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ON THE DISTRIBUTION OF SALINE GROUNDWATER IN THE POOPÓ BASIN, CENTRAL BOLIVIAN HIGHLAND

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Abstract

Lake Poopó is a terminal lake of the Bolivian Altiplano, with high salinity and heavy anthropogenic pollution from centuries of extensive mining activity. This study aims to describe how the water quality of groundwater and surface water system in different subwater-sheds of the Lake Poopó varies with geology and hydrology. Measurements of total dissolved solids (TDS) in wells show groundwater becoming more saline close to the lake. The results indicate high natural contamination from weathering of minerals with high concentrations of lead and arsenic, generally dry conditions which results in high salinity in water and soil, and most importantly, anthropogenic contamination from the intensive mining and metallurgic activities. Fresh groundwater can be found in the upper part of the soil and bedrock to a small extent. Up-coning and saline water intrusion is very common in the wells, which need to be shallow in order to avoid abstraction of saline groundwater. The groundwater is highly vulnerable and further on contaminated by acid mine drainage from the mining tails and by untreated effluents from the towns and villages of the area.

Key words – Groundwater, salinity, lake Poopó, Bolivia, acid mine tailings, water quality

Introduction

Mining in Bolivia

Bolivia is a country with important mineral resources and has a unique and long mining tradition. In the Poopó basin historical and ongoing mining operations cause the formation of acid wastewaters, loaded with metals coming from mines, mineral residuals (mainly pyrites and arsenopyrites) and closed mines. The mining activities at the Poopó basin have, with time, caused severe disturbances in the ecological system.

As a result a number of animals and plants have disappeared from the area. An important part of the environmental damage can be attributed to the acid mine drainage (AMD), generated from the mining waste of mines either closed or still in operation. These effluents have contaminated the water with lead, arsenic, cadmium

and others, the lakes as well as the groundwater, and have eliminated the flora and aquatic fauna in large parts of the rivers and have degraded the water quality below the standard set by the Bolivian Environmental Regulations.

In addition, the Poopó basin has been subject to an elevated natural heavy metal load due to the weathering of minerals containing high metal concentrations, which is why so many mines have been in operation in the area. Low and chronic exposure to heavy metals causes damages in ecosystems and may even be lethal to some organisms, also humans. Lead, arsenic, cadmium and mercury are the most common toxic and ecotoxic metals. The metals contaminate the water and soil, degrading the chemical quality of the water below the security levels. In humans, lead poisoning may cause neurological damage in children with subsequent reduction in

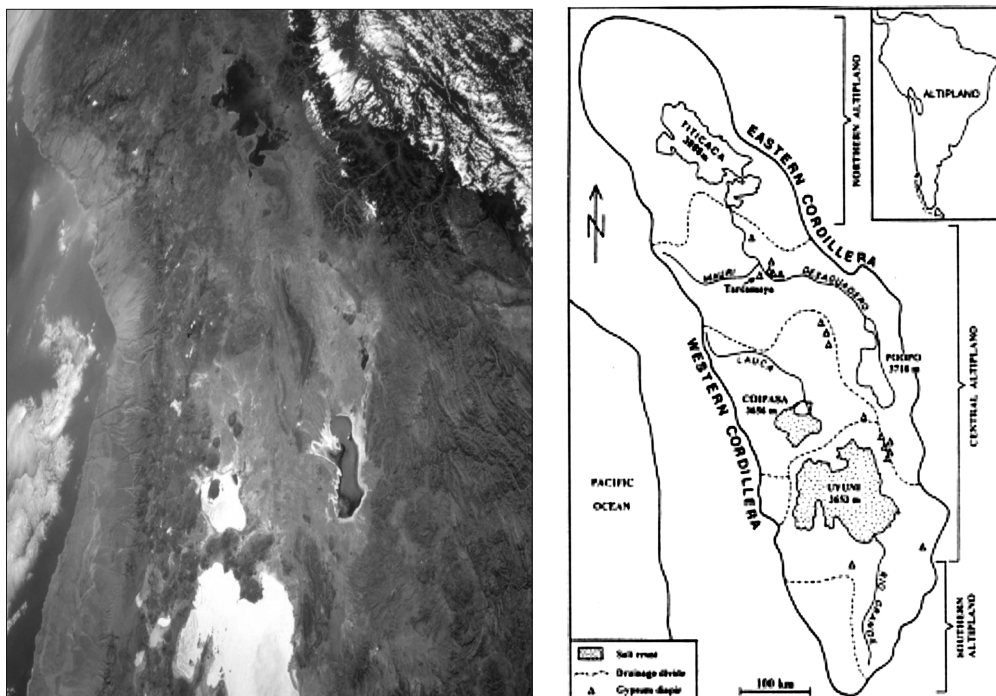


Figure 1. Bolivian map showing the TDPS System, located in the Andean part of Bolivia. (Photo No. STS057-99-65 from NASA, 1993 and Schematic Map of the High Planes showing the TDPS System. (Risacher et al 2000) with transect for Figure 3.

intelligence, loss of short term memory, learning disabilities and problems with coordination. Arsenic exposure causes cardiovascular problems, skin cancer and other skin effects, peripheral neuropathy and kidney damage. Cadmium may accumulate in the kidneys and is implicated in a range of kidney diseases. Mercury exposure causes damage to the nervous system, uncontrollable shaking, muscle wasting, partial blindness, and deformities of fetus.

The geology of Lake Poopo basin

Lake Poopo basin (Figure 1) is located in the center of the Bolivian High Planes which is a plateau lying at altitudes between 3600 and 3900 m above sea level. It is a mountainous basin, surrounded by the Western Range of the Andes on the west, and the Eastern Range on the east. This lake is part of a bigger system, consisting of the basins of Lake Titicaca, Desaguadero River, Lake Poopo, and the salt flats. This system is often abbreviated as TDPS. The Desaguadero River links Lake Titicaca to Lakes Uru Uru and Poopó. The Desaguadero receives water from several tributaries and has a mean annual flow of $89 \text{ m}^3 \text{ s}^{-1}$ before bifurcating to Lake Uru Uru and Lake Poopó (Garcia, 2006). The climate around

Poopo is semi-arid and cold ($8\text{--}10^\circ\text{C}$, annual average). Its rains are typically monomodal, from December to March, and its dry season extends from May to August. From 1950 to 2000, the average annual rainfall has been 364 mm.

The Mountains are of Upper and Lower Silurian sedimentary rocks. The Lower Silurian sedimentary rocks (Ss1) consist predominantly of thick layers of grey-white quartzite deposited in a marine proximal environment. It may have a thickness of up to 250 m and thins out towards east. The Pleistocene to Holocene glacial sediments (PHsg) are made up of sediments deposited in a continental glacial environment and includes glacial, fluvioglacial, and colluvioglacial deposits. The deposits are products of the erosion during the latest glacial period. The Pleistocene to Holocene lacustrine and fluvial deposits (PHsL) were deposited in a lacustrine to fluvial and evaporitic continental setting. The Holocene alluvial and colluvial sediments (Hsa) consists of material deposited in a continental environment and includes alluvial fans, colluvial, fluvial and terrace deposits made up principally of gravel, sand, silt and clay (Troëng & Riera 1996). Lake Poopo is very shallow and has depths ranging from 0.5 to 2.5m with a surface area that is very variable. Aside from the lake, the central and western

parts of this basin are composed of fluvial-lake plateaus and terraces, with areas of eolic deposits, which lower the water speed.

These plateaus, and specially their lower parts, are prone to periodical and variable flooding during the rainy season. Due to the water scarcity, the social situation on Altiplano is marked by poverty. The water quality is fairly good in the uppermost part of the basin while there are many problems with pollution due to mining activity further downstream. Several different deposits are present: tin, wolfram, bismuth, zinc, lead, silver, copper, antimony and gold mines are located along the Eastern and Western Ranges of the Andes. Downstream the Lake Poopó, deposits related to alkaline lakes and salt flats, especially salt, brine, and boron, are present. The most common salt present is sodium chloride. The salt flats made of clay and salt contain high concentrations of lithium, potassium, boron, magnesium, and sodium. All these minerals are extracted by several mines in the region. Surface waters, especially from the main river Desaguadero, are used in the extraction of minerals. Residues and acid-pH, sulfur-rich washings are released directly back into the water shed.

Research question and methodology

The objective of this study has been to follow the salinity gradient in a part of the Poopo basin as a function of the topography, i.e. to investigate groundwater composition of wells located from the Andes down to the Lake Poopó. Is it be possible to identify a significant difference in water chemistry in the wells according to topography?

Water sampling from eight wells and seven surface waters representing different locations of water in the watersheds of the Rivers Antequera and Urmiri and their joint River Pazna down to Lake Poopo is presented in the paper (for specific locations, see Figure 2). PALP11 is a well located where the River Antequera merges with river Urmiri. North of the River Pazna and also closest to Lake Poopó sampling from a well PALP12, was done. Downstream the River Antequera, between the river and Lake Poopó, water was sampled at different wells situated relatively close to each other; PALP2 and PALP5. PALP 7 and PALP8 are located south of the River Pazna. Close to the River Antequera at the Totoral mine, sampling was done from the well TOSP2. URLT1 is water sample from the thermal spring close to Urmiri. The sample was taken from the spring situated in the hillside. The temperature of this water was significantly higher than the other water samples.

AVLR1 is a sampling point close to the mine Avicaya, situated downstream from Totoral in River Antequera. BOLR2 is the sampling point in the River Antequera

located downstream the Bolivar mine outlet. CHALR1 is an upstream sampling point in River Antequera, situated upstream the mine Bolívar. MASV1 is a sampling point of water discharged from a pipeline into the river Antequera downstream the mine Bolivar, yet the origin of the pipelined water is probably from further uphill the mountains. Women and children in the village were laundering cloth in the water at the time of sampling. PALR2 is the most downstream measuring point in the River Pazna and also closest to Lake Poopó. The landscape surrounding the river is flat and the surroundings are richer in vegetation. The sediments are very fine and sandy and have a whiter color, which may be found on precipitated salts. The river bed consists of fine sediments such as sand. TOSR1 is a sampling point from the River Antequera close to the Totoral mine. The valley opens up a little and the river divides into several branches as it meanders. The surrounding mountain sides are steep. The river bed at this location consists of course material such as stones of different size and also compact fine sand. URLR1 is an upstream sampling point in River Urmiri, situated upstream the thermal spring URLT1. The stream water at this point originates from the mountains and vegetation is abundant around the river. The river bed consists of stones and a concrete construction.

The water sampling was carried out during a field trip in the beginning of March 2008. Basic physical proper-

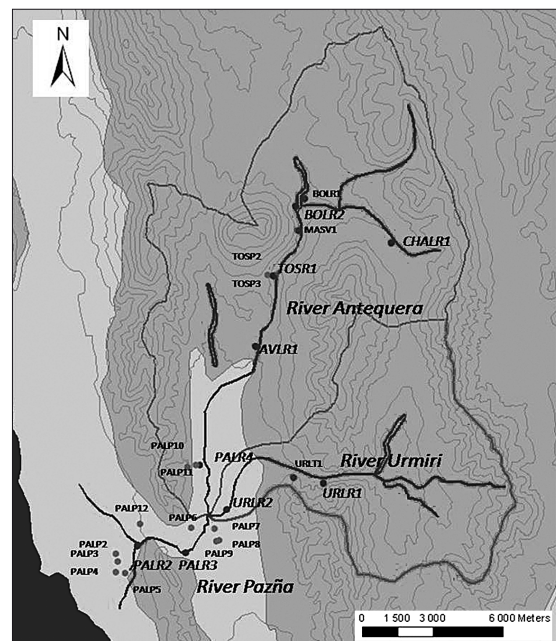


Figure 2. Sampling points in the study area of Central Altiplano.

Table 1. Some water analysis of groundwaters and surface waters of Altiplano. For sampling point locations, see Figure 2.

Sampling point	Ca (mg/l)	Mg + Ca (mg/l)	Na (mg/l)	SO ₄ (mg/l)	NO ₃ (mg/l)	Cl (mg/l)	TDS (mg/l)	pH
<i>WHO guidelines</i>	100–300	< 200	< 200	< 250	< 50	< 250	< 600	6.5–9.5
<i>Ground Water</i>								
PALP11	91	97.2	50	130	710	15	368	8.9
PALP12	190	218	3300	78	760	17	7150	7.4
PALP2	220	238	640	630	620	1000	1843	7.2
PALP5	310	324	770	400	1100	1800	2260	7.5
PALP7	200	240	590	140	1200	14	1788	7.4
PALP8	160	195	640	200	1100	1300	1750	7.4
TOSP2	28	29.4	210	270	72	42	614	6.7
URLT1	110	115.8	1400	31	870	2500	3160	6.7
<i>Surface Water</i>								
AVLR1	270	285	38	1600	16	4.1	1376	2.7
BOLR2	29	37.5	13	1400	33	22	988	2.2
CHALR1	16	19.1	13	43	700	0.8	113	7.6
MASV1	36	39.8	32	76	980	29	195	6.9
PALR2	190	204	79	750	5.3	23	920	3.0
TOSR1	400	416	32	2100	12	20	1359	3.2
URLR1	19	22.2	15	44	1300	15	127	8.1

ties of the water was analyzed in the field and chemical properties were analyzed in the laboratory at the University of San Andrés, La Paz.

Water samples were collected with duplicates, for analyze in the laboratory. The water from the river was sampled using a bucket. The wells were sampled and the sample water was taken from half of the water depth, using a water collector tube; Nansen Wildco, model 1930-D65 0797. In the field pH; electrical conductivity; temperature; total dissolved solids (TDS); and redox potential were measured using a Hach pH-meter. In the field the collected water was filtered through a 45 µm filter before it was poured into polyethylene bottles, two large bottles (volume 150 ml) and two small ones (volume 75 ml) for each sampling location. The further chemical analyses were done in the laboratory at the Chemistry Research Institute, University of San Andrés in La Paz, Bolivia. Most of the analyses were done during four weeks in the middle of March to the middle of April 2008. The samples were stored in a refrigerator before the chemical analyzing started.

The cations calcium, magnesium, sodium and potassium were measured with flame atomic absorption spectrometry, FAAS. The analyses were done using a Perkin Elmer Analyst 100 Atomic Absorption Spectrometer, a high efficiency burner system. Sulfate, nitrate and chloride was measured in a spectrophotometer Thermo Spectronic-vision32 Software V1.24. The alkalinity was determined in the field by titrating 5 ml sample with 0.01 M HCl to pH 4.5.

Results and discussion

Surface waters and groundwaters of the Bolivian Altiplano have generally high salinity, see Table 1. The mineralization and weathering of rocks are important in determining the saline concentrations in the basin, especially when referring to the saline soils, enhanced by evaporation and subsequent mineralization (García, 2006). During the Quaternary the central Altiplano was covered by saline lakes, among them Lake Michin and Lake Ballivián (Orsag, 2002). The basin has always been endorheic.

Thermal springs with high TDS influence the water chemistry with a high ion content, especially for sodium and chloride (1400 mg/l and 2500 mg/l respectively, sampling point URLT1; also well PALP12). Saline groundwater discharges to creeks in the lower parts of

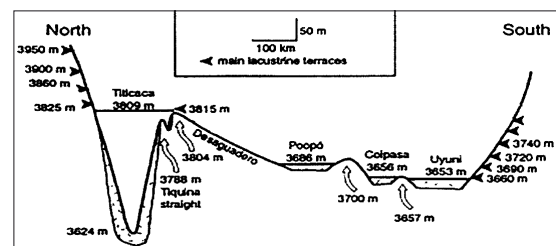


Figure 3. Topographic cross-sections showing physiographic relationships between High Planes lakes and salt flats along transect in Figure 1.

the basin. The flow increase as well as magnesium and calcium concentrations. The groundwater chemistry of the area reveals that lower TDS concentrations in wells located in the upstream part of the basin can be found, at altitudes above 3800 m (PALP11 and TOSP2), but high or very high TDS values in the downstream part (PALP12, PALP5).

Several wells have very high nitrate content and are possibly contaminated by urban wastewater. Wells close to the lake have a high salinity. The sulfate concentration is high in the wells located in the area closest to Lake Poopó. Even though the wells are situated in the same type of geology, there is a distinct difference in sulfate concentrations (Table 1). Acid drainage from the mines and tailings of the region also affects several groundwater wells. Thermal spring waters have high alkalinity and high TDS (URLT1). Lake Poopo waters have an alkaline pH, increasing slightly in the rainy season samples, which coincides with the higher sulfate concentrations in this season. The first strong rain leaches great quantities of material on the land. After a period of time, most of the easily movable pollutants have already been leached and their dilution in water is notorious.

In the river and lake waters of Poopó basin, the highest concentrations of Pb were found in the rainy season, maximum Cd is found in the dry season. In respect to arsenic, in Poopó Lake, the highest As-concentrations correspond to the dry season, whereas in the rivers, which are not affected by mining activities, the highest As-values belong to the rainy season. Evaporation in the dry season can explain the As increase in the dry season for Poopó Lake water, however other As-sinks, as uptake by aquatic plants and microorganisms need to be considered. Dissolution of sulphate- and chloride-salts on the wide banks of the river in the beginning of the rainy season, when a fast increase of the lake water table and corresponding flooding of wide areas occurs, can explain the SO_4^{2-} (and Cl^-) increase in the lake water in the rainy season, which is in contrast to the simultaneous SO_4^{2-} decrease in the river waters.

Conclusions

The water quality of this study area is not suitable for drinking purposes without post-treatment. Due to high nitrate, no groundwater is acceptable as drinking water according to the guideline values of WHO. Only two

wells have a TDS lower than 600 mg/l. Surface waters upstream mines and mining tails have neutral or slightly alkaline pH, but downstream the mines, all surface water turns acidic and the sulphate concentrations increase with one order of magnitude or more. All concentrations of analyzed ions increase significantly in the reach through the mine district due to extensive weathering. Further south a tributary is connecting and this result in dilution. As the river approaches the low land all ion concentrations increase which indicates intrusion of shallow ground water. Sodium and chloride increase toward the saline Lake Poopó. Measurements of total dissolved solids (TDS) in wells show that groundwater becomes more saline close to the lake.

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