otros ríos importantes que contribuyen a la contaminación son el río Antequera, con 57% Zn, 32,9% Cd y 0.66% Pb, y el río Huanuni con 61.2% Cd, 2.23% Pb y 34.3% Zn. La fundición de Vinto, la mina Kori Kollo y principalmente la mina San José contaminan el lago Poopó con arsénico y plomo a través del río Desaguadero. Las minas Bolivar y Huanuni contaminan el lago con cadmio y zinc por medio de los ríos Antequera y Huanuni.

Adicionalmente, las actividades mineras contaminan el Lago Poopó con sólidos suspendidos y disueltos, que son transportados por los ríos Desaguadero, Antequera y Huanuni.

Palabras clave: Lago, minería, medio ambiente, contaminación, metales pesados, sólidos suspendidos, sólidos disueltos.

Riscos ambientais no Lago Poopó relacionados com a atividade mineira

Resumo

Hidrograficamente, o lago boliviano Poopó, fica numa bacia onde o rio Desaguadero é o principal tributário, além de outros doze rios de menor caudal, que estão contaminados pela atividade mineira atual e pelas minas abandonadas. Os rios também carregam metais pesados e material sólido para o lago Poopó, contaminando assim o lago.

No presente artigo, são relacionados os riscos ambientais com as atividades mineiras com o objetivo de determinar a qualidade ambiental do Lago Poopó e seus rios tributários, baseando-se na análise físico-química da água superficial e amostras de sedimento.

Os resultados da pesquisa mostram que a qualidade da água do Lago Poopó é altamente salina, a concentração de sólidos dissolvidos ou em suspensão, tais como: Pb, Cd, Zn e outros minerais pesados, fica muito acima dos limites admissíveis.

O rio Desaguadero contribui para a contaminação do Lago Poopó com 70% As, 64% Pb, 4.27% Zn e 2.18% Cd, do total dos minerais pesados presentes. Outros rios importantes que contribuem para a contaminação s3ao: O rio Antequera, com 57% Zn, 32.9% Cd e 0.66% Pb, e o rio Huanuni com 61,2% Cd, 2.23% Pb e 34,3% Zn. A fundição de Vinto, a mina Kori Kollo e principalmente a mina San José contaminam o Lago Poopó com arsênico e chumbo através do rio Desaguadero. As minas Bolívar e Huanuni contaminam o lago com cádmio e zinco através dos rios Antequera e Huanuni.

Palavras chave: Lago, mine ria, ambiente, contaminação, minerais pesados, sólidos em suspensão, sólidos dissolvidos.

1. Introduction

The environmental hazards of natural systems by toxic metals is a global environmental of increasing significance (Plant, J., et al, 2001). Chemical data related to environmental studies of mine water and water draining in mining areas typically show extremely high values (Navarro Torres V.F., et al, 2005).

Environmental effects of past and actual mining activities are a potentially important source of toxic elements (e.g., As, Ba, Cd, Cu, Pb and Zn) and could have significant impacts on the surrounding environment. The mineralogical composition of the rocks and ores is the main factor in the development of environmental pollution (Barie Jhonson D, et al, 2005, Piatak N.M., 2004).

The toxic elements originating from abandoned mines can be dispersed due to mechanical and chemical weathering of mining wastes. Resolution of background concentration is especially important in highly mineralized areas, because natural weathering of metallic-ore deposits and weathering of metal-rich rocks are the primary sources of surface- and groundwater contamination (Carrillo Chavez A. et al, 2003). Numerous studies have been undertaken on metal contamination of sediments, soils, waters and plants that have occurred as a result of mining activities in various regions (Jung M.C. et al, 2004).

To date, few research works have investigated the environmental heritage associated with industrialization in the South American Andes. Example, the historic environmental pollution by mining activities of de Chipian Lake (figure 1), located near the Cerro de Pasco metallurgical region and Pirhuacocha Lake (figure 2), located near the Morococha mining region and the La Oroya smelting complex.

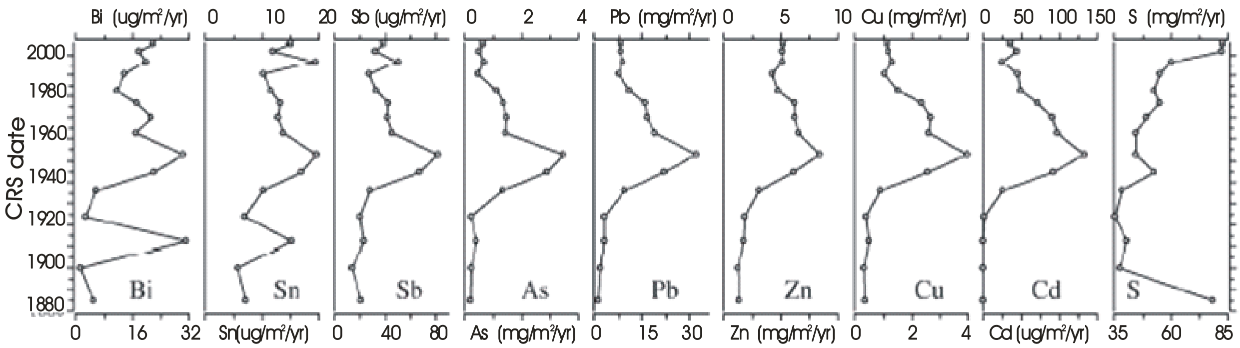

Figure 1. Historical environmental pollution by mining activities of Peruvian Chipian lake (Cooke, C.A., et al, 2008).

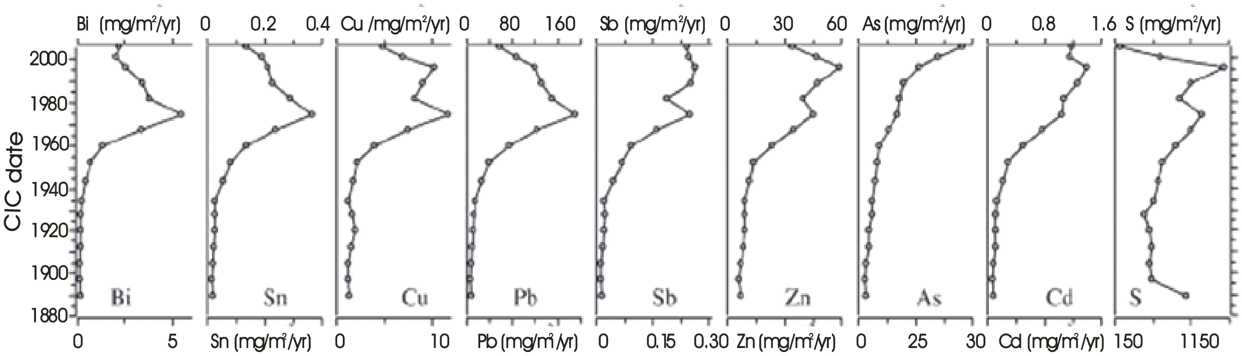

Figure 2. Historical environmental pollution by mining activities of Peruvian Piruacocha Lake (Cooke, C.A., et al, 2008).

Other example is environmental impact by surrounding mining operations of Titicaca Peruvian Lake, near of Poopó Bolivian Lake (figure 3). According to a scientific study carried out by Peru's Ocean Institute, or Imarpe, proteins and mercury have been detected in the lake's fish. Although the quantities have yet to exceed the 0.3 mg/kg limits set by the Environmental Protection Agency - EPA, mercury even in small quantities affects people's health.

Besides receiving sewage and industrial waste from the city of Puno, Lake Titicaca receives agricultural run-offs from the surrounding areas and tailings from mineral processing plants and the regions more than 30,000 informal miners. During the dry season, the Katari, Ramis, Seco, Seque, Pallina and Jalaqueri rivers deposit solids and metal contaminants (Peruvian Times, May 20, 2009).

Poopó Lake, purpose of the present paper, is located on the Bolivian altiplano and in the Oruro mining region, is located in 18º48´27"S, 67º02´12"W and 3,686 m of altitude, have 2,378 km^2 of the water surface.

The Poopó Lake is part of the Titicaca Basin and the closed hydrological system of approximately 144,000 Km^2 located between 3,600 and 4,500 m of altitude (table 1).

Within that system lie four major basins: Lake Titicaca, Desaguadero River, Lake Poopó and Coipasa Salt Lake, called TDPC system (figure 3). Desaguadero River is Titicaca's only outlet and flows into Lake Poopó, the overflow from which in turn gives rise to Coipasa Salt Lake. For these four basins, Lake Titicaca, is the largest in South America, the highest navigable lake in the world, and, according to Inca cosmology, the origin of human life.

Table 1. Sub basins of Titicaca Lake basin (ALT, http://www.unesco.org/water/)

Basin		Lake	
Sub basin	Area (Km^2)	Average	Area (Km^2)
Titicaca lake (T)	56,300	Altitude 3,810m	8,400
Desaguadero river (D)	29,800	Flow 70 m^3/s	Length 398 Km
Poopó lake (P)	24,800	Altitude 3,686m	3,191
Coipasa Salt Lake (C)	33,000	Altitude 3,657m	2,225
TDPC system	143900		

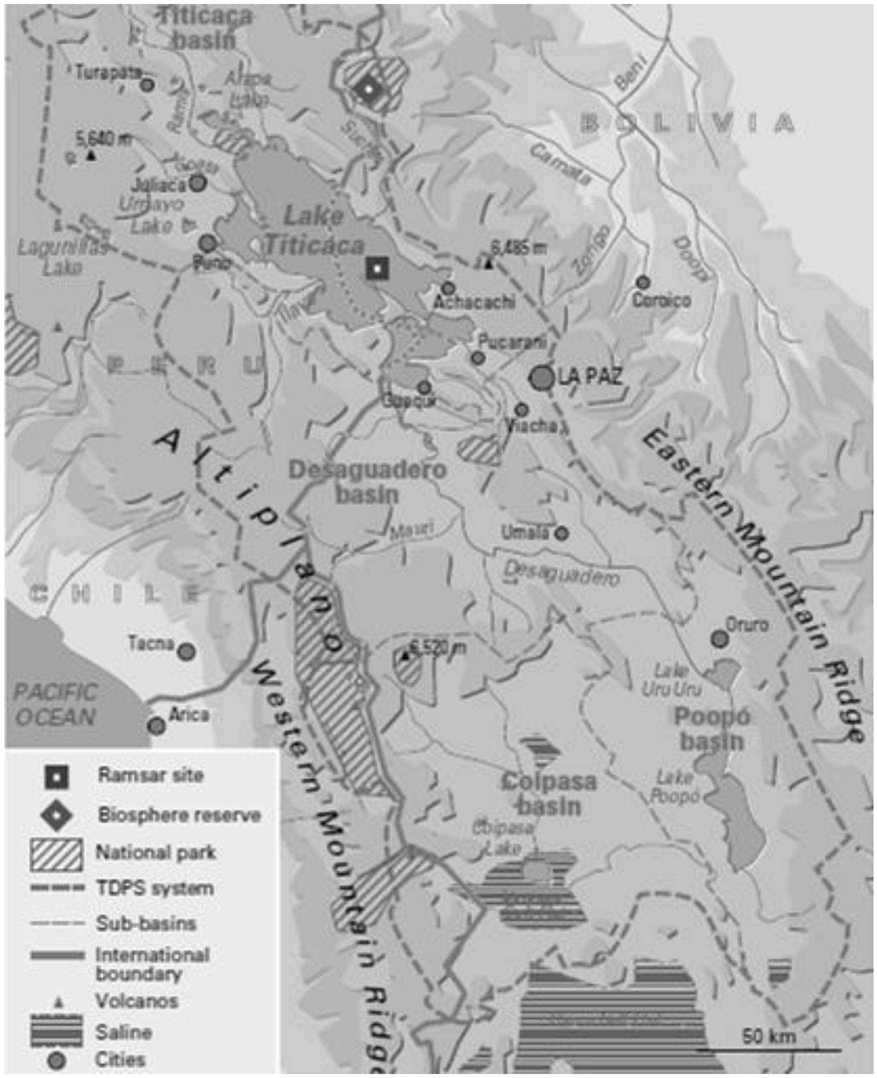

Figure 3. Poopó Lake basin within part of major Titicaca Lake basins (ALT, http://www.unesco.org/water/)

2. Mathematical models

For the Lake superficial hydric balance can be used the following simple mathematic model:

$$Q + P = E_v + E_t + L \qquad (1)$$

where: Q is the river contribution, P is pluvial contribution in lake influenced area, E_v is lake evaporation, E_t is evapotrans-piration and L is water flow loses.

For determination of heavy metal concentration in river water flow will be apply the following model:

$$C_{mn} = \frac{C_p.Q_p + C_1.Q_1 + C_2.Q_2 + ... + C_n.Q_n}{Q_p + Q_1 + Q_2 + ... + Q_n} \qquad (2)$$

where, C_{mn} is heavy metal concentration after tributary river n, C_p is concentration of heavy metal in principal receptor river, C_1, C_2, ..., C_n are heavy metal concentration of 1, 2, …., n tributary rivers, Q_p is water flow of principal river, Q_1, Q_2, ..., Q_n are water flow are 1, 2, …, n tributary rivers. In equation (2) the heavy metal concentration will be expressed in mg/l or ppm/l and the rivers water flows in l/s.

For total heavy metal or solids contributed to Lake environmental pollution, M_c, expressed in kg/day, for each river calculated using the equation (3) based in heavy metal or solid concentration, C_r, expressed in mg/l and river water flow, Q_r, expressed in l/s, where r is number of each correspond tributary river.

$$M_c = 0.0864 \sum_1^r C_r.Q_r \qquad (3)$$

The chemistry of acid mine drainage is based in oxidation of pyrites, the production of ferrous ions and subsequently ferric ions, is very complex, and this complexity has considerably inhibited the design of effective treatment options.

Although a host of chemical processes contribute to acid mine drainage, pyrite oxidation is by far the greatest contributor (Navarro Torres V.F., et al, 2005; Blodau, C., 2006). A general equation for this process is:

$$2FeS_2(s) + 7O_2(g) + 2H_2O(l) \rightarrow 2Fe^{2+}(aq) + 4SO_4^{2-}(aq) + 4H^+(aq) \quad (4)$$

The oxidation of the sulfide to sulfate solubilizes the ferrous iron (iron II), which is subsequently oxidized to ferric iron (iron III):

$$4Fe^{2+}(aq) + O_2(g) + 4H^+(aq) \rightarrow 4Fe^{3+}(aq) + 2H_2O(l) \quad (5)$$

Either of these reactions can occur spontaneously or can be catalyzed by microorganisms that derive energy from the oxidation reaction. The ferric irons produced can also oxidize additional pyrite and oxidize into ferrous ions:

$$FeS_2(s) + 14Fe^{3+}(aq) + 8H_2O(l) \rightarrow 15Fe^{2+}(aq) + 2SO_4^{2-}(aq) + 16H^+(aq) \quad (6)$$

The net effect of these reactions is to release H^+, which lowers the pH and maintains the solubility of the ferric ion (Zinck, J. M. et al, 2000).

3. Poopó Lake, river affluent and mining activities

3.1. General information

Historically Poopó Lake was a huge salt water Lake, geologically, to the superior Pleistocene age, when several glacier faces happened, which determined a progressive reduction of the Lake surface that at the beginnings of the Pleistocene was leveled about of 200 m, above the current level.

The Poopó Lake, with a 3,191 Km^2 surface, is defined as the drainage area of the Desaguadero River (downstream Chuquiña). The Poopó sub river basin is considered closed because the Lacajahuira riverbed that takes the waters from the Poopó Lake to the Coipasa Salt Flat only flows occa-sionally.

The annual average temperatures vary between 7.6 ^oC and 10.7 °C, and low values reaches between -9 ^oC y -10 ^oC and high values between 20 ^oC y 23 ^oC.

The average precipitations decrease progressively from 450mm in the northern lake and 200 mm in the southern (December to March). The evaporations in the Titicaca Lake and in the southern TDPS system area are of 1,450 mm and 1,900 mm, while the evapotranspiration vary between 1,000 mm and 1,500 mm, respectively.

The water depth of the Poopó Lake doesn´t high, it descends towards the center of the lake, where the profundities are until 2 meters.

3.2. Variation of surface of Poopó Lake

The variation of Poopó Lake area can be perceived by contrasting the satellite images which were taken in April 1990 and July 2001, see figure 4.

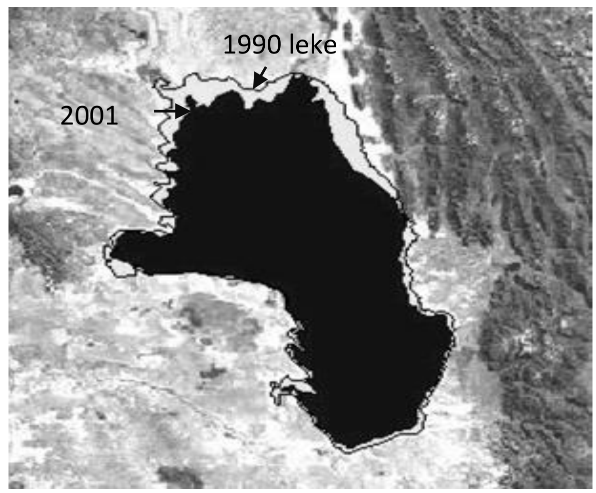

Figure 4. Variation of the Poopó Lake area after 11 years (Zamora E. G., 2010).

The comparison of the satellite images shows the considerable decrease of the Poopó Lake area after 11 years. The water surface area in 1990 was 2,797.15 km^2 and in 2001 was 2,378.07 km^2; these results show that reduction of Lake area in 419.08 km^2 at average rate of 38.1 km^2/year. The summary of the hydric balance is represented in the table 2.

Table 2. Summary hydric balance of Poopó basin.

Hydric parameters	Period estimation 1990 - 2004	Aprox. Area (km^2)	Average flow (10^6 m^3/year)
Precipitation	373.2 mm	22,301.43	8,322.89
Lake evaporation	1,793,71 mm	2,587.61	4,641.42
Evapotranspiration Coef$_{eic}$ = 20	310 mm	19,713.82	6,111.28
Flow of the inflows	92.885 m^3/s		2,929.22

Applied equation (1) using the hydric balance values (table 2) the water flow loses in Poopó lake result 499.41x10^6 m^3.

3.3. Mining activities surrounding Poopó basin and tributary rivers

Mining activities surrounding Poopó Lake have been going on since the pre-Colombian times. The mines are located along the north-eastern side of the Poopó basin, in the Eastern Cordillera.

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The most important mines in Poopó basin are Bolivar and Huanuni. Bolivar underground mine is zinc, silver and lead producer and the ore deposits discovered in the early 19th century. Huanuni mine production started in the early 20th century, with average production 6,000 tons/year of tin concentrate. It is owned by a Swiss company called Sinchi Wayra and is situated in the Antequera basin, together with the Totoral and Avicaya mines.

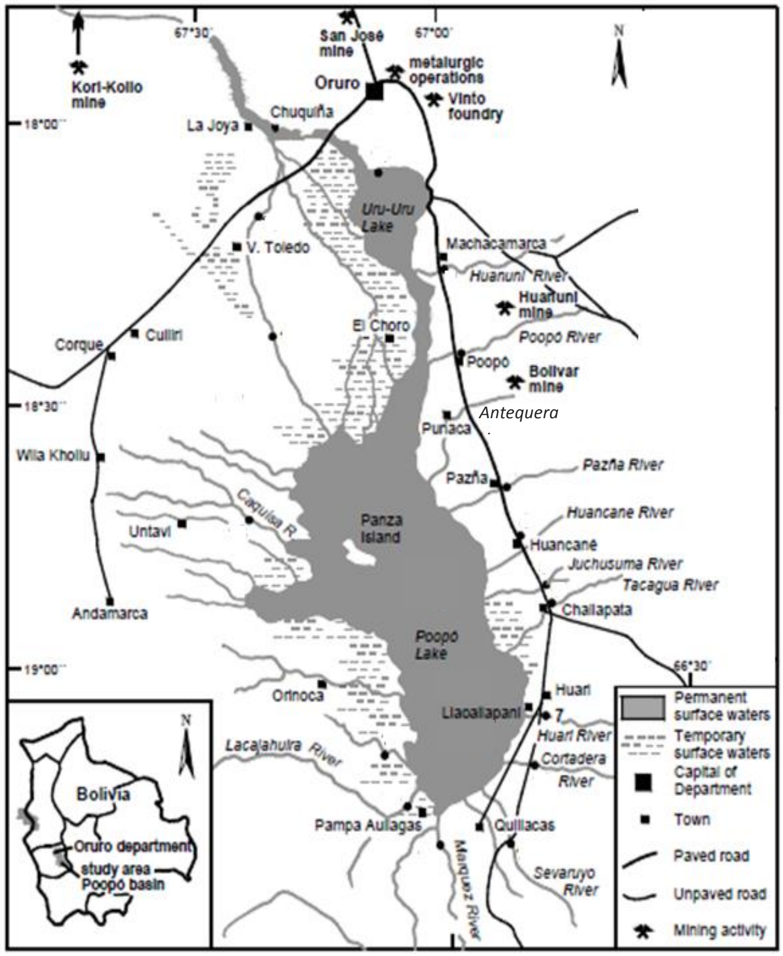

Figure. 5. Poopó Lake, rivers and surrounding past and present mining activities (Garcia M.E. et al, 2005)

Another underground mine is San José mine, situated in north of the Poopó Lake, has been extracting lead, silver, antimony, copper and tin minerals for many years. The San José mine is inactive since 1992, though illegal extraction is still going on.

In addition to mines, there is also a major group of foundries in the Poopó region, called Vinto foundry, situated in the north east of the basin.

The main tributary rivers of Poopó Lake are Desaguadero, Márquez, Cortadera Tacagua, Juchusuma, Antequera (Pazña), Termas Pazña, Poopó, Huanuni and Tajarita (figure 5).

4. Monitoring and assessment method

The monitoring of the Poopó Lake and its tributary rivers was made in four different climatic seasons: wet, semi wet, dry and semi dry. In each sampling points (figure 5), water and sediments samples were taken.

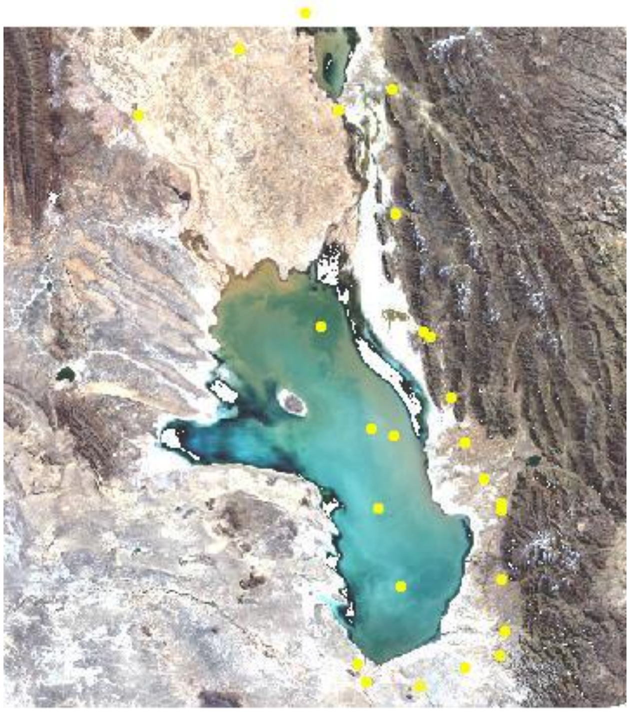

Figure 5. Sampling points satellite location in the Poopó Lake and its tributary rivers.

5. Monitoring, physical and chemical analysis results

5.1 Physical and chemical water quality of Poopó Lake

The physical and chemical water quality of Poopó Lake (Fig. 6, Fig. 7) results obtained based in four samples obtained in dry, wet, semi-dry and wet season's shows that the heavy metal, pH, conductivity, dissolved and suspended solids and other components are approximately similar in LPO-AG-2-1, LPO-AG-2-2 and LPO-AG-2-3 sample points and slightly higher in LPO-AG-2-5 sample point.

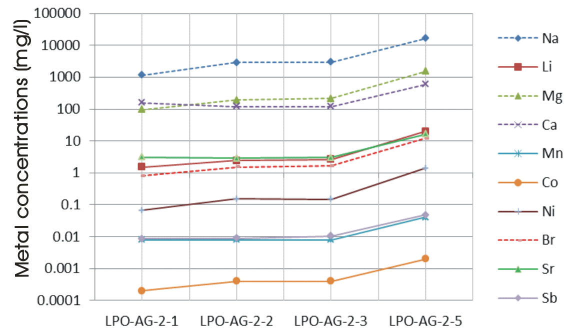

Figure 6. Heavy metals in the Poopo Lake water samples in the Dry Season.

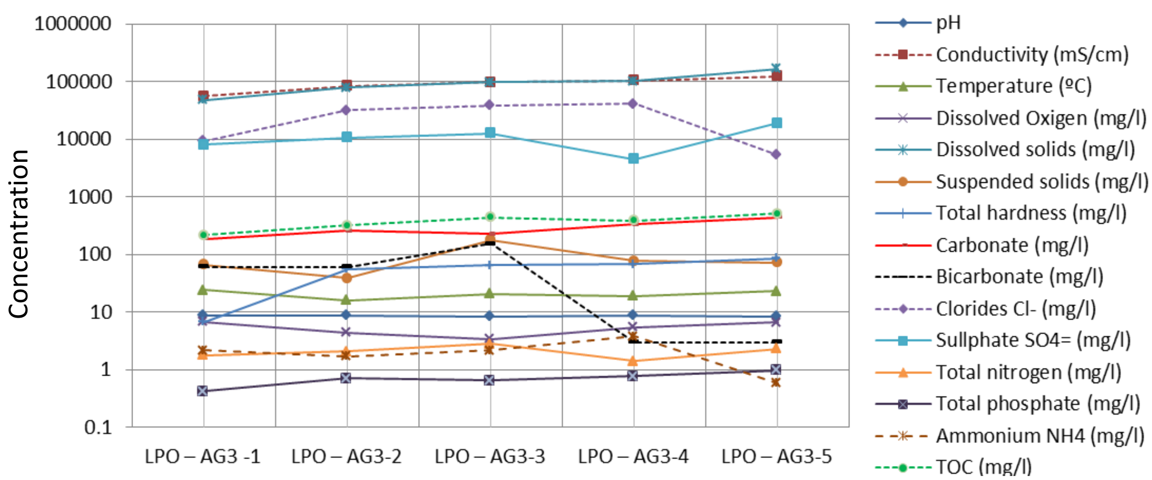

Figure 7. Complementary Analysis results of the Poopó Lake water samples

The Poopó Lake water polluted by Na, Ni, Mg, Dissolved solids, suspended solids, Chlorides Cl^- and Sulphate $SO4^=$ because they are highest of Bolivian permissible values and less polluted by Li, Sb, Ca and Cr because occasionally highest the permissible value (table 3), but the pH is high and lake water is no acid.

Table 3. Heavy metals highest Bolivian permissible value in Poopó Lake.

Metals	Samples
Na, Ni	All
Li, Sb	LPO-AG-2-3 and LPO-AG-2-5
Mg	LPO-AG-2-2, LPO-AG-2-3 and LPO-AG-2-5
Ca, Cr	LPO-AG-2-5
Dissolved and suspended solids	All
Chlorides Cl^-, Sulphate $SO4^=$	All

a. Physical and chemical water quality of the tributary river of Poopo Lake

The heavy metals concentrations in tributary thirteen rivers of Poopó Lake (figure 8 and figure 9) results obtained based in samples in dry, wet, semi-dry and wet seasons shows that the heavy metals concentration in Desaguadero and Tajarita rivers (RD1-AG-2-1, RD2-AD-2-1 and STJ-AG-2-1) mainly are slightly lower compared with other rivers.

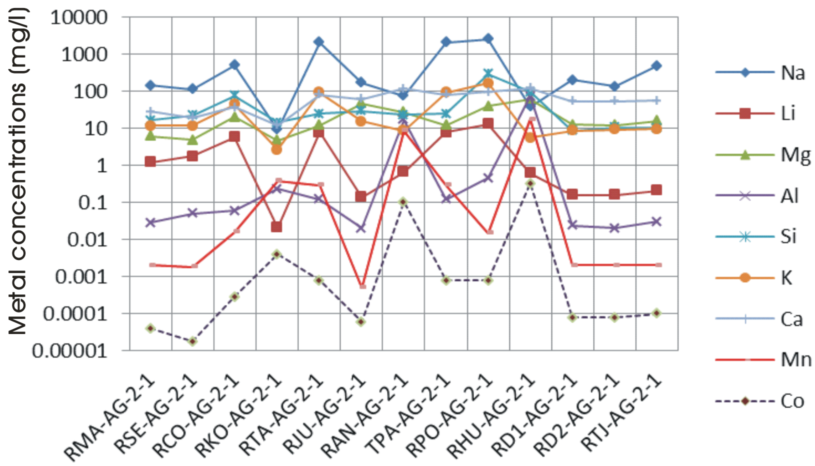

Figure 8. Heavy metals(Na, Li, Mg, Al, Si, K, Ca, Mn and Co) through ICP – MS of the waters of the Poopó Lake tributary rivers.

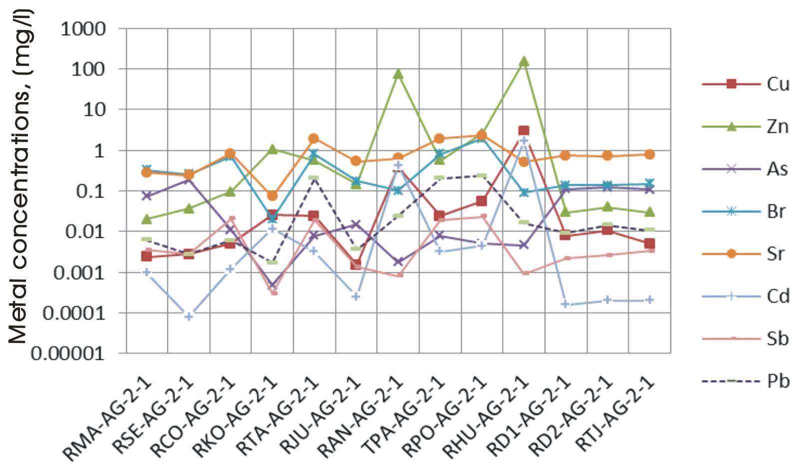

Figure 9. Heavy metals (Cu, Zn, As, Br, Sr, Cd, Sb and Pb) through ICP – MS of the waters of the Poopó Lake tributary rivers.

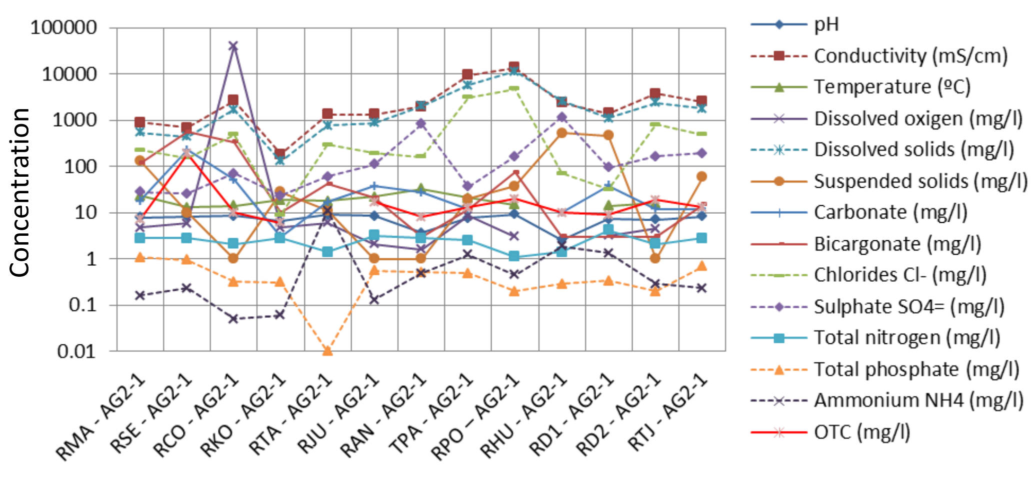

Figure 10. Physical and chemical Analysis of the tributary rivers of the Poopó Lake

The pH, conductivity, dissolved and suspended solids and other concentrations in tributary thirteen rivers of Poopó Lake (figure 10) results obtained based in samples obtained in dry, wet, semi-dry and wet season's shows are variable.

In figures and tables of this paper used following codes: RMA, Márquez river; RSE, Sevaruyo river; RCO, Cortadera river; RTA, Tacagua river; RJU, Juchusuma river; RAN, Antequera (Pazña) river; TPA, Termas Pazña river; RPO, Poopó river; RHU, Huanuni (Machacamarca Bridge) river ; RD1: Desaguadero (Karasilla Bridge) river; RD2, Desaguadero (Aroma Bridge) river; RTJ, Tajarita (Español Bridge) river.

Huanuni river is most polluted because six heavy metals are highest permissible values (Al, Mn, Cd, Ni and Cu). In the next place Poopó river polluted by five metals (Na, Li, Zn, S bans Pb), thereupon Antequera river polluted by four heavy metals (Al, Mn, Cd and Zn) and then Cortadera, Termas Pazña and Tajarita rivers are polluted by three metals (Na, Li, As, Zn or Pb). Finally, Tacagua river polluted by two metals (Na and Zn), Márquez, Sevaruyo and Desaguadero rivers only by one metal (As) and the Juchusuma river no polluted (Table 4). All river water present pH high values except Antequera river where the water is acid.

Table 4. Heavy metals highest Bolivian permissible value in tributary rivers.

Metals	Rivers											
	RMA	RSE	RCO	RTA	RJU	RAN	TPA	RPO	RHU	RD1	RD2	RTJ
Na			x	x			x	x				x
Li			x				x	x				
Al, Mn, Cd						x			x			
Ni, Cu									x			
Zn			x	x		x	x	x	x			
As	x	x								x	x	x
Sb								x				
Pb								x				x
pH						x						

Applied equations (2) and (3), daily total thirteen tributary rivers contribution to the Poopó Lake is following: 3,358,307.520 kg of suspended solids, 2,215,448.690 kg of chlorides, 3,969.490 kg of zinc, 821,848 kg of arsenic, 39.945 kg of cadmium and 73.052 kg of lead (table 3).

The Desaguadero 1 River (Karasilla Bridge) contributes a 70% of As, 64 % of Pb, 4.27 % of Zn, and 2.18 % of Cd; on the other hand, the Huanuni River contributes with 61.23 % of Cd, 34.33 % of Zn and 2.23 % of Pb. The Antequera River contributes a 56.92 % of Zn, 32.92 % of Cd, and 0.66 % of Pb. The Desaguadero 2 River (Aroma Bridge) contributes a 17.7 % of As, 17.97 % of Pb, 1.90 % of Cd, and 1.09 % of Zn (table 4).

Table 5. Tributary rivers contribution of heavy metals, suspended solid and chlorides to the Poopó Lake.

Tributary rivers	Heavy metal, suspended solids and chlorides (kg/day)					
	Susp. solids	Chlorides	Zn	As	Cd	Pb
Marquez	2,002.000	5,824.000	3.300	1.910	0.020	0.270
Cortadera	55.820	4,142.000	0.710	0.220	0.005	0.112
Pazña termal water	5.580	2,307.000	0.240	0.003	0.001	0.070
Desaguadero 2	397,225.000	196,615.000	43.320	92.160	0.760	13.130
Desaguadero 1	2,847,548.000	1,642,863.000	169.450	578.140	0.870	47.070
Huanuni	15,557.000	5,390.000	1,363.000	0.124	24.460	1.630
Poopó	214.000	17,363.000	4.820	0.070	0.024	0.422
Tajarita	94,463.000	326,764.000	109.690	141.420	0.500	9.620
Antequera	161.800	8,000.000	2,260.000	0.045	13.150	0.480
Juchsumar	14.340	851.300	0.330	0.070	0.001	0.025
Tacagua	2.980	214.800	0.220	0.010	0.000	0.003
Kondo	356.000	114.590	13.370	0.006	0.150	0.020
Sevaruyo	702.000	5,000.000	1.040	7.670	0.004	0.200
Total Poopó Lake	335,8307.520	2,215,448.690	3969.490	821.848	39.945	73.052

Table 6. Percentage tributary rivers ccontributions of heavy metals, suspended solid and chlorides to the Poopó Lake.

Tributary River	Susp. solids	Zn	As	Cd	Pb
Desaguadero 1	84.79	56.92	70.36	61.23	64.44
Desaguadero 2	11.83	34.33	17.21	32.92	17.97
Tajarita	2.81	4.27	11.22	2.18	13.17
Huanuni	0.46	2.76	0.23	1.90	2.23
Others	0.11	1.09	0.03	1.77	0.66
Total	100.00	100.00	100.00	100.00	100.00

The results shows that the heavy metals, suspended solid and chlorides contributor to the Poopó Lake is Desaguadero river.

4.3. Physical and chemical Analysis of sediment in Poopó Lake and tributary rivers

The heavy metals in sediments of Poopó Lake (figure 11) obtained based in four samples are variable. As, Cd, Pb, As and Zn are highest Bolivian permissible values in sediments of Poopó Lake (table 5), this result indicates that the lake sediments are polluted by these metals.

Chemical analysis results of sediment samples collected in tributary rivers compared with Bolivian standard show that Antequera, Huanuni and Tajarita rivers are polluted for five metals (Cu, Zn, As, Cd, Pb), Juchusuma, Poopó and Desaguadero for three metals (As, Cd, Pb), Márquez, Sevaruyo and Cortadera rivers for two metlas (As, Pb or Cd) and Tacagua and Kondo River (RKO) polluted for only As (table 6).

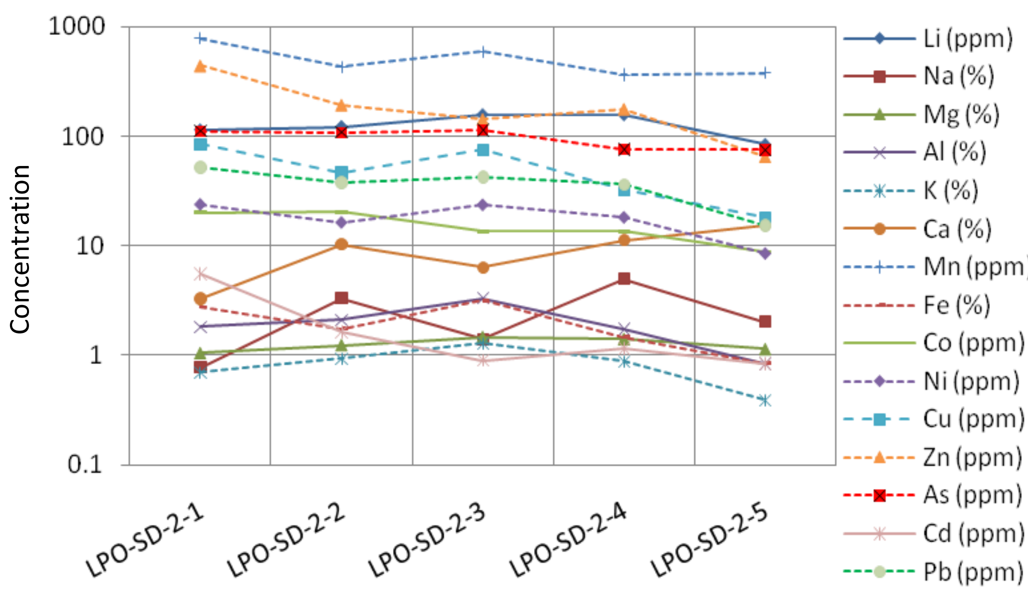

Figure 11. Heavy metals in Poopo Lake sediments

Table 7. Heavy metals highest Bolivian permissible value in Poopó Lake sediments

Metals	Samples				
	LPO-SD-2-1	LPO-SD-2-2	LPO-SD-2-3	LPO-SD-2-4	LPO-SD-2-5
Mn	x				
Cu, Zn	x	x	x	x	
As, Cd, Pb	x	x	x	x	x

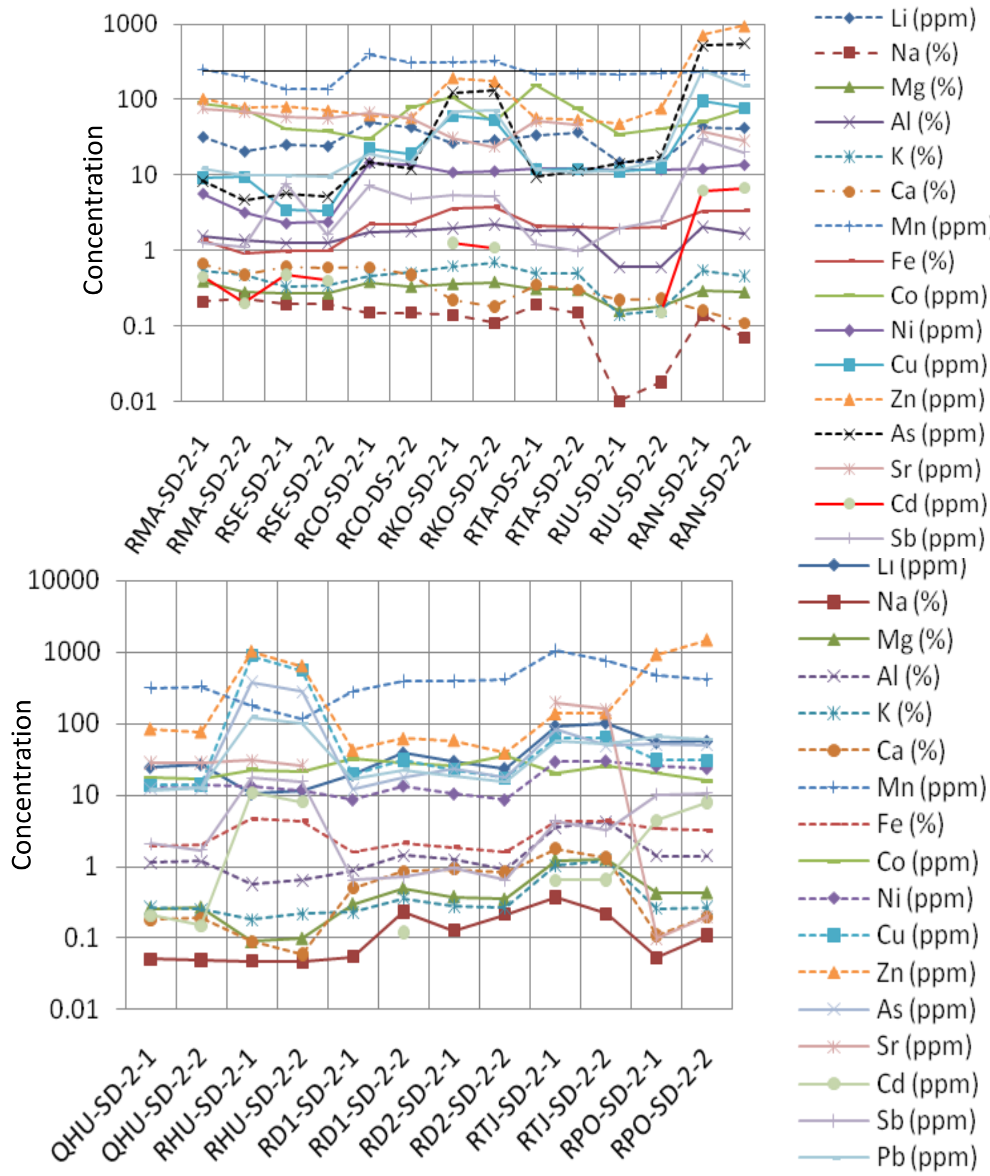

Figure 12. Heavy metals in the tributary rivers sediments.

Table 8. Heavy metals highest Bolivian permissible value in tributary rivers

Metals	Rivers											
	RMA	RSE	RCO	RTA	RJU	RAN	RKO	RPO	RHU	RD1	RD2	RTJ
Cu, Zn						x		x	x			x
As	x	x	x	x	x	x	x	x	x	x	x	x
Cd	x	x			x	x		x	x	x	x	
Pb			x		x	x			x	x	x	x
Mn												x

6. Discussion

Poopó lake pollution due to mining activities can be characterized correlating the principal metals production and associate heavy metals in surrounding mines, mines adjacent river pollution by heavy metal and solids flowing in o the Poopó Lake and pollution situation of this lake.

Trough Desaguadero river, Poopó Lake polluted with 64% of lead, 70% of arsenic, 4.27% de zinc and 2.18% of cadmium. Correlated with principal metals production of adjacent mines, San José mine is higher polluted by lead and on the other hand Vinto foundry and Kori Kollo mines contribute for pollution by associate heavy metals arsenic, zinc and cadmium (figure 13).

Trough Antequera river, Poopó Lake polluted with 57% zin, 32.9% cadmium, 0.66% lead and Hununi river with 34.3% zinc, 61.2% cadmium, 2.23% lead. Associated with principal metals production in these mines, they are higher polluted by zinc and cadmium and lead (figure 13). Near Huanuni mine located the Totoral and Avicaya mines.

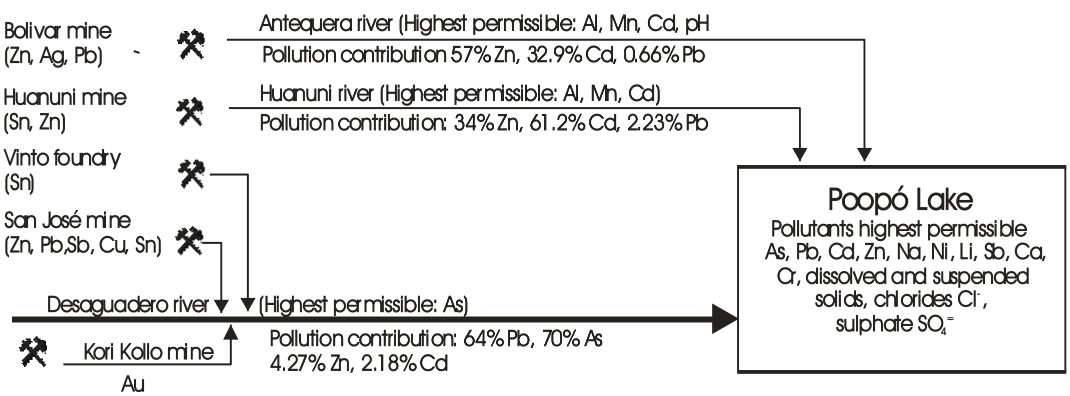

Figure 13. Mining activities and main tributary rivers contributions for Poopó Lake pollution.

Compared mining activities, tributary river pollution contribution and highest permissible metal concentrations with pollutants highest permissible values of Poopó Lake (figure 13), mining activities polluted of Poopó Lake by arsenic, lead, cadmium and zinc. Additionally mining activities will be contributed by dissolved and suspended solids.

Others heavy metals pollutants will be associated to geological and hydrological characteristics of diverse river basins, such as: sodium pollutant is associated to Cortadera, Tacagua, Termas Pazña, Poopó and Tajarita rivers; nickel pollutant comes trough Huanuni river, but will be no related with mining activities; lithium pollutant is linked to Termas Pazña and Poopó river; antimony pollutant related to only Poopó river.

Measure result and analisys used equations (4), (5) and (6), the acidity of Lake Poopó Lake water represents by pH 8.5 to 8.8 and the tributary rivers the pH varies mostly from 6.6 to 8.9 and only Antequera river have low 3.6 of pH. This result indicates that the mining activities acidic only Antequera river by Bolivar mine, but not acidic the lake-Poopó.

Daily charge of the suspended solids and dissolved heavy metals by tributary rivers are 3,358,307.87 Kg suspended solids, 2,215,448.99 kg chlorides, 3,970.49 kg zinc 821.62 kg arsenic, 30.95 kg cadmium and 73.05 kg lead.

In pollution process of Poopó Lake, Desaguadero river contributes with 70% arsenic, 64% lead, 4.27% zinc and 2.18% cadmium, then Antequera river contributes with 57 % zinc, 32.9 % cadmium and 0.66% lead and finally Huanuni river contributes with 61.2% cadmium, 2.23% lead and 34.3% zinc.

7. Conclusions

Poopó Lake water is highly saline, As, Pb, Cd and Zn concentrations are above the permissible limits and suspended and dissolved solids concentrations also above the permissible limits.

Mining activities polluted of Poopó Lake by arsenic, lead, cadmium and zinc. Additionally mining activities will be contributed by dissolved and suspended solids.

Vinto foundry, Kori Kollo and mainly San José mines polluted of Poopó Lake by arsenic and lead trough Desaguadero river.

Bolivar and Huanuni mines polluted of Poopó Lake by cadmium and zinc trough Antequera and Huanuni rivers.

Acid mine drainage no environmental impact of all rivers and Poopó Lake, except Bolivar mine acidic Atequera river.

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