Working Paper

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Water risk and its management in

Bolivia's Altiplano development strategy

# The water chemistry and chemical status of sites in Sora Sora, Poopó, Antequera, Urmiri and Pazña, 2013 - 2014


Megan French

*Institute for Risk and Disaster Reduction*

*University College London*

In collaboration with:

Stephen J Edwards (UCL)

Karen A Hudson-Edwards (Birkbeck)

Jorge E Quintanilla (CEEDI)

Natalie Alem (CENDA)



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**Glossary of terms used:**

**AMD**: Acid mine drainage.

**Class 'A'** is the highest water quality classification for receiving water's and is considered potable water without treatment other than bacterial disinfection (refer to Table 1a for criteria).

**Class 'B' and 'C'** classify water for general use that requires physical (and chemical for C) treatment and bacterial disinfection for human consumption.

**Class 'D'** classifies water of minimum quality.

**DO**: dissolved oxygen (mg/L or % saturation).

**EC:** Electrical conductivity; is a measure of the capacity of water to conduct electrical current and is directly related to the concentration of dissolved salts. Generally, recommended drinking water EC <0.9 dS/m and at maximum 1.5 dS/m (i.e., <600 ppm TDS and maximum 1000 ppm TDS as recommend by the WHO (2011a) for taste and palatability). EC >2.5 dS/m is not recommended for consumption and that with >10 dS/m is considered not for consumption.

**FAO**: Food and Agriculture Organization (United Nations) (refer to Table 1a,b for irrigation and livestock recommendations).

**pH**: is a measurement of the acidity or basicity of water (in this report). The pH scale is 0 – 14 with a pH below 7 considered acidic, 7 neutral and above 7 basic or alkaline.

**HQ**: Hazard Quotient = the ratio of an element concentration / 'A' criteria. Where HQ>1 indicates exceedance. Note: Bolivian 'A' criteria for As, Cd, Mn and Pb are greater than WHO guidelines (all health based except Mn; refer to notes in Table 1a), however detection limits for As and Pb are above the provisional WHO guidelines. Whereas 'A' criteria for B, Cu, Ni and Sb are lower than WHO guidelines, thus these elements HQ would rank lower if with respect to WHO guidelines (refer to Table 1a and associated notes).

**SAR**: Sodium Adsorption Ratio; defines sodicity in terms of the relative concentration of sodium (Na) compared to the sum of calcium (Ca) and magnesium (Mg) ions (refer to Table 1b). The SAR assesses the potential for infiltration problems due to a sodium imbalance in irrigation water. $SAR = [Na\ meq/l]/(\{[Ca\ meq/l]+[Mg\ meq/l]\}/2\})^{1/2}$

**TDS**: total dissolved solids.

**WHO**: World Health Organization (refer to Table 1a for guidelines).

**WQR**: Water Quality Rating (see Table 2 for qualitative description).

## 1. INTRODUCTION

The municipalities of Poopó, Antequera and Pazña on the central eastern margin of the Lake Poopó Basin were identified in June 2012 as the foci for the University College London (UCL)-Birkbeck College-Catholic Agency for Overseas Development (CAFOD)-Centro de Comunicación y Desarrollo Andino (CENDA)-Instituto de Investigaciones Químicas, Universidad Mayor de San Andres (IIQ UMSA) water risk project. The main rivers in the Poopó municipality are the Poopó River, which flows through Poopó Village, and the Uma Purwa Ravine that flows from the Callipampa area. Both drain into Lake Poopó. The main river in the Antequera municipality is the headwaters of the Antequera River, which flows south-west into to the municipality of Pazña where the river confluences with the Urmiri River prior to becoming the Pazña River near Pazña Village (Figure 1).

Chemical water quality (and some quantity) and social data were collected over the period August 2013 – July 2014[*] to try and assess water risk by quantifying and qualifying water hazard and social vulnerability in these communities (refer to CENDA, 2014, for social vulnerability study). These new data have been used in conjunction with previously collected water quality data from the same sites sampled during the Catchment Management and Mining Impacts in Arid and Semi-arid South America (CAMINAR, 2013) project (June 2007 – May 2009). Aims include i) making recommendations for certain restrictions on water sources for human and livestock consumption and for irrigation purposes, ii) highlighting favourable water sources, and iii) suggesting possibilities for dealing with various water problems.

Water quality refers to water's physical (appearance, taste etc.), chemical (salts, nutrients, industrial chemicals etc.) and biological (micro-organisms etc.) characteristics. We focus here on chemical assessment of elements derived from natural geology and mining activity and some physical aspects. We have not analysed agricultural chemicals (herbicide, pesticides etc.) as these are not understood to be used in the study area (Ekdahl, 2007), nor petroleum- and industrially-derived chemicals (solvents, plastic related etc.), water treatment chemicals (chlorination by products etc.), organic material (humics, faecal etc.) or microbial contaminates (waterborne pathogens such as *legionella*, *cryptosporidium* etc.). Table 1a gives the full suite of chemical elements and parameters analysed in this study and guideline values.

Chemical data from 2013 – 2014[*] for 45 surface water and groundwater sites (shown in Figure 1, methods in Section 3) are discussed in this report (Sections 4 - 6) in comparison to previous CAMINAR data. We discuss information by providing i) a brief site description including quantity information where available, ii) a description of each sites general chemical water quality status with reference to a) World Health Organization (WHO) guidelines for drinking water quality (2011a) (with emphasis made to elements with a health-

[*] Water quality and quantity sampling undertaken: August 13-16th 2013, December 16-20th 2013, April 7-12th 2014, and July 9-13th 2014. 45 sites include: one tap, one tank, two irrigation canals/pools, two slopes/springs, 16 wells, 18 river sites, two mine water sites and three thermal waters. Refer to Appendix A1-A4, respectively for data.

based guideline, refer to Table 1a), b) Food and Agriculture Organization (FAO UN, 1985) recommendations for non-restricted use of water use in agriculture (refer to Table 1b), c) FAO recommendations for livestock (Table 1a), and d) Bolivian class 'A - D' criteria for receiving waters (referred to here as 'A', 'B', 'C', or 'D' criteria) (Table 1a). We then iii) determine a Water Quality Rating (WQR, see Table 2) for each sample site as a relative indication of the overall chemical status as a baseline for recommending actions, and iv) calculate and rank Hazard Quotients (HQ; the ratio of an element concentration to 'A' criteria) for metals (not reported for site WQR ≤4). Appendices A1 – A4 provides in-situ measured parameters and concentration data for each site during August 2013, December 2013, April 2014, and July 2014, respectively. Section 7 provides a summary of water quality status, followed by options for treatment (Section 8.1) and recommended actions for different sites and water conditions (Section 8.2, Table 6).

Important aspects to bear in mind with the information presented in this report include specific local considerations as well as the other aspects of water quality. All water should be assessed for microbial contamination and undergo basic treatment for potable supply if used for human consumption (refer to Section 8.1). For human health, intake of chemicals is dependent upon the volume of water consumed, and also the diet and inhalation routes for local residents (WHO, 2011a). For example, a diet containing food types that have a high concentration of certain elements (e.g., fluoride or arsenic) may reduce the recommended concentration for that element via water consumption. Alternatively, water consumption significantly below ~2 L/day[†] might reduce exposure and health risk in certain circumstances. Furthermore, not all elements have health-based guidelines (refer to Table 1a notes) as many aspects of water quality relate to appearance, taste and odour or to corrosion of pipes and equipment, although some elements do not have health-based guidelines because they would exceed practically achievable levels due to treatment processes (e.g., aluminium), at high concentrations elements without health-based guidelines may be toxic or incur health effects. We refer to those with a health-based guideline as element of health significance (WHO, 2011a), but reiterate that other elements may have health-risk at elevated concentrations. Additional points to bear in mind relate to the susceptibility of livestock, as this depends on the type and age of animal; for instance poultry are less tolerant to salt intake than cattle. If an animal is pregnant or lactating they are also less tolerant (FAO UN, 1985). For irrigation, soil type, composition, and structure and the actual crops grown are important considerations for irrigation water restrictions. For example, crops have different tolerances to salts and can be more or less sensitive to ion-toxicity (FAO UN, 1985, refer to Table 1b).

[†] General recommendations by the United States Department of Agriculture are 2.7 L/day for woman and men, girls and boys (aged 9-13) 2.1 – 2.4 L/d respectively, children 3-8 years old ~ 1.7 L/d, toddlers ~1.3 L/d, and infants 0.8 L/d. The amount of water required by a person depends on age, sex, health, physical activity level and also the environmental temperature. Recommendations are generally set to prevent dehydration.

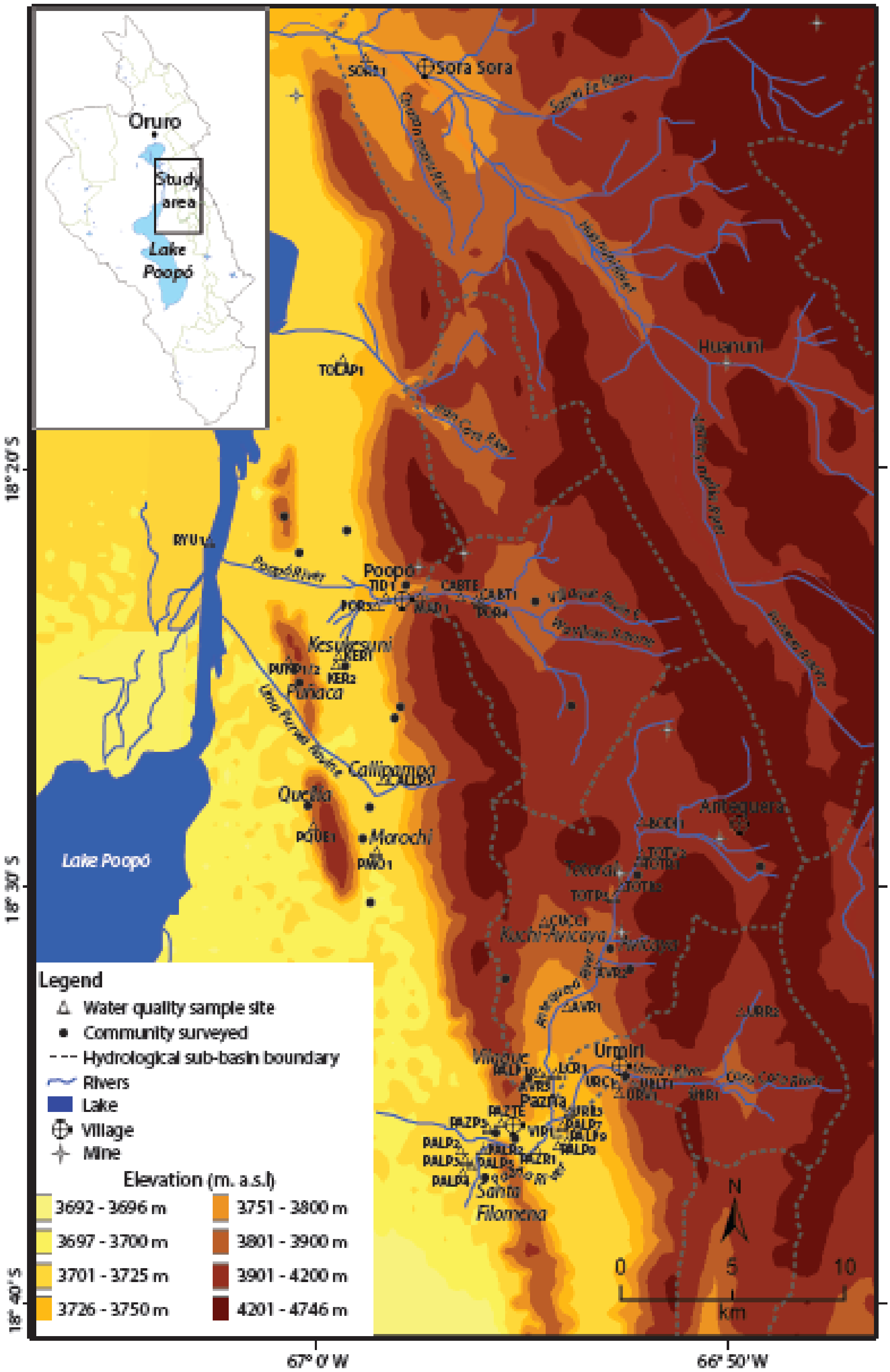


Figure 1 Elevation map (m a.s.l) showing study area and all water quality sample sites (triangles) and communities surveyed (dots) (500 m resolution, SRTM data, 2000).

Table 1a Guideline limit concentrations for water constituents and quality indicators for: Bolivian Class A, B, C, and 'D' criteria for receiving waters, WHO guidelines for drinking water (2011a), and Food and Agriculture Organization (FAO, 1985) recommended limits for livestock and non-restricted water use in agriculture. All in mg/L except pH, dissolved oxygen (DO, % saturation), and EC (dS/m).

| Parameter (mg/L unless other stated) | Bolivian class A | Bolivian class B | Bolivian class C | Bolivian class D | WHO guideline | FAO recommendation for livestock | FAO recommendation for non-restricted irrigation use |
|---|---|---|---|---|---|---|---|
| pH | pH 6 – 8.5 | pH 6 – 9 | pH 6 – 9 | pH 6 – 9 | pH 6.5 – 8.5 | --- | pH 6.5 - 8.4 |
| DO, dissolved oxygen (% saturation) | >80% | >70% | >60% | >50% | --- | --- | --- |
| Electrical conductivity (EC, dS/m)❶ | <1.5dS/m❶ | --- | --- | --- | (<0.9dS/m) <1.5dS/m❶ | <5-8dS/m (<5 poultry) | <0.7 dS/m (>3 dS/m severe restriction) |
| TDS | 1000 | 1000 | 1500 | 1500 | (600) 1000 | 5100 (3200) | <450 good (>2000 severe restriction) |
| SAR (unit less) ❷ | --- | --- | --- | --- | --- | --- | 0-3, EC>0.7dS/m; 3-6, EC >1.2 dS/m❷ |
| Cl, chloride | 250 | 300 | 400 | 500 | 250 | --- | 140 (>350 severe) (as ion toxicity) |
| F, fluoride | 0.6 – 1.7 | --- | --- | --- | 1.5^ | 2.0 | 1.0 |
| $NO_3$, nitrate | 20 | 30 | 50 | 50 | 50^ | --- | 5.0 (>30 severe) |
| $SO_4$, sulphate | 300 | 400 | 400 | 400 | 500 | --- | 500 |
| Al, aluminium | 0.2 | 0.5 | 1.0 | 1.0 | 0.2 | 5.0 | 5.0 |
| As, arsenic | 0.05 | 0.05 | 0.05 | 0.1 | 0.01^^ | 0.2 | 0.1 |
| B, boron | 1.0 | 1.0 | 1.0 | 1.0 | 2.4^ | 5.0 | 0.7 (>3 severe) |
| Ba, barium | --- | --- | --- | --- | 0.7^ | --- | --- |
| Ca, calcium | 200 | 300 | 300 | 400 | --- | --- | --- |
| Cd, cadmium | 0.005 | 0.005 | 0.005 | 0.005 | 0.003^^^ | 0.05 | 0.01 |
| Co, cobalt | 0.1 | 0.2 | 0.2 | 0.2 | --- | 1.0 | 0.05 |
| Cr, chromium (III) | 0.05 | 0.6 | 0.6 | 1.1 | 0.05^^ | 1.0 | 0.1 |
| Cu, copper | 0.05 | 1.0 | 1.0 | 1.0 | 2.0^ | 2.0 | 0.2 |
| Fe, iron | 0.3 | 0.3 | 1.0 | 1.0 | --- | --- | 5.0 |
| K, potassium | --- | --- | --- | --- | --- | --- | --- |
| Li, lithium | --- | --- | --- | --- | --- | --- | 2.5 |
| Mg, magnesium | 100 | 100 | 150 | 150 | --- | 250 (cattle 400) | --- |
| Mn, manganese | 0.5 | 1.0 | 1.0 | 1.0 | 0.4 | --- | 0.2 |
| Mo, molybdenum | --- | --- | --- | --- | 0.02 | --- | 0.01 |
| Na, sodium | 200 | 200 | 200 | 200 | 200 | --- | 69 (>206 severe) (as ion toxicity) |
| Ni, nickel | 0.05 | 0.05 | 0.5 | 0.5 | 0.07^ | --- | 0.2 |
| Pb, lead | 0.05 | 0.05 | 0.05 | 0.1 | 0.01^^ | 0.1 | 5.0 |
| Sb, antimony | 0.01 | 0.01 | 0.01 | 0.01 | 0.02^ | --- | --- |
| Si, silica | --- | --- | --- | --- | --- | --- | --- |
| Sn, tin ❸ | 0.025❸ | --- | --- | --- | --- | --- | --- |
| Zn, zinc | 0.2 | 0.2 | 5.0 | 5.0 | 3.0 | 24.0 | 2.0 |

❶ Generally, recommended drinking water EC <0.9 dS/m and at maximum 1.5 dS/m (i.e., <600 ppm TDS and maximum 1000 ppm TDS as recommended by the WHO (2011a) for taste and palatability). EC >2.5 dS/m is not recommended for consumption and that with >10 dS/m is considered not for consumption (livestock included).

❷ Sodium Adsorption Ratio (SAR); defines sodicity in terms of the relative concentration of sodium (Na) compared to the sum of calcium (Ca) and magnesium (Mg) ions. The SAR assesses the potential for infiltration problems due to a sodium imbalance in irrigation water. Recommendations by the FAO (1985) for non-restricted use as irrigation water are given to avoid infiltration problems depending on associated EC and local soil type/condition. SAR = [Na meq/l]/({[Ca meq/l]+[Mg meq/l]})/2})$^{1/2}$

^ Element of health significance in WHO guidelines (2011a). Guidelines for other elements not included generally refer to acceptability for taste, odour, scaling etc. (NB. Mn guideline is based on intake assessment, and Al guideline is based on the use in water treatment flocculation despite possible health concerns).

^^ Provisional WHO health based guideline value set higher (i.e., as achievable) than initially calculated value which was below i) the achievable quantification level, and ii) the level achievable through practical treatment etc. (WHO, 2011a).

^^^ Provisional health based WHO guideline value due to scientific uncertainty (WHO, 2011a).

❸ UK Environment Agency non-statutory recommended limit for protection of aquatic life.

Table 1b Guidelines for assessing sodium hazard and infiltration of water, and specific ion toxicity for agricultural use[a] (FAO UN, 1985).

| **Potential irrigation problem** | **Degree of restriction on use[b]** | | |
|---|---|---|---|
| **Salinity** (affects crop water availability)*: | **None** | **Slight to moderate** | **Severe** |
| Electrical conductivity, EC | <0.7 dS/m | 0.7 – 3.0 dS/m | >3.0 dS/m |
| or Total Dissolved Solids, TDS | <450 mg/L | 450 – 2000 mg/L | >2000 mg/L |
| **Infiltration** (rate of water to soil)**: | | | |
| If SAR = 0 - 3 when EC = | >0.7 dS/m | 0.7 – 0.2 dS/m | <0.2 dS/m |
| If SAR = 3 - 6 when EC = | >1.2 dS/m | 1.2 – 0.3 dS/m | <0.3 dS/m |
| If SAR = 6 - 12 when EC = | >1.9 dS/m | 1.9 – 0.5 dS/m | <0.5 dS/m |
| If SAR = 12 - 20 when EC = | >2.9 dS/m | 2.9 – 1.3 dS/m | <1.3 dS/m |
| If SAR = 20 - 40 when EC = | >5.0 dS/m | 5.0 – 2.9 dS/m | <2.9 dS/m |
| **Specific ion toxicity** (affects sensitive crops)***: | | | |
| Na, sodium (mg/L): Surface irrigation | <69 mg/L (3 meq/L) | 69 - 206 mg/L | >206 mg/L (9 meq/L) |
| Na, sodium (mg/L): Sprinkler irrigation | <69 mg/L (3 meq/L) | >69 mg/L | |
| Cl, chloride (mg/L): Surface irrigation | <140 mg/L (4 meq/L) | 140 – 350 mg/L | >350 mg/L |
| Cl, chloride (mg/L): Sprinkler irrigation | <105 mg/L (3 meq/L) | >105 mg/L | |
| B, boron (mg/L) | <0.7 mg/L | 0.7 – 3.0 mg/L | >3.0 mg/L |
| Trace elements | Refer to Table 1a | Refer to Table 1a | Refer to Table 1a |
| **Other effects** on susceptible crops: | | | |
| Nitrogen as nitrate ($NO_3$)^ | < 5 mg/L | 5 – 30 mg/L | >30 mg/L |
| Bicarbonate ($HCO_3$) (overhead sprinklers only)^^ | <92 mg/L (1.5 meq/L) | 92 – 519 mg/L | >519 mg/L |
| pH ^^^ | 6.5 – 8.4 | | |

[a] Notes (FAO UN, 1985)
*Salinity: salts in soil or water reduce water availability to crops and thus can affect crop yield. If salt accumulates in the crop root zone to a certain concentration, crops become water stressed and yields can be reduced.
**Water infiltration: relatively high Na or low Ca content of soil or water reduces the rate of infiltration and affects crop yield, although infiltration depends on local soil type and soil properties such as structure. Infiltration problems can also lead to vector disease issues. Low salinity water can be corrosive and leach soluble minerals to reduce infiltration. Water with a high Na:Ca ratio reduces infiltration rates; high Na or low Ca content waters can weaken a soil structure.
***Specific ion toxicity: certain ions from soil or water can accumulate in crops and cause crop damage (e.g., marginal leaf burn) and reduce yields at high accumulation. However, the degree of damage depends on the uptake, duration of exposure, and also the sensitivity of the crop being grown. Perennial crops are generally more sensitive. SAR-ESP indicator shows sensitive crops to Na toxicity to be crops such as Maize and green beans (SAR<12, ESP<15), tolerant crop examples are alfalfa and barley.
^Excessive nutrients (e.g., nitrate, $NO_3$) can cause excessive growth and delayed crop maturity.
^^Water with high bicarbonate ($HCO_3$) or high iron (Fe) content can damage crops and result in poor visual appearance that reduces marketability.
^^^Corrosion and deterioration due to pH or alkalinity imbalance can increase the need for equipment repair.
[b] Restrictions in the slight to moderate range do not necessarily indicate water is unsuitable for use, it indicates that there may be a limitation in crop selection, and/or special management requirements based on the specific field conditions in order to optimise yields. Severe range of restricted use involves a high level of management skill related to the specific field conditions.

Table 2 Qualitative description of chemical Water Quality Rating (WQR). Note: chemical reference excludes industrial, agricultural, and petroleum chemicals etc.

| | |
|---|---|
| **1** | Chemically and biologically of good quality for consumption and other uses. Undergone any necessary treatment for potable water. |
| **2** | Chemically good for consumption and other uses (excluding assessment of industrial, agricultural, and petroleum chemicals), pending microbial assessment. |
| **3** | Chemically good for consumption (electrical conductivity, EC, <0.5 dS/m, sodium adsorption ratio, SAR, <3); meeting Bolivian class 'A' criteria with the exception of a maximum of two elements that have health-based World Health Organization (WHO) guideline (referred to here as element of health significance) that sometimes exceed ‘A’ criteria (or WHO if no 'A' criteria exists) but not to excessive concentrations (i.e., Hazard Quotient, HQ; sample element concentration/Bolivian 'A' criteria = <3), and occasional/seasonal appearance factors (e.g., some algae or slightly turbid at times). Good for irrigation but infiltration may be problematic due to combination of low EC and SAR. Microbial assessment required. Treatment to reduce elements exceeding health-based guidelines recommended in addition to basic treatment for potable water (e.g., filtration, disinfection). |
| **4** | Chemically acceptable with EC <0.9 dS/m but with a maximum of three elements that exceed Bolivian ‘A’ criteria (or WHO guideline if no 'A' criteria exists) but not excessively, especially for any element of health significance (i.e., Hazard Quotient, HQ <3). Concern over appearance factors (e.g., algae, turbidity, suspended particulate/organic material, and/or stagnation) that suggests poor microbial quality, especially in wells. Water generally good for livestock, and not too bad for human consumption with caution due to element of health significance and pending microbial status. Suitable for irrigation but infiltration may be problematic due to combination of low EC and SAR. Microbial assessment required and actions such as cleaning of tanks/pools, pumping and covering of wells. Treatment to reduce element of health significance such as fluoride recommended in addition to basic treatment for potable water (e.g., filtration, disinfection). |
| **5** | Reduced quality in comparison to WQR 4 due to higher electrical conductivity (1 - 2 dS/m) in addition to caution over human consumption due to (naturally sourced) elements of health significance exceeding 'A' criteria (or WHO guideline if no 'A' criteria exists), and concern over appearance factors (e.g., algae, turbidity, suspended particulate/organic material, and/or stagnation) that suggests poor microbial quality. Not recommended for human consumption due to EC and any element of health significance exceedances. Acceptable for most livestock and not too bad for irrigation, but infiltration may be problematic when EC <1.2 dS/m when SAR 3 - 6. |
| **6** | Quality issues due to general exceedance of many Bolivian ‘A’ criteria and often ‘B-D’, thus numerous elements (mining and/or naturally sourced) Hazard Quotient (HQ) >1 and often >5. May be affected by mine water infiltration or migration, and is not therefore recommended for human consumption for this reason and due to concern over microbial status. May be acceptable for livestock with caution (depending on elements with exceedance possibly only for higher tolerant livestock). Some waters may be acceptable for irrigation depending on elements HQ >1, but infiltration maybe problematic if EC <0.7dS/m when SAR 0 - 3, EC <1.2 dS/m when SAR 3 - 6, EC <1.9 dS/m when SAR 6 - 12. |
| **7** | Water with naturally high salts, of very poor quality for human (and lower tolerant livestock) consumption and not recommended for irrigation use due to high EC (>1.5 dS/m) and TDS (>1000 mg/L) in addition to >2 elements of health significance exceeding 'A' criteria (or WHO guideline if no 'A' criteria) and FAO recommendations. With numerous elements HQ >1, and possibly concerns over biological quality. Not recommended for consumption without significant treatment (e.g., desalination, reduction of metals). |
| **8** | Mine affected water. Unsuitable for any use due to exceedance of ‘A-D’ criteria for sulphate and >4 metals that have high to very high concentrations (at least two with HQ>10), >2 metals being elements of health significance, and high EC (>1.5 dS/m). Not suitable for any use without significant treatment (e.g., desalination, removal of metals). |
| **9** | Thermal waters that can >60 $^{0}$C. Unsuitable for human or animal consumption or irrigation/agriculture because of naturally very high concentrations of salts (EC >8) in addition to high concentrations of Li and elements of health significance; boron, fluoride and antimony. Recreational use as bathing waters. |
| **10** | High level mine affected water. Complete restriction on use for humans, animal or irrigation/agriculture because of exceedance of ‘A-D’ criteria for sulphate and >2 metals that have extremely high concentrations (HQ>100), >3 other metals HQ >5 (>4 being elements of health significance), and very high EC (>8). Many elements HQ>100. Waters that require significant remediation for major reduction of many metals with subsequent desalination. |

## 2. BACKGROUND

### 2.1. Environmental

The study area is located in the central eastern margin of the Lake Poopó Basin, ~60 km south east of Oruro city. It is a rural region located at elevations of ~3700 – 4750 m above sea level (m a.s.l) (Figure 1) and is semi-arid with relatively low, seasonal rainfall. Total rainfall in Poopó Village in 2013 was 470.8 mm, which is ~30% less than in Oruro in 2013. Nearly 70% of rainfall occurs in December, January, and February (shown in Figure 4). Minimum average temperatures range from ~-3°C in winter to 7°C in summer, and maximum average temperatures are ~15°C in winter to ~20°C in summer (SENAMHI, 2014). Low rainfall and water availability, in addition to seasonal frost, erosion, salinization of soils, soil compaction, loss of vegetation cover and loss of soil fertility are limiting for agricultural activities.

The geology of the study area is mapped and detailed by Sergeotecmin, the National Geologic Service (Uncia, hoja numero 6238). Within this region is the Antequera tin mining district. Briefly, the regional geology comprises steeply folded Paleozoic rocks, which form parallel bands with a north-westerly strike directions. Overlying this are Quaternary deposits that include fluvial sediments, aeolian sediments, and lacustrine deposits that correspond to the paleolakes that once covered the Altiplano (Argollo and Mourguiart, 2000; Wirrmann and Mourguiart, 1995).

Metallic minerals are economically important to the region, and there is a history of unregulated mining activity that has affected the environment both aesthetically (tailing heaps) and due to contamination of soil and water. Poly-metallic deposits include tin (Sn), gold (Au), silver (Ag), tungsten (W), bismuth (Bi), zinc (Zn) and lead (Pb). Mineral deposits in the area also include non-igneous metals and metalloids such as copper (Cu) and antimony (Sb). The most abundant non-metallic mineral is sodium chloride salt (NaCl), which is often associated with high concentrations of lithium (Li), boron (B), potassium (K), and magnesium (Mg). Other common salt deposits include gypsum, potassium carbonate, sodium carbonate and sodium sulphate (UNEP, 1996).

### 2.2. Socio-economic

The rural municipalities of Poopó, Pazña and Antequera have 6163, 5469 and 3352 inhabitants, respectively (2001 Census). Livelihoods in the study area depend largely on agriculture (livestock and some crops) and mining. Between 1992 and 2001, there was an increase in agricultural work and a reduction in mine work in the area. In 2001 ~60% of the areas labour force worked in the agricultural sector and ~12-20% in the mining sector (2001 Census in CAMINAR atlas, 2013).

### 2.3. Water usage

The main uses of water in the wider Lake Poopó Basin are for agricultural irrigation (8.1 m $s^{-1}$), domestic use (0.2 m $s^{-1}$), and for mining, industry and for animal consumption (0.5 – 0.6 m $s^{-1}$) (Calizaya, 2009). It is thought that ~80% of all water used is returned to the system (Calizaya et al., 2006). Although there are no water meters in the rural areas and in remote communities there are no water systems or records of usage/abstraction, domestic water consumption in rural areas estimated to be range from 5 l/p/d to a maximum of 30 l/p/d (Calizaya et al. 2009).

Most households in Poopó, Pazña and Antequera obtain water for drinking and cooking from (informal) piped networks or from groundwater wells. The source of water for households is summarised in Table 3. Piped water for Poopó Village and some nearby communities (Puñaca, Yuracarí, Quesu Quesuni) is transferred from storage tanks (e.g., CABT1, Figure 1) that receive spring water from the upper catchment, which is treated by chlorination (Felicidad Mamani, Councillor of the municipality of Poopó, *pers. comm*. February 2015). Similarly, piped water to communities in Antequera and Pazña municipalities, which includes Urmiri Village, is believed to be transferred from artesian springs/slope runoff, although Pazña Village transfers water from wetlands in the upper catchment, which is then filtered through gravel and chlorinated (Zacarías Ortega, oficial mayor técnico del Municipio de Pazña *pers. comm*. February 2015). Communities not receiving piped water largely obtain (untreated) water from groundwater wells, directly from springs and/or rivers (Table 3).

Table 3 Water source type supplied to households (%) in the municipalities of Poopó, Pazña and Antequera (2001 Census in Quintanilla et al., 2012).

| | | Municipality | | |
|---|---|---|---|---|
| | | Poopó | Pazña | Antequera |
| Water source: | *Population:* | *6163* | *5469* | *3352* |
| Piped network or standpipe | | 39.0% | 58.6% | 48.4% |
| Delivered by vehicle | | 0.1% | 0.3% | 0.0% |
| Groundwater well/pump | | 40.7% | 22.9% | 22.3% |
| Surface source (river/slope) | | 19.7% | 16.3% | 29.0% |
| Other | | 0.5% | 1.9% | 0.3% |

## 3. METHODOLOGY

### 3.1. Field sampling

Water quality and quantity sampling was undertaken in four periods, i) August 13-16th 2013, ii) December 16-20th 2013, iii) April 7-12th 2014, and iv) July 9-13th 2014. A total of 45 sites were sampled for water quality analysis, including: one tap, one tank, two irrigation canals/pools, two slopes/springs, 16 wells, 18 river sites, two mine water sites and three thermal waters. Table 4 provides details of all site codes, locations, general site type and when each site was sampling. Chemical data for each sampling period is provided in Appendices A1 - A4, respectively.

Table 4 Sample site codes, location, site type, and sample dates 2013 - 2014.

| **Code** | **X UTM** | **Y UTM** | **Location** | **Type** | **Aug'13** | **Dec'13** | **Apr'14** | **Jul'14** |
|---|---|---|---|---|---|---|---|---|
| AVR1 | 721868 | 7948250 | Antequera - Avicaya | River | ✓ | ✓ | ✓ | ✓ |
| AVR2 | 723257 | 7950256 | Antequera - Avicaya | River | ✓ | ✓ | ✓ | ✓ |
| AVR3 | 720873 | 7945303 | Antequera - Avicaya | River | ✓ | ✓ | ✓ | ✓ |
| BODI1 | 725275 | 7956447 | Antequera - Bolivar | River channel | ✓ | ✓ | ✓ | ✓ |
| CABT1 | 717883 | 7965960 | Poopó - Cabreria | Storage tank | ✓ | ✓ | | ✓ |
| CABTE | 717192 | 7966236 | Poopó - Cabreria | Thermal | ✓ | | ✓ | ✓ |
| CALLP3 | 713792 | 7958284 | Callipampa | Well | ✓ | | ✓ | ✓ |
| CUCC1 | 720881 | 7952032 | Kuchi-Avicaya | Irrigation channel/ pool | ✓ | ✓ | ✓ | ✓ |
| KER1 | 711693 | 7963142 | Poopó - Kesukesuni | River | | ✓ | | |
| KER2 | 711741 | 7963557 | Poopó - Kesukesuni | River | | | ✓ | ✓ |
| LCR1 | 721365 | 7945358 | Antequera - Laca Laca River | River | | | | ✓ |
| MAD1 | 715384 | 7966183 | Poopó - Machacamaquita | Mine water | ✓ | ✓ | ✓ | ✓ |
| PALP10 | 720684 | 7945357 | Vilaque | Well | ✓ | ✓ | ✓ | ✓ |
| PALP2 | 717228 | 7941747 | Pazña | Well | ✓ | ✓ | | |
| PALP3 | 717395 | 7941413 | Pazña | Well | ✓ | ✓ | ✓ | ✓ |
| PALP4 | 717278 | 7940974 | Pazña | Well | ✓ | ✓ | ✓ | ✓ |
| PALP5 | 717660 | 7940927 | Pazña | Well | ✓ | ✓ | | |
| PALP7 | 721495 | 7942739 | Pazña | Well | ✓ | ✓ | ✓ | ✓ |
| PALP8 | 721565 | 7942213 | Pazña | Well | ✓ | ✓ | ✓ | ✓ |
| PALP9 | 721696 | 7942283 | Pazña | Well | ✓ | ✓ | | |
| PALR2 | 718182 | 7942031 | Pazña | River | ✓ | ✓ | ✓ | ✓ |
| PAZP3 | 718347 | 7942945 | Pazña | Well | ✓ | ✓ | ✓ | ✓ |
| PAZR1 | 720513 | 7941972 | Pazña | River | ✓ | ✓ | ✓ | ✓ |
| PAZTE | 718945 | 7943143 | Pazña | Thermal | ✓ | ✓ | ✓ | ✓ |
| PMO1 | 713483 | 7955167 | Callipampa - Morochi | Well | | | ✓ | ✓ |
| POR3 | 713497 | 7965976 | Poopó | River | ✓ | ✓ | ✓ | ✓ |
| POR4 | 717866 | 7965991 | Poopó | River | | | ✓ | ✓ |
| PQUE1 | 710738 | 7956331 | Callipampa - Quellia | Well | | | ✓ | ✓ |
| PUNP1 | 709557 | 7963756 | Poopó - Puñaca | Tap | | | ✓ | ✓ |
| PUNP2 | 709682 | 7963601 | Poopó - Puñaca | Well | | | ✓ | ✓ |
| RYU1 | 706180 | 7968784 | Poopó River - Lake Poopó | River/Lake | | | ✓ | ✓ |
| SORR1 | 713078 | 7990305 | Sora Sora | River | ✓ | ✓ | ✓ | ✓ |
| TID1 | 713941 | 7966300 | Poopó - Tiahunacu | Mine water | ✓ | ✓ | ✓ | ✓ |
| TOLAP1 | 711966 | 7976804 | Tolapampa | Well | ✓ | ✓ | ✓ | ✓ |
| TOTP5 | 724069 | 7953180 | Antequera - Totoral | Well | | ✓ | ✓ | |
| TOTR1 | 724723 | 7954208 | Antequera - Totoral-Martha | River | ✓ | ✓ | ✓ | ✓ |
| TOTR2 | 723994 | 7953177 | Antequera - Totoral | River | ✓ | ✓ | ✓ | ✓ |
| TOTV2 | 725130 | 7954922 | Antequera - Totoral-Martha | Spring/ slope runoff | ✓ | ✓ | ✓ | ✓ |
| URC1 | 724127 | 7944804 | Urmiri | Irrigation channel | ✓ | ✓ | ✓ | ✓ |
| URLT1 | 724880 | 7944826 | Urmiri | Thermal | ✓ | ✓ | ✓ | ✓ |
| URR1 | 727604 | 7944725 | Urmiri | River | ✓ | ✓ | ✓ | ✓ |
| URR2 | 729627 | 7948149 | Urmiri - Talaco | River | | ✓ | ✓ | ✓ |
| URR3 | 721998 | 7943603 | Urmiri | River | ✓ | ✓ | ✓ | ✓ |
| URV1 | 724170 | 7944497 | Urmiri | Spring/ slope runoff | ✓ | ✓ | ✓ | ✓ |
| VIP1 | 720258 | 7942289 | Pazña | Well | | | | ✓ |

Sampling was performed by collecting sample water in a bucket (first rinsed three times with sample water). Water was then left for a few minutes to allow any suspended material to settle out. In-situ measurements were taken from the bucket for pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), oxygen reduction potential (ORP), and dissolved oxygen (DO). A 50 ml syringe (pre-washed with Milli-Q water) was used to take sampled water from the bucket. Water was sampled through a filter cartridge (0.45 µm) into two clean plastic vials (30 ml). A few drops of 50% nitric acid were added to one vial for analysis of cations. Blank samples were also prepared using Milli-Q water. Vials were labelled and sealed, and stored in a cool box awaiting shipment to the UK for laboratory analysis.

Quantity assessment involved measuring the water levels using a standard dip meter in most wells. River flow measurements were performed by a SENAMHI technician using a standard horizontal axis flow meter (SIAP, 0.05 $ms^{-1}$ to 5 $ms^{-1}$) at many surface water sites in April and July 2014 (Appendix B).

### 3.2. Laboratory analysis

Water samples were shipped to UCL (UK) and analysed for 22 cations (aluminium, Al; arsenic, As; boron, B; barium, Ba; calcium, Ca; cadmium, Cd; cobalt, Co; chromium, Cr; copper, Cu; iron, Fe; potassium, K; lithium, Li; magnesium, Mg; manganese, Mn; molybdenum, Mo; sodium, Na; nickel, Ni; lead, Pb; antimony, Sb; silica, Si; tin, Sn; zinc, Zn) and four anions (chloride, Cl; fluoride, F; nitrate, $NO_3$; sulphate, $SO_4$). Cations were analysed using a Varian 720-ES ICP-OES CCD Simultaneous ICP Optical Emission Spectrophotometer. Anions were analysed using a Dionex (Thermo) AS50 Autosampler. Sample data were corrected for drift between standards (for other analysis information refer to UCL-Birkbeck Laboratory control document).

## 4. MACHACAMARCA MUNICIPALITY

### 4.1. Sora Sora River: SORR1

***Site description***

The SORR1 river sampling site (Figure 1, ~3757 m a.s.l) on the Sora Sora River contains water that have flowed from the Huanuni mine. Artisanal mining also occurs in some parts of the river. The river in the sampled area is scattered with general refuse and little to no vegetation. The river flow varies significantly with season (April 0.65 $m^3/s$, July 0.28 $m^3/s$) (Figure 2a, Appendix B). The water is observed to be turbid throughout the year, with yellow-grey coloured water and sometimes sulphur odour.

***Water quality status***

Data from 2008 and 2013 - 2014 show that the river is acidic (pH ~3), and with an electrical conductivity (EC) of ~1 – 2 dS/m. Dissolved oxygen (DO) is low (<60% saturation) and near zero in December, which do not meet 'A-C' criteria. Bolivian class 'A-D' criteria (Table 1a) are exceeded for fluoride (F), sulphate ($SO_4$), aluminium (Al), arsenic (As), cadmium (Cd), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni) and zinc (Zn) (see HQ ranking below and Appendix A). Levels of As and Fe have increased since 2008. Class 'A' criteria are exceeded for cobalt (Co). The concentrations of F, Cd, Mn, Ni and Zn also exceed World Health Organization (WHO) guidelines (2011a). In one sample, tin (Sn) (for which no Bolivian or WHO criteria exists) exceeds UK EA non-statutory guidelines for protection of aquatic life. FAO recommendations for irrigation water are exceeded for Al, As, Cd, Cu, Fe, Mn and Zn. The river water here has more elements elevated and generally at higher concentrations than in the Poopó River (see POR3), but the latter is more saline. Furthermore, because of the relatively higher flow (Figure 2a, e.g., April 2014; four times TOTR1, twice PALR2) in addition to high metal concentrations, the metal fluxes transported from upstream mining activities (e.g., Huanuni) are significantly higher than other rivers sampled during this study. This is illustrated in Figure 2, which shows how the fluxes of Al (~1710 - 2010 kg/day, dry and wet season) and Cd (~33 - 47 kg/day) at SORR1 are approximately ten times greater than at sites affected by mining from the Antequera River (TOTR1-AVR3-PALR2), whereas Zn (~900 - 1860 kg/day) is similar due to higher Zn concentrations in the Antequera River. Figure 2e illustrates how lithium is naturally sourced, in so much the flux is considerably lower at SORR1 and at sites along the Antequera, whereas Li fluxes are high downstream Poopó River (POR3) and Urmiri River – Pazña due to thermal inputs (CABTE and URTL1, respectively, see later discussions). The plots also show how metal fluxes increase significantly during the wet season due to higher river flows.

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| ***WQR:* SORR1** | **10** |

(refer to Table 2 for qualitative description of WQR).

***Hazard Quotient (HQ): metal ranking and concerns at SORR1***

Trace metals HQ >1 in 2013 – 2014 (i.e., the ratio of element concentration/ class 'A' criteria) are ranked (bold type indicates element of health significance, i.e., those with a WHO health based guideline but not a ratio of this, see Table 1a) for SORR1: Fe (HQ 284-1043)>Al (38-131) >Zn (90-285)>**Cd** (86-283)>**Cu** (33-48)>Mn (17-48)>**Ni** (4-13)>**As** (0-15)>**F** (3-5)>Co (2-4). Note: WHO guidelines for As, Cd, Mn and lead (Pb) are lower than 'A' criteria, thus these elements HQ would rank higher if with respect to WHO guidelines. Whereas 'A' criteria for B, Cu, Ni and Sb are lower than WHO guidelines, thus these elements HQ would rank lower if with respect to WHO guidelines.

***Limitations on use***

River water at SORR1 is affected by mining activity and is unsuitable for any consumption or irrigation use as it contains metal concentrations that far exceed 'A-D' criteria, WHO and FAO recommendations (e.g., Fe, Al, Zn, and Cd are all more than 80 times 'A' criteria). Elements that are of health significance and usually associated with a health-risk (WHO, 2011a; hereafter referred to as element of health significance) and exceed 'A' criteria are of a particular concern, which applies to Cd, Cu, Ni, As and F in samples from SORR1. Control of mine activity upstream (and artisanal practices throughout the river reach) including containment of waste is necessary to prevent high metal loadings in the river (refer to Sections 8.1.4 and 8.2.7).

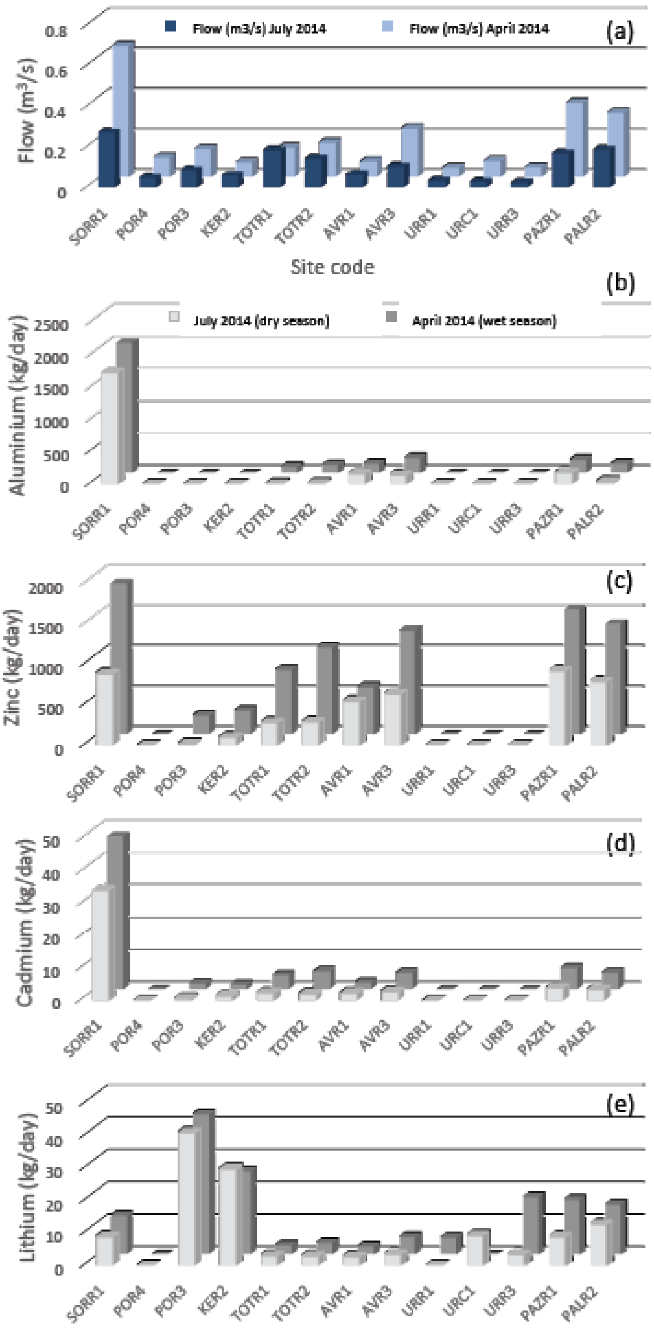


Figure 2 Graphs showing a) river flows ($m^3/s$, Appendix B), and b) aluminium flux (kg Al/day), c) zinc flux (kg Zn/day), d) cadmium flux (kg Cd/day), e) lithium flux (kg Li/day) during April (wet season) and July (dry season) 2014 at surface water sites in the study area (refer to Figure 1 for site code locations). Fluxes determined from site metal concentrations (mg/L) and river flows ($m^3/s$ converted to L/s). Refer to Figures 5 and 11 for Poopó and Antequera areas only, respectively.

## 5. POOPÓ MUNICIPALITY

Poopó municipality sample sites are show in Figure 3. In the north, the sampled site in the Tolapampa Village is one well (TOLAP1). In the area around the Poopó River and Village, sample sites include (from upstream to downstream) one river (POR4), one tank (CABT1), one thermal water site (CABTE), two acid mine drainage (AMD) sites (MAD1, TID1), and a downstream river site (POR3). The river in Kesukesuni Village was sampled (KER1/2), and in the nearby Puñaca Village, one well (PUNP2) and a tap in the local school (PUNP1) (Figure 3). A lake sample site in the vicinity of the point of discharge of the Poopó River into Lake Poopó is RYU1. In the south of the municipality in the upstream area of the Uma Purwa Ravine, three wells were sampled: CALLP3 in Callipampa Village, PMO1 in Morochi Village, and PQUE1 in Quellía Village (Figure 3).

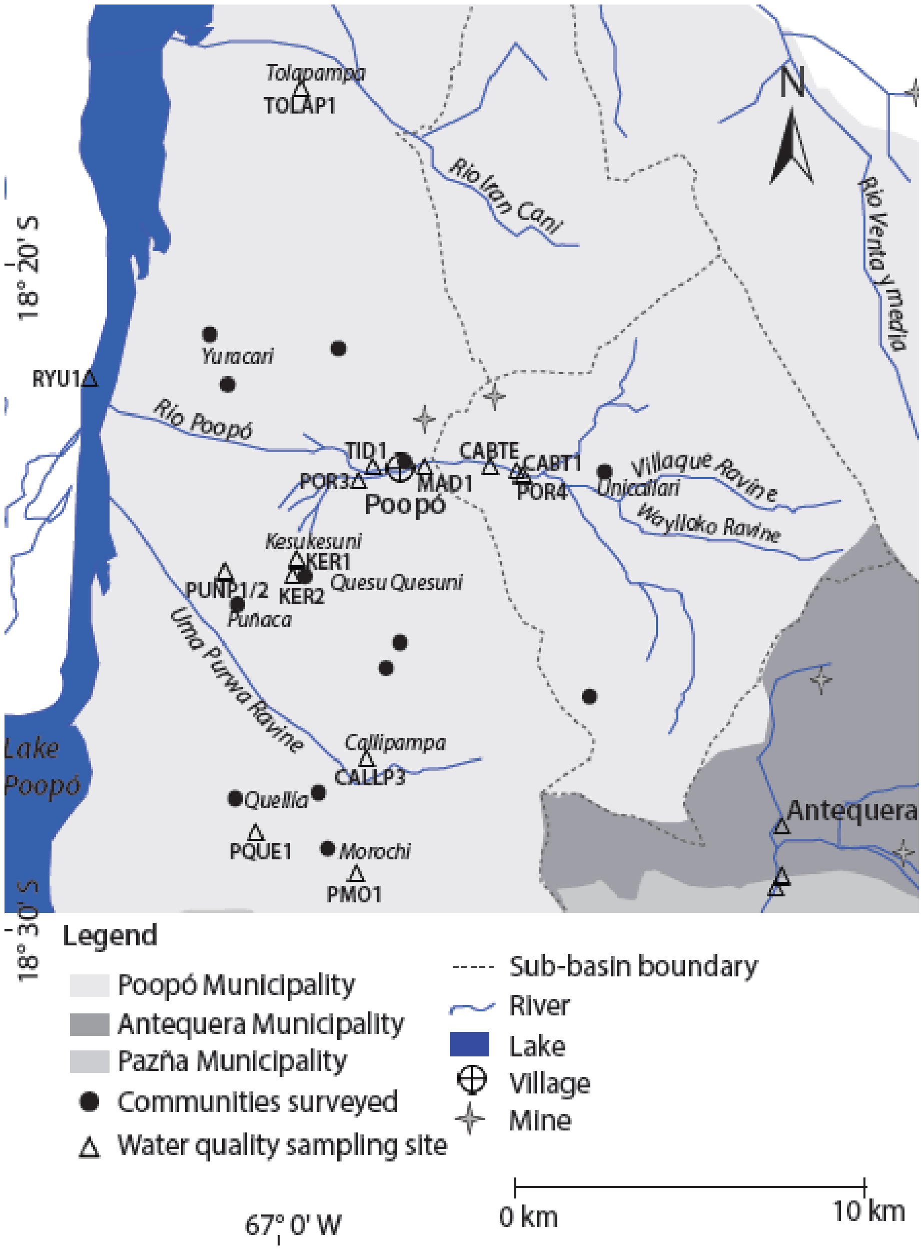


Figure 3 Map showing sampling sites in Poopó municipality.

## 5.1. Tolapampa

### 5.1.1. Water source site: TOLAP1 well

***Site description***

The TOLAP1 well (~3721 m a.s.l) is a relatively deep (~9 m) open well with a loose tin cover that sits on a wood frame. The well is used as a source of water for livestock consumption, domestic use and possibly human consumption. The water table in Tolapampa fluctuates more than other (shallower) sampled wells (Figure 4). Within the study period the water table increased by ~3m as the water level in the well increases from 7.05 m below datum (b.d) in mid-August 2013 (following relatively low rainfall in January 2013) to 4.72 m b.d in April 2013, and then to 4.09 m b.d in mid-July 2014 (Appendix B) after summer rainfall in December 2013 – January 2014 (Figure 4). Groundwater levels in this area continue to recover after a time lag of ~4 months following rainfall (Figure 4).

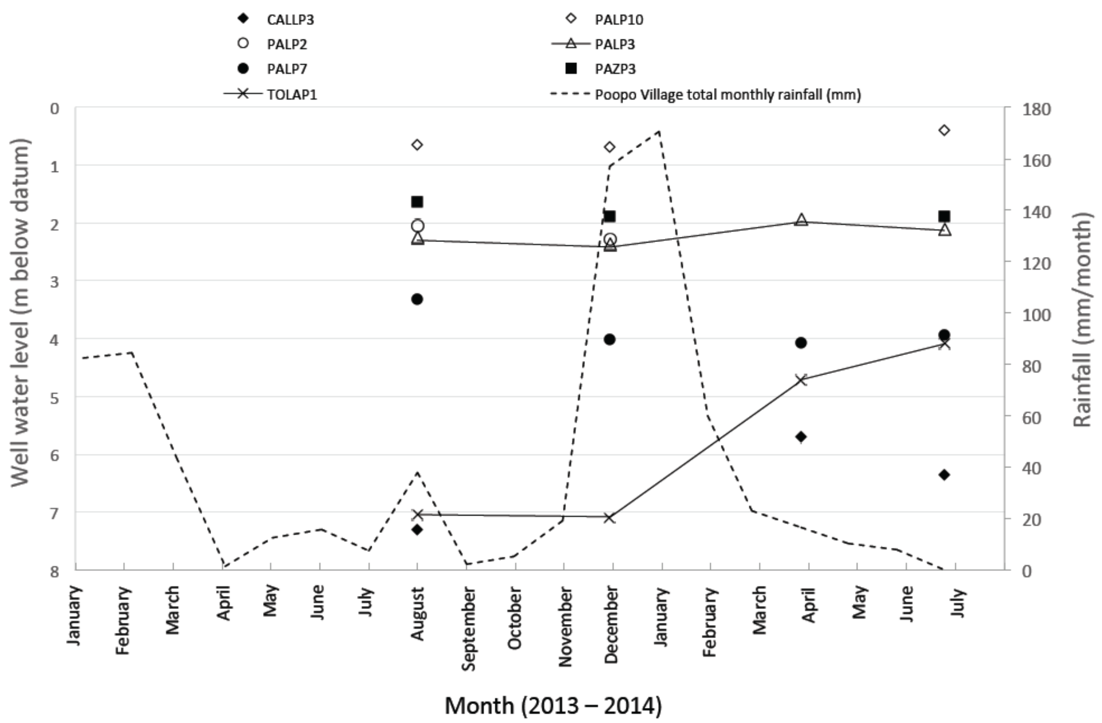


Figure 4 Water levels (m below datum) at wells in the study area (refer to Figure 1 for site code locations) and rainfall (mm/month) in Poopó Village in 2013 and 2014 (SENAMHI, 2014).

***Water quality status TOLAP1***

The well was not sampled during the CAMINAR project in 2007-2009. Electrical conductivity values are low (~0.4 dS/m) and within drinking water recommendations. The combination of low EC with low SAR values (0.8 - 1.9) suggests some restriction may be required (depending on the local soil type) for irrigation use due to possible water-soil infiltration problems (see Table 1b). Chemical data from 2013 - 2014 showed low levels of DO (<22% saturation) that do not meet 'A-D' criteria. Fluoride (F, up to 2.7 mg/L) and antimony (Sb) concentrations (up to 0.05 mg/L) generally exceeded 'A-D' criteria and WHO guidelines (Table 1a). In July 2014, Cd (0.005 mg/L) was at 'A-D' criteria but above WHO guidelines. Also, Sn exceeds UK EA non-statutory guidelines for protection of aquatic life. The well is observed to be of visibly poor appearance due to organic/plant material in suspension and sometimes turbid, which may suggest poor biological quality (WHO, 2011a).

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| ***WQR:*** **TOLAP1** | **4** |

***Limitations on use and initial recommendations***

Use of the well water for human consumption is limited due to elements of health significance F and Sb, and sometimes Cd. Treatment to reduce these elements is recommended, and basic treatment for potable water applies if used for human consumption (see Section 8.1 and Table 6). A water quality analysis should be made to assess microbial contamination. The water is good for irrigation with the exception of higher F concentrations and possible soil infiltration problems. The well water is chemically suitable for livestock consumption with the exception of higher F concentrations. However, the well should be pumped before use as it maybe stagnant and turbidity may indicate poor biological quality. Improving the cover on the well is also recommended (see Table 6).

## 5.2. Poopó River/Village

### 5.2.1. Water source site: CABT1 Tank

***Site description***

CABT1 is a gated tank (~3810 m a.s.l) in the region of Cabreria, ~3.5 km east/upstream of Poopó Village (near POR4 river sample site). It is understood that the tank stores spring water, which is subsequently chlorinated and piped for to communities for human consumption.

***Water quality status***

The EC values of water from the tank are low (~0.3 dS/m) and within the range generally recommended for drinking water. This with low SAR (1.4 - 2.2) suggests possible soil infiltration problems if used for irrigation (depending on local soils, Table 1b). Chemical data for the CABT1 tank in 2013 -2014 shows an improvement since sampling in 2007 – 2009, when 'A' criteria were exceeded for chloride (Cl), and on one occasion (January 2008) WHO guidelines and 'A-D' criteria were exceeded for Cd and lead (Pb). In 2013 – 2014, 'A-D' criteria, FAO and WHO guidelines (Table 1a) were exceeded for F (1.4 - 3.4 mg/L). In August 2013, Sb (0.026 mg/L) exceeded 'A-D' criteria and the WHO guideline. Also, Sn exceeded UK EA non-statutory guidelines for protection of aquatic life. Levels of DO do not meet 'A-D' criteria, as they are <50% saturation. The water is observed to be clear.

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|---|---|
| ***WQR:*** **CABT1** | **3** |

***Limitations on use and initial recommendations***

The only chemical caution assessed here for use of water for consumption from CABT1 tank are for F, and sometimes for Sb, which are both elements of health significance. Treatment for reducing these is recommended, as is basic treatment for potable water (Section 8.1). A water quality analysis should be made to assess microbial contamination. It is suitable for livestock and irrigation with the exception of higher F concentrations, although there may be possible soil infiltration problems.

### 5.2.2. Thermal water: CABTE

***Site description***

The CABTE site (~3801 m a.s.l) is downstream of the CABT1 tank, and east of Poopó Village. The site is a concrete containment where thermal waters are below the surface. Thermal waters in the region are often used for bathing purposes.

***Water quality status***

Data from 2007 – 2009 and 2013 – 2014 for CABTE thermal waters show very high EC values (~17 dS/m, brackish) that greatly exceed those recommended for consumption or irrigation use. SAR values are extremely high (58). Total Dissolved Solids (TDS) greatly exceed 'A-D' criteria (~8300 mg/L versus 'D' criteria 1500 mg/L), and sodium (Na) and Cl concentrations are an order of magnitude greater than Bolivian class 'A-D' criteria (Table 1a). Boron (B, ~13 mg/L), fluoride (F, ~6 mg/L), and Antimony (Sb, 0.03 mg/L) exceed 'A-D' criteria, FAO and WHO guidelines. There is not a known Bolivian criteria set for lithium (Li), but concentrations (~13 mg/L) are an order of magnitude greater than that recommended by the FAO for irrigation water. 'A' criteria are also exceeded in some thermal samples for calcium (Ca). Waters have temperatures >30°C. Levels of DO are low and don't meet 'A-D' criteria.

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| ***WQR:* CABTE** | **9** |

***Hazard Quotient (HQ): metal ranking and concerns***

Trace metals [1]HQs in 2013 – 2014 ranked at CABTE: **B** (12-13)>*L (5)*> **F** (3-4)> **Sb** (0-2.7).

***Limitations on use***

CABTE thermal waters are unsuitable for human (or livestock) consumption or irrigation due to extremely high EC, TDS, Na, Cl, and very high B and Li, and high F and Sb. This suggests that B, Li, F, and Sb are naturally sourced in other waters in the region.

[1] **HQ** Risk Quotient = the ratio of an element concentration / 'A' criteria (except lithium, Li, ratio with FAO recommendation (2.5 mg/L). Where HQ>1 indicates exceedance. Note: Bolivian 'A' criteria for As, Cd, Mn and Pb are greater than WHO guidelines (all health based except Mn), thus these elements HQ would rank higher if with respect to WHO guidelines. Whereas 'A' criteria for B, Cu, Ni and Sb are lower than WHO health based guidelines, thus these elements HQ would rank lower if with respect to WHO guidelines (refer to Table 1a and associated notes).

### 5.2.3. AMD water: MAD1, TID1

***Site description MAD1***

The MAD1 site (~3766 m a.s.l) is located on the southeast outskirts of Poopó Village. It is a stony area where grey-brown-orange water exits a mine entrance at a low rate of flow (e.g., July 2014, 0.0035 $m^3/s$, Figure 5a). Infiltration of mine water elsewhere is not known but may be a significant pathway for transport of mine water to local surface water or groundwater.

***Water quality status MAD1***

Data in 2013 show that the pH at MAD1 is lower and more acidic than in 2007 -2009 (pH 2.9 versus 5.3 - 6.5, indicated on Figure 6a), which all fail 'A-D' criteria. The DO levels do not meet 'A-D' criteria. TDS (~6500 mg/L) greatly exceed 'A-D' criteria. In 2007 – 2009 and 2013 - 2014, EC (10.8 – 15.7 dS/m) greatly exceeded recommendations for drinking water or irrigation use. SAR (~21) values are very high. Arsenic, Al, B, Cd, Cl, Co, F, Fe, magnesium (Mg), Mn, Na, Ni, Pb, Sb, $SO_4$, and Zn exceed 'A-D' criteria, WHO guidelines (except B) and FAO recommendations (except Pb) where applicable (see HQ ranking below and Appendix A). Between 2009 and 2013, $SO_4$ and Mn concentrations increased by an order of magnitude (to 6267 mg/L and 31 mg/L, respectively), Fe, As, and Cd by two orders of magnitude (to 1201 mg/L, 1.6 mg/L and 2.0 mg/L, respectively), and Zn by 3 orders of magnitude (to 3692 mg/L). Tin exceeds UK non-statutory guidelines for protection of aquatic life. Calcium exceeded 'A' criteria. The water is observed as being of grey to brown-orange colouration and sometimes turbid.

Figure 5 shows the clear magnitude of contamination at MAD1 in comparison to river sites in the area, in so much as despite the low flow from the mine, the extremely high concentrations correspond to a huge flux of many elements from the mine exit, especially Zn (480 kg/day) and Al (48 kg/day). Figure 6a,b shows the scale of contamination at MAD1 by plotting pH and concentrations of $SO_4$, Zn, Fe, Cd, and As from the upper reach to downstream Poopó River; showing how these elements are orders of magnitude greater than in surface waters. Figure 6c, however, illustrates the impact of mining on surface waters by showing how downstream concentrations at POR3 are considerably higher than upstream concentrations (POR4). Figure 6b illustrates how Li and F are naturally sourced as these increase at CABTE thermal waters, which supports Figure 2e and related discussion in Section 4.1.

| ***WQR:* MAD1** | **10** |
|---|---|

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQ >1 in 2013 – 2014 at MAD1: Zn (4863-18463)> Fe (4004-12961)> Al (426-1408)> **Cd** (393-2801)> Mn (43-67)> **As** (32-180)> **Sb** (1-38)> **F** (2-4)> Co (0-4)>Mg (2)> **B** (1.5-2).

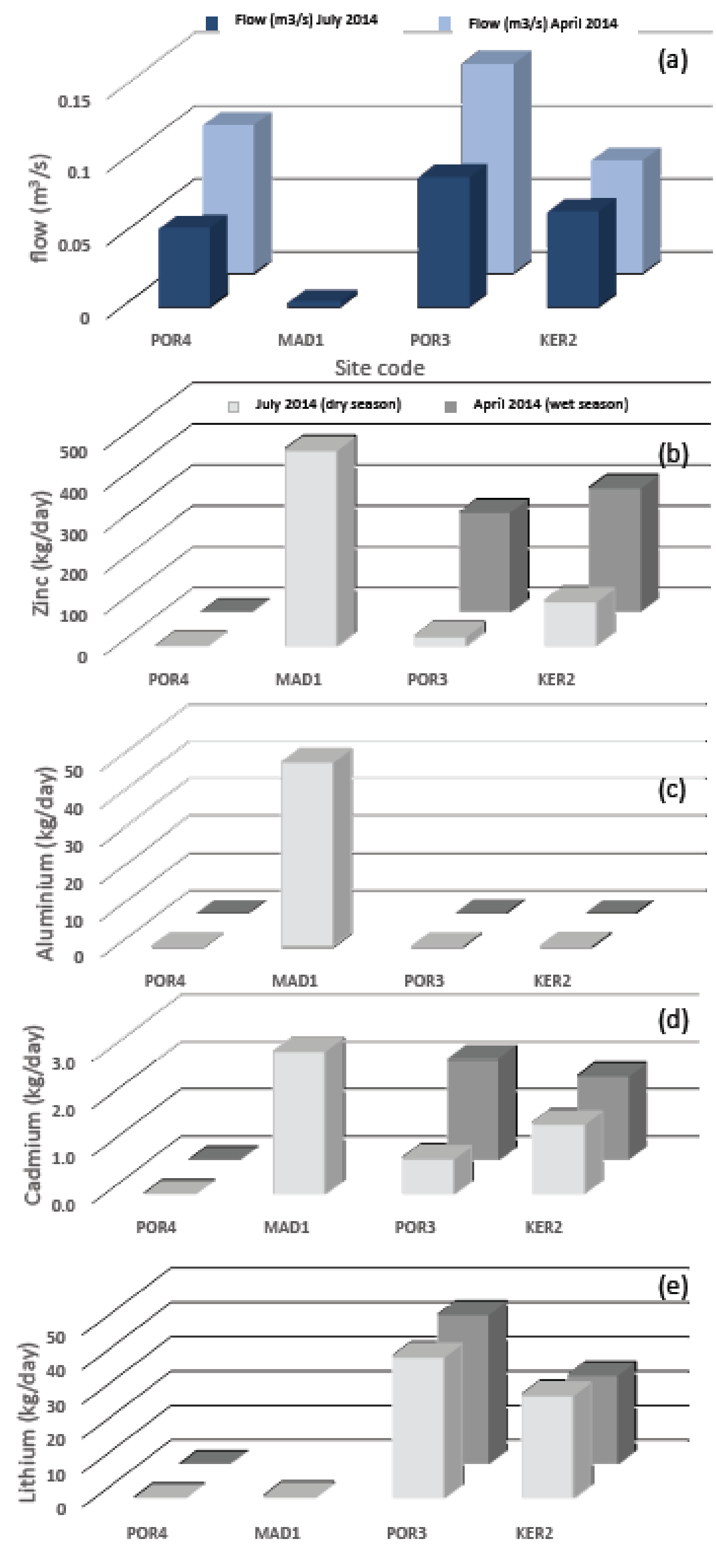


Figure 5 Graphs showing a) river flows ($m^3/s$, Appendix B), and b) zinc flux (kg Zn/day), c) aluminium flux (kg Al/day), d) cadmium flux (kg Cd/day), e) lithium flux (kg Li/day) during April (wet season) and July (dry season) 2014 at surface water sites in the Poopó area (refer to Figure 1 for site code locations). Fluxes determined from site metal concentrations (mg/L) and river flows ($m^3/s$ converted to L/s).

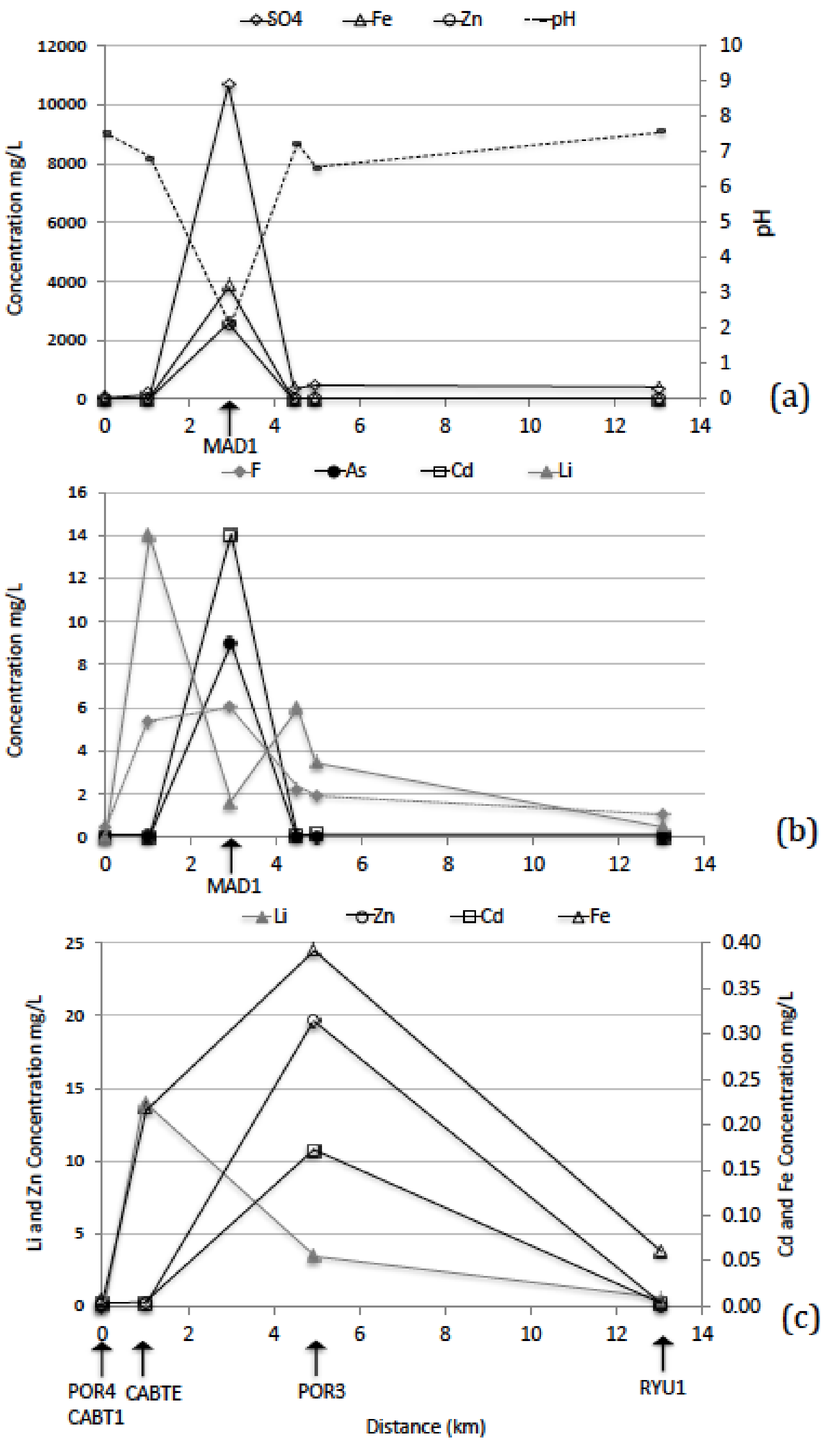


Figure 6 Graph showing concentrations (mg/L) of a) $SO_4$ (empty diamonds), Fe (empty triangles), Zn (empty circles) and pH (dashed line), b) Cd (empty squares), As (solid circles), F (grey diamonds), and Li (grey triangles) against approximate distance downstream in Poopó from POR4 (river), CABT1 tank (0.25 km), CABTE (thermal, 1.01 km), MAD1 (AMD, 2.92 km), TID1 (AMD, 4.47 km), POR3 (river, 4.95 km) and RYU1 (lake, 13.05 km) in April 2014, and c) Li (grey triangles), Zn empty circles), Cd (empty squares), and Fe (empty triangles) as data from (a) and (b) profiles without MAD1 or TID1 data.

***Site description TID1***

TID1 is a canal/channel leading from a mill on the western outskirts of Poopó Village (~3743 m a.s.l). There is a lot of general refuse in the area. Water here is captured (and contained) as it over-spills and seeps from a levee, and is re-used for mining purposes.

***Water quality status TID1***

The DO levels do not meet 'A-D' criteria. High EC (7.8 – 11.7 dS/m) values exceed recommendations for drinking water or irrigation. SAR values (42) are also very high. High TDS (~3800 mg/L) greatly exceeds 'A-D' criteria. Concentrations of elements in 2013 - 2014 are similar to 2007 – 2009 and generally lower than at MAD1. Boron, Cl, Cd, F, Fe, Mn, Na, Ni, Sb, $SO_4$, and Zn exceeds 'A-D' criteria (and FAO and WHO guidelines where applicable, see Table 1a) (see HQ ranking below and Appendix A). Arsenic exceeds 'A-C' criteria. Copper exceeds 'A' criteria and FAO recommendation. Calcium exceeds 'A' criteria. Li exceeds FAO recommendations. Tin exceeds UK EA guideline for protection of aquatic life. Water is observed as turbid and of yellowish colour.

| | |
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| ***WQR:*** **TID1** | **10** |

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQ >1 in 2013 – 2014 at TID1: Zn (HQ 16-6415)> **Cd** (15-310)> Fe (0-28)>**B** (3-6)> **Cu** (0-6.4)> Mn (2-3.5)> **Sb** (0-3)> **F** (1.5-3.4)> *Li (1.2-2.4)*> **Ni** (0-2)> **As** (0-1.2).

***Limitations on use MAD1 and TID1***

Water from AMD sites are unsuitable for any use due to HQs >10, acidic pH and EC>10. The spatial profile in Figure 6 from CABT1 to POR3 shows the orders of magnitude difference in concentrations of AMD relative to tank and river concentrations, emphasising the high level of contaminates in AMD sites. Of particular concern is the possibility of leakage to groundwater and adjacent surface water, and the high concentration of elements of health significance in TID1 mine water; Cd, As, Sb, B, Cu, Ni. It should be ensured that these waters be contained and treated (see Table 6, and Sections 8.1.4 and 8.2.7).

### 5.2.4. Poopó River: POR4, POR3

***Site description POR4***

The POR4 site (3812 m a.s.l) is in the upper reach of the Poopó River before Poopó Village (in the region of Cabreria in proximity of the CABT1 tank). It was not monitored during the CAMINAR project in 2007 – 2009, but was sampled as part of student projects (Rosenberg and Stålhammer, 2010). It was sampled for this study in April and July 2014. Flow varies seasonally (April 0.10 $m^3/s$, July 0.05 $m^3/s$, refer to Figures 2a, 5a and 7).

***Water quality status POR4***

The water at POR4 is observed as clear/transparent (July) to turbid with white-green colloidal material (April). The water is of good quality for the parameters assessed in this study, EC values are low (~0.4 dS/m) and within drinking water recommendations. SAR values are also low (0.8) and suggest some soil infiltration problems (depending on local soils) if used for irrigation (Table 1b). Dissolved oxygen was not measured. The only element exceeding 'A-D' criteria is Sb (0.02 mg/L), which is at the WHO guideline (Table 1a). Tin exceeded UK EA non-regulatory guideline for protection of aquatic life in April.

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|---|---|
| ***WQR:* POR4** | **3** |

***Limitations on use and initial recommendations***

The only restriction on water at POR4 for the elements assessed in this study is for Sb, which is twice 'A' criteria but the same concentration as the WHO health-based guideline. Basic treatment for potable water applies if used for human consumption (Section 8.1). The water is of good chemical quality for livestock and also for irrigation but infiltration problems may occur. A water quality analysis should be made to assess microbial contamination, especially due to observed colloidal material, which may suggest poor biological quality.

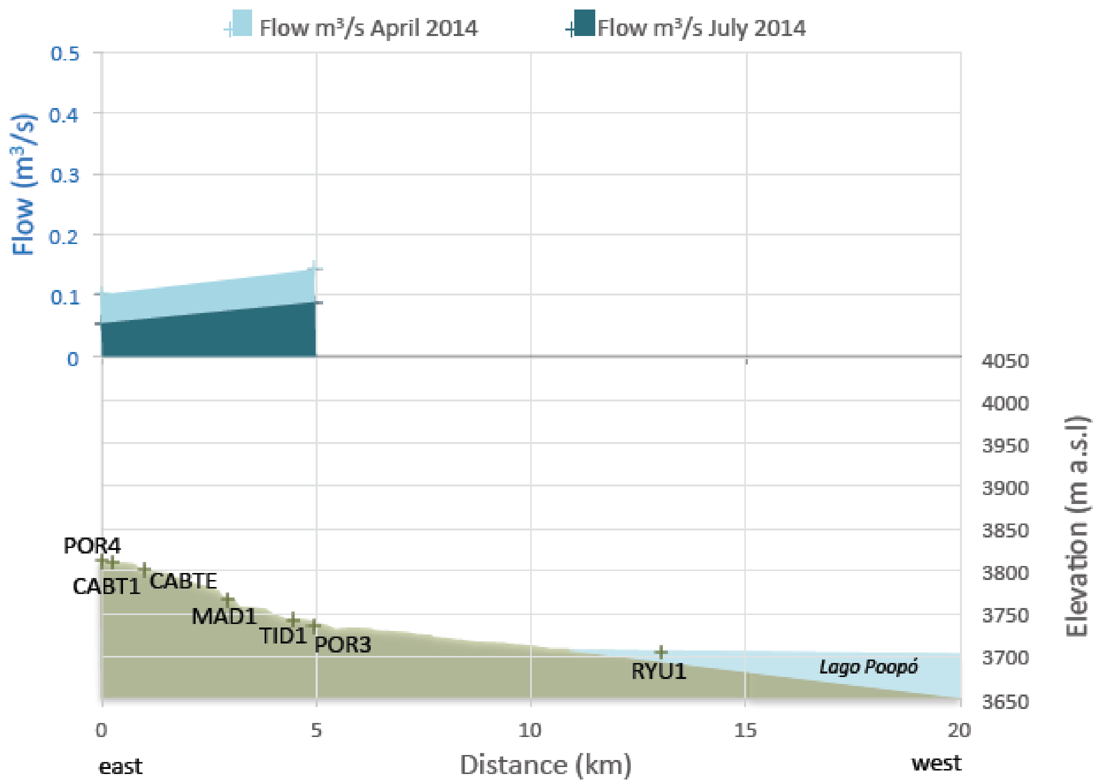


Figure 7 Conceptual elevation (m a.s.l. exaggerated by 20 relative to x axis) cross-section along the Poopó River (east to west, solid shaded area as land mass), including accretion profile from POR4 to POR3 (flow, $m^3/s$) in April 2014 (dark and light shaded area) and July 2014 (light shaded area).

***Site description POR3***

The POR3 site (~3735 m a.s.l) is in the lower reaches of the Poopó River after Poopó Village and numerous mines. It is below the main road and near the Tiahuanaco mill. There is a lot of general refuse in the area. Flow varies seasonally (April 0.14 $m^3$/s, July 0.09 $m^3$/s, refer to Figures 2a, 5a and 7), and flows in the lower reach of the Poopó River are around half of those in the Pazña River (at PAZP1, Appendix B). Further downstream from POR3 the river discharges into Lake Poopó.

***Water quality status POR3***

In 2013 - 2014 EC values (up to 9.4 dS/m) greatly exceed that recommended for drinking water or irrigation use. However, a low EC value (0.8 dS/m) was obtained in December 2013, perhaps due to high rainfall/dilution and/or lack of mining activity/waste inputs; $SO_4$ and most metals were very low, but fluoride remained similar to other sample periods when metals and EC were high. Similarly, a low TDS was obtained in December (403 mg/L) in comparison to other sampling periods (~4700 mg/L) that greatly exceeds 'A-D' criteria. SAR values (27) are very high. During 2007 – 2009 all samples from POR3 exceeded 'A-D' criteria, WHO and FAO recommendations for Cl, F, Na, and Cd. Some samples exceeded 'A' criteria for Zn, Pb, $SO_4$ and Fe. Samples in 2013 - 2014 (i.e., excluding December data when samples may have been affected by other factors) exceeded 'A-D' criteria, FAO irrigation recommendations and WHO guidelines (except Fe) for B, Cd, Fe, Mn, Na, and Zn (see HQ ranking below and Appendix A for data). Chloride and Ca exceeded 'A' criteria. Tin exceeded UK EA non-regulatory guideline for protection of aquatic life. The water is observed as being turbid throughout the year sometimes with suspended solids and of a brown-yellow colour.

Figure 5 and 6c illustrates the impact of mining at POR3 by showing how concentrations of Zn and Cd are considerably higher than upstream concentrations (POR4). Figure 6 also shows how Fe is sourced naturally and from mining, and how Li is naturally sourced (i.e., increases at CABTE thermal site).

| ***WQR:* POR3** | **8** |
|---|---|

***HQ: metal ranking and concerns*[1]**

Trace metals [1]HQ >1 in 2013 – 2014 (excluding December 2013) ranked at POR3: Zn (HQ 16-101)> **Cd** (20-34)> Fe (0-13)> **B** (3.6-5.8)> Mn (1.4-4.4)> *Li (1.4-2.1)* ~**F** (1.3-2.6).

***Limitations on use***

POR3 is not suitable for human (or livestock) consumption or irrigation without treatment based on very high EC, Zn, Cd, and Na, and on high Cl, Fe, B, and Mn. Of particular concern are elements of health significance; Cd, F and B. The river here appears to be significantly affected by mining activity, but may be diluted during the rainy season. Control of mining activities and containment of upstream mine waste is recommended.

5.2.5. Lake Poopó (Poopó River tributary): RYU1

***Site description***

The RYU1 is a lake site (~3705 m a.s.l) situated on the bridge that connects Poopó Village with Choro, opposite the Poopó River tributary input to Lake Poopó (location shown in Figure 3). There are a lot of totoral plants growing in the area. This is a new site sampled in April and July 2014.

***Water quality status***

EC values (~3.2 – 3.7 dS/m) exceed recommendations for drinking water or non-restricted irrigation. SAR values are ~10. Total dissolved solids (TDS, 1597-1829 mg/L), Cl (~750 mg/L), B (~3 mg/L), and Na (~550 mg/L) exceeded 'A-D' criteria, WHO guidelines and FAO irrigation recommendations. 'A-B' criteria are exceeded for $SO_4$ (>300 mg/L). In July, F (3.4 mg/L) exceeded all guidelines. In April, Cd was just over WHO guidelines (0.003 mg/L, meets 'A-D' criteria). Tin exceeds UK EA non-regulatory guideline for protection of aquatic life.

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| ***WQR:*** **RYU1** | **7** |

***Limitations on use***

The water at RYU1 is not suitable for human (or lower tolerant livestock) consumption due to high EC, and concentrations of Na, Cl, and B, and sometimes F and Cd. It is not recommended for irrigation since EC>3 dS/m are considered as requiring a high-level irrigation management strategy (Table 1b).

## 5.3. Kesukesuni

5.3.1. Kesukesuni River: KER1

***Site description***

KER1/2 are river sites (continuation/tributary of the Poopó River tributary) in the Kesukesuni Village (~3714 m a.s.l, Figures 1 and 3) that were not monitored by the CAMINAR project in 2007 - 2009. This area is used for sheep grazing. The river flow (at KER2) varies a little seasonally but was not monitored at KER1. KER1 was only sampled in December 2013, as KER2 was unaccessable.

***Water quality status KER1***

Chemical data in 2013 - 2014 suggest that the river at KER1 may have been diluted by rainfall at the time of its only sampling in December 2013 (EC 1.7 dS/m, TDS 843 mg/L), because the adjacent KER2 (see Section 3.3.2) at other times had a much higher EC (6-9 dS/m) and TDS (unless the former, in December, was a non-mine waste input period). The SAR value at KER1 in December (9) was also considerably less than at KER2 in April (30). Levels of DO are low (~28% saturation) and do not meet 'A-D' criteria. Fluoride (3.5 mg/L) exceeds all guidelines. Antimony (Sb, 0.03 mg/L) exceeded 'A-D' criteria and WHO guidelines (see HQ ranking below and Appendix A). Chloride and Na exceed 'A-B' criteria and FAO irrigation recommendations.

Arsenic (0.03 mg/L) met 'A' criteria (and FAO) is just over WHO guidelines. Boron exceeds 'A-D' criteria and irrigation recommendations (1.1 mg/L, meets WHO). Zinc exceeds 'A-B' criteria (0.97 mg/L, meets FAO and WHO guidelines). Tin exceeds the UK EA guideline for protection of aquatic life.

| ***WQR:* KER1** | **6** |
|---|---|

***HQ: metal ranking and concerns*[1]**

Trace metals [1]HQ>1 in December 2013 ranked at KER1: Zn (HQ 5)> **Sb** (2.5)>**F** (2.3)>**B** (1.1).

***Limitations on use***

KER1 (in the rainy season) is of better quality than KER2 but is unsuitable for human consumption due to EC, and elements of health significance F, Sb, As, and Cd. Waters are generally chemically acceptable for livestock with the exception of F. KER1 (in the rainy season) is not really recommended for non-restricted irrigation due to F, B, Cl, and Na, but might be acceptable with restriction, e.g., special management strategy or for particular crops (Table 1b). The poor quality of the river at KER2 suggests caution for use of the river water at KER1 since this site was only sampled in December 2013.

### 5.3.2. Kesukesuni River: KER2

***Site description***

KER2 is adjacent to KER1 and was also not monitored by the CAMINAR project in 2007 - 2009 The site was sampled in April and July 2014. The river flow (at KER2) varies a little seasonally (April 0.0775 $m^3/s$, July 0.0065 $m^3/s$, Figure 2a and 5a, Appendix B). The river water is observed as being turbid and of brown-yellow coloration.

***Water quality status KER2***

The river at KER2 has high EC (6.5 – 9.2 dS/m) and TDS (3224 - 4608 mg/L) that greatly exceed recommendations for drinking water or irrigation. SAR values (30) are very high. Concentrations of Zn, Cd and Fe are very high, and exceed 'A-D' criteria, FAO recommendations and WHO guidelines (except Fe) (see HQ ranking below and Appendix A). All criteria and guidelines are also exceeded for $SO_4$, Cl, Na, F, B, Mn, and Sb at KER2. Lithium exceeds FAO irrigation recommendations, and Sn exceeds the UK EA guideline for protection of aquatic life. The fluxes of some metals at KER2 is shown in Figure 5 in comparison to POR4 and POR3 and further support that the river is affected by mining activity.

| ***WQR:* KER2** | **8** |
|---|---|

***HQ: metal ranking and concerns*[1]**

Trace metals [1]HQ>1 in 2014 ranked at KER2: Zn (HQ 97-225)> **Cd** (53)> Fe (0-40)> **B** (4.1-5.6)> Mn (3)> *Li (1.6-2.1* > **Sb** (1.9-3.4)> **F** (0-1.1).

***Limitations on use***

KER2 is of poor quality for and similar to POR3. The river appears to be affected by mining activity and is unsuitable for human consumption, livestock or irrigation due to very high Zn, Cd and Fe, and high EC, B, Mn, Sb, F, Li, Na, Cl, and $SO_4$. Of particular concern are elements of health significance; Cd, F, B, and Sb. Control of mining activities and containment of upstream mine waste is recommended.

## 5.4. Puñaca

### 5.4.1. Water source site: PUNP1 tap

***Site description***

The PUNP1 site is the tap in the school of Puñaca village (location in Figure 3), which has a piped network for drinking water that is supposedly water treated by chlorination, that has originated from storage tanks containing spring water from upstream of Poopó Village. This is a new site monitored in April and July 2014.

***Water quality status***

The tap water is of clear appearance and of good chemical quality for the elements assessed here. EC values are low (0.3 dS/m) and are within drinking water recommendations, and no measured parameters exceed criteria.

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| ***WQR:*** **PUNP1** | **2** |

***Limitations on use and initial recommendations***

PUNP1 tap water is of good quality and has no restrictions for use for the chemical parameters analysed in this study. Basic treatment for potable water applies (Section 8.1). A water quality analysis should be made to assess microbial contamination.

### 5.4.2. Water source site: PUNP2 well

***Site description***

The PUNP2 well is in Puñaca Village (~3712 m a.s.l). The well is ~5.3 m deep and has a concrete surround/stand, fitted lid and a hand pump and is used for irrigation (potato) and livestock watering (sheep). This is a new site monitored in April and July 2014. The water level in the well reduced very little (0.06 m) between mid-April (4.68 m b.d) and mid-July (4.74 m b.d).

***Water quality status***

Electrical conductivity values (~0.9 - 1 dS/m) are at the upper limit of recommendations for drinking water but still acceptable (maximum 1.5 dS/m as equivalent of 1000 mg/L TDS) and also not too bad for irrigation. SAR values are low (2). Fluoride (2.2 – 3.2 mg/L) exceeds all guidelines. In April 2014, As (0.08 mg/L) and Mn (3.2 mg/L) exceeded 'A-D' criteria and WHO guidelines, and Boron (1.1 mg/L) exceeded ‘A-D’ and irrigation recommendations. In July 2014, water quality improved as concentrations were below guidelines with the exception of Sb (0.22 mg/L), which exceeded all criteria. In July, Sn exceeded the UK EA guideline for protection of aquatic life. The well water is observed to be clear but at times with some decomposing organic material.

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| ***WQR:*** **PUNP2** | **5** |

***HQ: metal ranking and concerns[1]***

Trace metals [1]HQ>1 in 2014 ranked at PUNP2: Mn (HQ 0-6.5)> **F** (1.5-2.1)> **Sb** (2.2)> **As** (0-1.6)~ **B** (0-1.1).

***Limitations on use and initial recommendations***

PUNP2 well water is not recommended for human consumption due to elements of health significance F, As, Sb, and also B and Mn. Treatment for these elements are recommended, as is basic treatment for potable water (Section 8.1). A water quality analysis should be made to assess microbial contamination if it is used for consumption. Water from the well is chemically acceptable for livestock with the exception of F and Mn. It may also be suitable for certain irrigation use, i.e., less sensitive crops that can tolerate F, Mn and B. The well should be pumped before use and sampling in the future.

## 5.5. Callipampa, Morochi and Quellea

### 5.5.1. Water source site: CALLP3 well

***Site description***

The CALLP3 well is located in Callipampa Village (~3717 m a.s.l). The well is ~7.5 m deep and has a concrete surround/stand, fitted lid and hand pump and is used as a source of water for irrigation, livestock and human consumption. Well levels and rainfall during the study period are shown in Figure 4. Although the well depth was not taken in December 2013, the water level increased by 1.6 m between mid-August 2013 (7.30 m b.d) and mid-April (5.70 m below datum). Three months later in mid-July 2014 levels reduced by 0.66 m (to 6.36 m b.d) (Appendix B), which was still ~1 m higher than the previous year (Figure 4).

***Water quality status***

Electrical conductivity values (0.7 - 0.8 dS/m) of the well water are within recommendations for drinking water and irrigation, but low SAR values (~3.2) may indicate slight infiltration problems depending on local soils (Table 1b). Data from 2007 – 2009 and 2013 - 2014 indicates that the chemical water quality here is of good quality with the exception of low DO level (~13% saturation), which does not meet ‘A-D’ criteria, and Fluoride (1.5-3.6 mg/L) that exceeds all guidelines. In August 2013, B (1.2 mg/L) concentrations exceeded ‘A-D’ and irrigation criteria (met WHO). Tin generally exceeds UK EA non-regulatory guideline for protection of aquatic life. The water from the well is observed as being usually clear, but occasionally slightly turbid.

| *WQR:* **CALLP3** | **4** |
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***Limitations on use and initial recommendations***

Although of good chemical quality, the use of the well as a human water source is limited due to F concentrations that exceeds WHO health-based guidelines. Also, low DO levels and turbidity may indicate poor biological status. The well should be pumped before sampling and use, and a water quality analysis should be made to assess microbial contamination. The water is suitable for irrigation with the exception of F and B (just over FAO recommendation), although soil infiltration maybe problematic. The well water is chemically acceptable for livestock.

5.5.2. Water source site: PQUE1 well

***Site description***

The PQUE1 well is located in Quellía Village (~3708 m a.s.l) near Callipampa. The well is ~5.4 m deep and has a concrete stand, fitted lid and both hand and electric pumps. The well water is used for human consumption, irrigation water for crops (alfalfa, potatoes) and for cattle consumption. This was a new site sampled in April and July 2014. The water level in the reduced a little (0.13 m) between April (3.98 m b.d) and July (4.11 m b.d).

***Water quality status***

EC values (~2.3 - 2.6 dS/m) at the well exceed recommendations for drinking water and non-restricted irrigation use. SAR values (21) are very high. Chloride, As (0.06 - 0.1 mg/L), B (2.6 - 2.9 mg/L), and Na exceed 'A-D' criteria and WHO guidelines (and irrigation recommendations for all except As). TDS (1169 – 1293 mg/L) exceed 'A-B' criteria, and $NO_3$ concentrations (40 mg/L) exceed 'A-B' and FAO recommendations. In July 2014, F concentrations (2.4 mg/L) exceeded all guidelines. Tin exceeds UK EA non-regulatory guideline for protection of aquatic life.

| *WQR:* **PQUE1** | **7** |
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***HQ: metal ranking and concerns***[1]

Trace metals [1]HQ >1 in 2014 at PQUE1: B (2.6-2.9)> **As** (1.3-1.9)> **F** (0-1.6)

***Limitations on use and initial recommendations***

The PQUE1 well is not suitable for human consumption or irrigation due to high EC, As, B, F, and $NO_3$ concentrations. Particular concern relates to exceedances for elements of health significance; As and F. Water from the well is chemically acceptable for livestock. A water quality analysis should be made to assess microbial contamination if it is to be used for consumption despite the exceedances. The well should be pumped before use and sampling in the future.

5.5.3. Water source site: PMO1 well

***Site description***

The PMO1 well is located in Morochi Village (~3712 m a.s.l) near Callipampa Village. The well is ~3.9 m deep and has a concrete stand and is operated by a manual pump. Well water is used for human consumption, as irrigation water (for alfalfa, potatoes and barley) and for cattle. The water level increased by 0.24 m between April (2.54 m b.d) and July 2014 (2.30 m b.d) (Appendix B).

***Water quality status***

The EC values of water from the well are low (0.4 dS/m) and are within drinking water recommendations. SAR values are low (0.9) and suggests infiltration problems if used for irrigation (Table 1b). DO is not known. In April 2014, As (0.085 mg/L) exceeded 'A-C' criteria and WHO guidelines. In July 2014, F (3.0 mg/L) and Sb (0.022 mg/L) exceeded all guidelines. Tin exceeds UK EA non-regulatory guideline for protection of aquatic life.

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| ***WQR:*** **PMO1** | **4** |

***Limitations on use and initial recommendations***

The well is limited for human consumption due to elements of health significance; F, As and Sb. Treatment to reduce these elements is recommended, and basic treatment for potable water applies (Section 8.1). The well should be pumped before sampling and use, and a water quality analysis should be made to assess microbial contamination. The water is chemically acceptable for livestock. There is no restriction for irrigation use but soil infiltration maybe problematic depending on local soils.

## 6. ANTEQUERA & PAZÑA MUNICIPALITIES

Figure 8 shows sample sites within the Antequera and Pazña municipalities. These are discussed by proximity to the nearest river; the Antequera, Urmiri or Pazña River. Sites along the Antequera River include one AMD site (BODI1), six river sites (TOTR1, TOTR2, AVR2, AVR1, AVR3, LCR1), one slope site (TOTV2), two wells (TOTP5, PALP10), and one tank (CUCC1). Mines in along the channel area include the Totoral and Avicaya mines. In the area of the Urmiri River, sample sites include one thermal water site (URLT1), one slope site (URV1), one channel site (URC1), and three river sites (URR1, URR2, URR3). In the area of the Pazña River, sample sites include one thermal water site (PAZTE), six well sites (VIP1, PALP7, PALP8, PAZP3, PALP3, PALP4), and two river sites (PALR2, PAZR1).

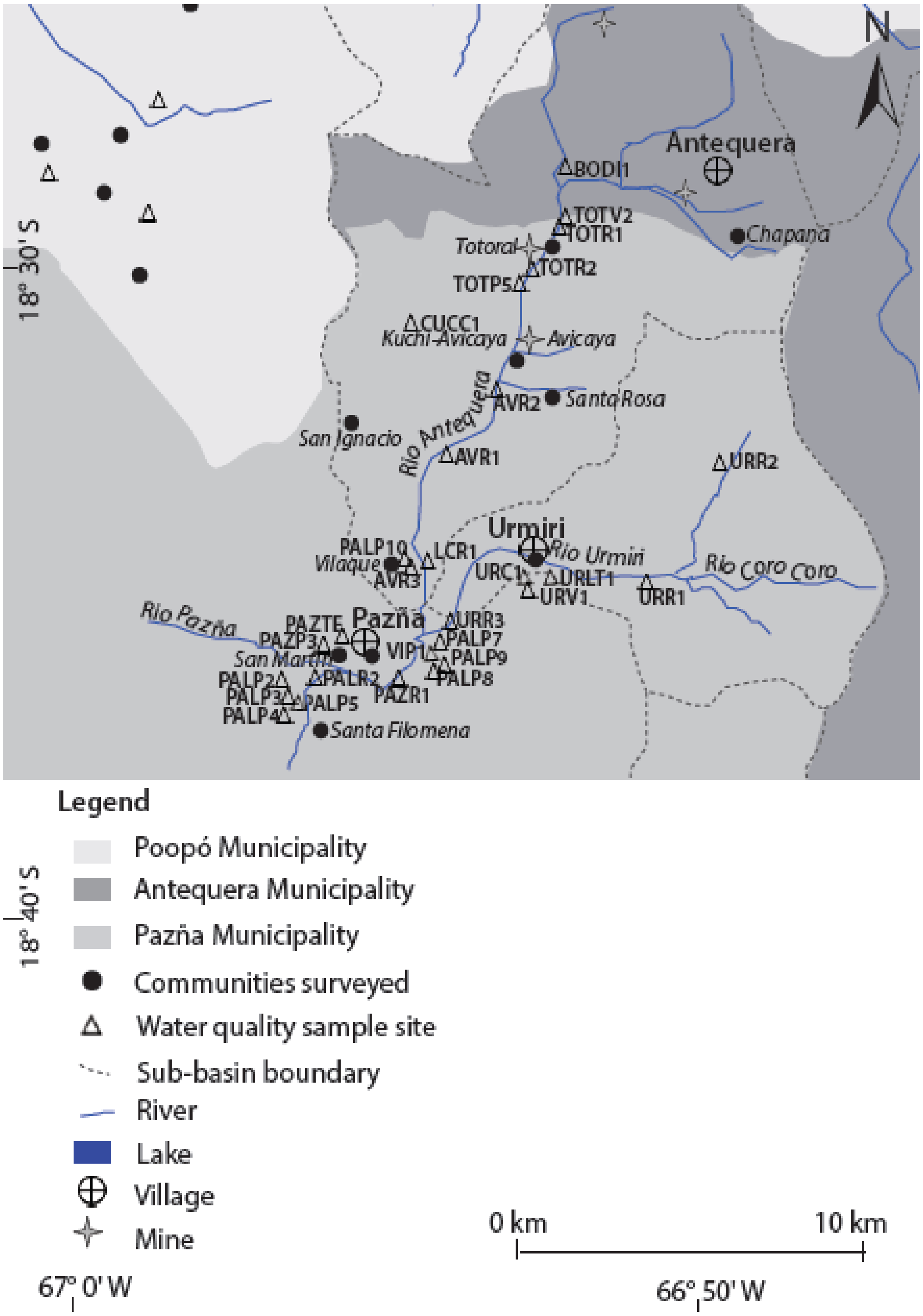


Figure 8 Map showing sampling sites in Antequera and Pazña municipalities.

### 6.1. Antequera River area: Totoral and Avicaya

6.1.1. Water sources sites: TOTV2, TOTP5, CUCC1, PALP10, LCR1

***Site description TOTV2***

TOTV2 is a slope site (3915 m a.s.l) upstream of the Totoral mine that is cased with plastic tubing that feeds into a small concrete tank (overflows to the river) that is used as a source of water for domestic purposes.

***Water quality status TOTV2***

EC values (~0.4 dS/m) are within recommendations for drinking water and irrigation. SAR values (0.8 – 2) suggest infiltration problems for irrigation use (depending on local soils, Table 1b). Data from samples in 2008 – 2009 show that the chemical quality of the water sampled here met ‘A’ criteria with the exception of Zn (met class C, WHO and FAO recommendations). Samples taken in 2013 – 2014, however, show poorer quality; generally ‘A-D’ criteria and WHO guidelines are exceeded for F (0.9 - 3.4 mg/L, also exceeds FAO recommendations). In December 2013, As (0.05 mg/L) and Al (0.2 mg/L) exceeded ‘A-B’ criteria and WHO guidelines. In December, Sb (0.03 mg/L) exceeded ‘A-D’ criteria and WHO guidelines. In April and July 2014, Cd (0.004 - 0.006 mg/L) exceeded the WHO guideline. All samples exceed ‘A-B’ criteria for Zn (meet other guidelines). Levels of DO (<40%) do not meet ‘A-D’ criteria. The water is observed as being usually clear but turbid during the rainy season.

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| ***WQR:* TOTV2** | **6** |

***HQ: metal ranking and concerns[1]***

Trace metals [1]HQ>1 in 2013 – 2014 ranked at TOTV2: Zn (HQ 1.4-6.8)> **Sb (0-3)**> **F** (1.6-2.2)> Al (0-1) ~**As (0-1)**.

***Limitations on use and initial recommendations***

TOTV2 water is not recommended for human consumption, in particular due to concentrations of elements of health significance; Sb, F and As. Treatment to reduce these elements is recommended and basic treatment for potable water applies if used for human consumption, and a water quality analysis should be made to assess microbial contamination. However, high Zn concentrations and the proximity to mine water highlight caution as it may be affected by mine water migration. Keeping this in mind, it is in fact acceptable for livestock and irrigation with the exception of fluoride. Also, soil infiltration maybe problematic if used for irrigation depending on local soils.

***Site description TOTP5***

TOTP5 is a shallow well (2.30 m) located on a slope at the foot of a small hill (3900 m a.s.l) downstream of the Totoral mine (location in Figure 8). The well is covered with a loose metal lid. The well is often dry in the winter (July and August), but after rainfall in November and early December 2013 (Figure 4 shows rainfall) the water level was 2.17 m b.d in mid-December, and after continued rainfall the water level increased by 0.77 m to 1.40 m b.d in April 2014 before becoming dry again 3 months later in July (Appendix B). When available, water is used as a source of water for domestic use.

***Water quality status TOTP5***

EC values range from ~0.5 dS/m to 1.3 dS/m. SAR values are ~3. Levels of DO (~20% saturation) do not meet ‘A-D’ criteria. Between 2009 and 2013, pH became more acidic (pH 6 to ~4). In 2008

- 2009, some sample exceeded 'A' criteria (and WHO guidelines where applicable except for Zn) for As, Fe, Mn, Zn, Na and Cl. In 2013 - 2014, 'A-D' criteria (WHO and FAO guidelines where applicable) were exceeded for Al, Cd, F, Fe, Ni, and Sb (see HQ ranking below and Appendix A). 'A' criteria were exceeded for Cu, Mn and Zn. Occasionally 'A-D' criteria are exceeded for B and $SO_4$. FAO recommendations were exceeded for Cd, Cu, Fe, Li and Mn. When there is water in the well (summer) it is sometimes observed to be turbid.

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| ***WQR:* TOTP5** | **8** |

***HQ: metal ranking and concerns[1]***

Trace metals [1]HQ>1 in December 2013 and April 2014 ranked at TOTP5: Al (HQ 18-128)> Fe (19-47)> **Cu** (5.7-37)> **Cd** (6-18)> Zn (7.6-13.3)> **Ni** (1.6-8.3)> **Sb** (0-3.8)> **F** (2.6)> Co (0-3.6)> Mn (1.2-1.8)> **B** (0-1.4).

***Limitations on use***

TOTP5 is unsuitable for human (or livestock) consumption or irrigation due to very high Al, Fe, Cu, Cd, and Zn, and high Ni, and F, and occasionally As, Sb and B. Particular concern related to elements of health significance; Cu, Cd, Ni, Sb, F and As. High metal concentrations appear to be sourced from the mining activities in the area, which should be controlled and waste contained.

***Site description PALP10***

PALP10 is a shallow (1.3 m), open-hole well (~ 3750 m a.s.l, near Vilaque and the AVR3 sample site) that has a loose metal lid that sits on a wood/stone stand. There is a lot of straw around the well, which is located near a shed housing livestock. The well water is used for domestic purposes, and for livestock and human consumption. The water levels in the well during the study period are shown in Figure 4. The water level varied little between mid-August (0.65 m b.d) and mid-December 2013 (0.69 m b.d), it was not monitored in April 2014, but the water level in July 2014 was 0.40 m b.d (Appendix B); an increase of 0.29 m relative to December and therefore again appears to have been a delayed response to summer rainfall (Figure 4).

***Water quality status PALP10***

The well water is of fair quality with the exception of low to zero DO, which does not meet 'A-D' criteria. TDS (~400 mg/L) meet 'A-D' criteria. EC values (0.7 – 1 dS/m) are at the upper threshold of drinking water recommendations (<0.9 dS/m), and are an order of magnitude less than wells further downstream in Pazña. SAR values are low (~1-2) and suitable for irrigation. Similarly, Na and Cl concentrations at PALP10 are also one to two orders of magnitude less than the other wells sites and meet all guidelines. Some $SO_4$ concentrations in 2007 – 2009 exceeded 'A' criteria. In 2013 - 2014, F (2.9 - 3.6 mg/L) and Mn concentrations exceeded 'A' criteria, FAO and WHO guidelines. In April and July 2014, Fe exceeded 'A-D' criteria. In July 2014, Cd (0.03 mg/L) was at the WHO guideline. Tin exceeds UK EA non-statutory guidelines for protection of aquatic life.

| ***WQR:* PALP10** | **4** |
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***Limitations on use and initial recommendations***

PALP10 is not recommended for human consumption due to F, Mn, and sometimes Cd concentrations. Concentrations of Fe are also high and may affect taste. If used for human consumption treatment for these elements is recommended, in addition to basic treatment for potable water (Section 8.1) and a water quality analysis to assess microbial contamination. It is not too bad for irrigation with the exception of F and Mn (depends on crop sensitivity). It is chemically acceptable for livestock with the exception of F. The well should be pumped before sampling in the future, and the well cover improved (see Table 6).

***Site description LCR1***

The LCR1 site is at a weir located on the Laca Laca River (3746 m a.s.l), which is a tributary feeding into the Antequera River (near AVR3). There are a lot of algae in the river before and after the weir (observed during the winter/dry season). The water might be used for livestock consumption and possibly for human consumption. This site was only monitored in July 2014.

***Water quality status LCR1***

EC values in July 2014 (~1.5 dS/m) were above recommendations for drinking water. Although EC is above general recommendations for non-restricted irrigation, SAR values are low (1.3) and suitable for irrigation. However, in July 2014, all guidelines were exceeded for Zn (39.1 mg/L). 'A-B' criteria and WHO guidelines were exceeded for Ni (0.2 mg/L) and Cd (0.006 mg/L, also fails 'C-D' criteria) (see HQ ranking below and Appendix A). 'A-D' criteria and FAO irrigation recommendations were exceeded for $SO_4$ (654 mg/L). Tin exceeds UK non-statutory guidelines for protection of aquatic life. DO was not measured.

| ***WQR:* LCR1** | **6** |
|---|---|

***HQ: metal ranking and concerns[1]***

Trace metals [1]HQ>1 in July 2014 ranked at LCR1: Zn (196)> **Ni** (4.1)> **Cd** (1.2).

***Limitations on use and initial recommendations***

Water from LCR1 is unsuitable for human consumption due to EC values, very high Zn, and high Ni and Cd, which both have WHO health-based guidelines. The river is strongly affected by algae, probably due to nutrient inputs. It is not recommended for non-restricted irrigation for these reasons. It is not recommended for livestock due to Zn concentrations as these as twice the maximum recommended for livestock. High Zn levels in particular suggest mine waste has affected this river either directly or through runoff/infiltration. Sourcing and containing Zn and other metals is recommended.

***Site description CUCC1***

In the area of Kuchi-Avicaya (3867 m a.s.l, location in Figure 8) and west of the Antequera River is CUCC1, which is an open concrete pool (volume ~150 $m^3$) that holds water channelled through a concrete channel from ~1km to the north after several small mountain rivers confluence (Appendix C). The input water is of quite small volume (July 0.004 $m^3$/s) and there are a lot of algae in the pool. Water from the pool is used as a source of water for irrigation and water from the channel may possibly be used human consumption. The channel, not the pool was sampled.

***Water quality status CUCC1***

EC values (~0.2 dS/m) are within recommendations for drinking water and irrigation. SAR values are low (0.2) and suggest problematic water-soil infiltration (Table 1b). Data from 2008 – 2009 and 2013 - 2014 met 'A-D' criteria, FAO recommendations and WHO guidelines for all measured parameters except for most F (1.1 – 3.3 mg/L) concentrations that exceed all guidelines, As (0.03 mg/L) in December 2013 that exceeded WHO guidelines, and DO since levels are low (<50% saturation) and do not meet 'A-D' criteria. Although the water is quite clear, there are algae in the pool.

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| ***WQR:*** **CUCC1** | **3 channel (pool unknown)** |

***Limitations on use and initial recommendations***

Water from the channel prior to entering the pool at CUCC1 is of relatively good chemical quality for human consumption with the exception of F that exceeds WHO health based guidelines. Treatment to reduce F is recommended, and basic treatment for potable water applies if used for human consumption as well as assessment for microbial contamination. Water is chemically acceptable for livestock and also for irrigation with the exception of F, but soil infiltration may be problematic if used for irrigation depending on local soils. The presence of algae in the pool highlights that it should be cleaned regularly and may be of poorer quality than assessed above. Future samples should be taken from within the pool itself, and not just the channel draining into it. Covering the pool with a rollback cover is recommended to prevent evaporation losses and contamination (Table 6).

### 6.1.2. AMD site (BODI1)

***Site description***

The BODI1 site is in the upper Antequera catchment (~3928 m a.s.l) and is a channel that contains water from an old dam, which is directed towards Martha mine. This area is near many mining activities (Bolivar mine) and waste ponds.

***Water quality status***

The water at BODI1 has high EC values (3.5 – 4.3 dS/m) that exceed recommendations for drinking water and irrigation use. SAR values are low (~1). TDS (~2000 mg/L) exceed 'A-D' criteria. Levels of DO do not meet ‘A-D’ criteria as they are below 50% saturation. Concentrations of $SO_4$ are an order of magnitude greater than ‘A-D’ criteria and FAO recommendations. ‘A-D’ criteria, FAO recommendations, and WHO guidelines are exceeded for Zn, Cd, Mn, and F, primarily during the rainy season when concentrations are significantly higher than the dry season. Tin exceeds UK EA non-statutory guideline for protection of aquatic life. Water is generally observed to be clear and transparent.

| ***WQR:* BODI1** | **8** |
|---|---|

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked at BODI1: Zn (0-69)>**Cd** (1-38)>Mn (0-2.5)>**F** (0-3)~Sb (0-2).

***Limitations on use***

The water at BODI1 is unsuitable for human (or livestock) consumption or irrigation purposes based on very high concentrations of Zn and Cd in the wet season, and high EC, Mn and F. However, the water quality at BODI1 is better than at sites further downstream on the Antequera River. Control of local mining activities and containment of waste is necessary (see Table 6, and Sections 8.1.4 and 8.2.7).

### 6.1.3. Antequera River sites: TOTR1, TOTR2, AVR2, AVR1, AVR3

***Site description***

TOTR1 (3905 m a.s.l), TOTR2 (3888 m a.s.l), AVR2 (3837 m a.s.l), AVR1 (3784 m a.s.l), and AVR3 (3748 m a.s.l) are sites located on the Antequera River (Figure 8 for locations, Figure 9 elevation and accretion profile). The river is characterised by mining activity and associated tailing heaps that are within and at the sides of the river channel. There is a large mine waste water pond to the east of AVR1 (Appendix C). There is a lot of general refuse in the river channel and little vegetation. Flows in the upper reach are similar seasonally, possibly as they are groundwater fed (e.g., TOTR1 April 0.15 $m^3/s$, July 0.19 $m^3/s$, Figures 2a and 9, and Appendix B for data). Spatially, flows nearly double in the rainy season from upstream TOTR2 (April, 0.18 $m^3/s$) to the lower reach AVR3 (April, 0.25 $m^3/s$, Figure 9) due to rainfall and runoff/tributary inputs. In contrast, the river loses from upper to lower reaches in the dry season (TOTR2 July, 0.15 $m^3/s$, AVR3 July, 0.11 $m^3/s$, Figure 9), which again supports the idea that the upper reach is groundwater fed.

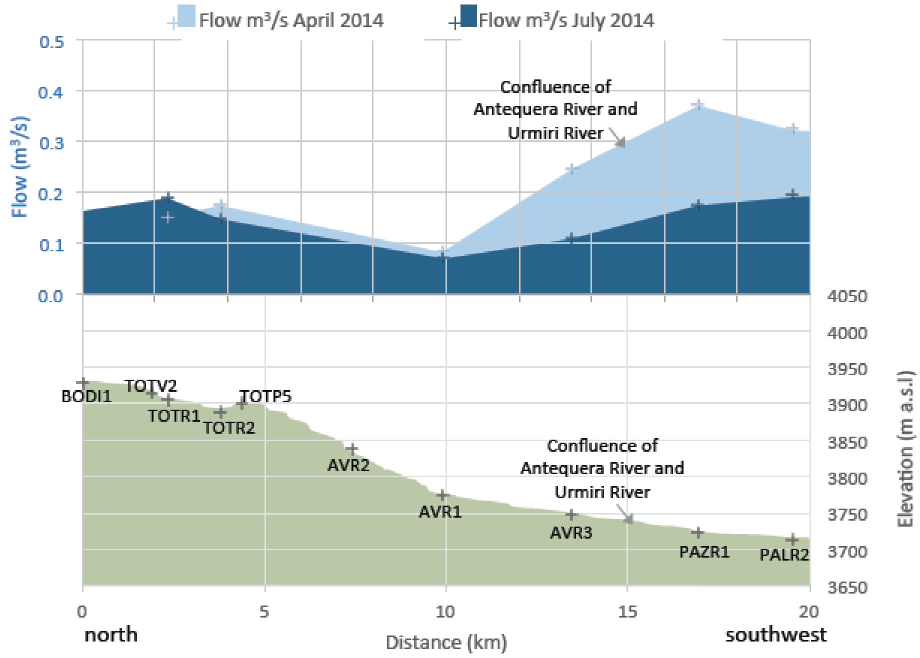


Figure 9 Conceptual elevation (m a.s.l. exaggerated by 20 relative to x axis) cross-section along the Antequera – Pazña River (north to southwest, solid shaded area as land mass), including accretion profile from TOTR1 to PALP2 (flow, $m^3/s$) in April 2014 (dark and light shaded area) and July 2014 (light shaded area). Refer to Figure 12 for Urmiri profile.

***Water quality status (grouped Antequera River sites)***

Data from 2007 – 2009 and 2013 - 2014 show that 100% of samples from all Antequera River sites are acidic (pH<6). All EC values >1.5 dS/m. SAR values are generally low (~0.7 - 1.5). TDS levels generally exceed 'A-B' criteria (>1000 mg/L). All sites have DO <60% saturation and therefore do not meet 'A-C' criteria. Data from 2007 – 2009 is similar to 2013 – 2014; 100% of samples exceed 'A-D' criteria, FAO irrigation and WHO guidelines for Zn, Cd, Mn (see HQ ranking below and Appendix A) and $SO_4$. Samples exceed 'A' criteria for Cu but usually meet 'B' criteria and WHO guidelines. Samples exceed 'A-D' criteria for Fe and most exceed the FAO recommendation. Samples near Totoral exceed 'A-D' criteria, irrigation recommendations, and WHO guidelines for As. In December 2013, Pb exceeded 'A-C' criteria and WHO guidelines in samples near Totoral (TOTR1, TOTR2, AVR2). 'A-D' criteria and FAO recommendations are exceeded for Al. Fluoride exceeds all guidelines, and Ni exceeds 'A-D' criteria and WHO guidelines. Most samples exceed 'A' criteria for Ca. Downstream samples from AVR2 and AVR1 exceed 'A-D' criteria for Sb, and AVR1 and AVR3 exceed 'A' criteria and FAO recommendations for Co. Most sites exceed the UK EA non-statutory guideline for protection of aquatic life for Sn.

River water in the upper reach (TOTR1/2 to AVR2) is observed as being colourless to yellowish and sometimes turbid with sulphur odour. After TOTR2 (and Totoral mine area) the river has a lot of algae for ~2 km (Appendix C Google Earth images), possibly due to delimitation on growth (e.g., Fe sourced from mining activity as historical data do not show elevated $PO_4$). In the lower reach (AVR1/3) there are still algae and the water is generally clear.

Figure 10 illustrates the magnitude of contaminates in April 2014, whereby $SO_4$ concentrations are ~1800 mg/L around mines (Figure 10a), and Zn, Fe and Al concentrations (Figure 10b) are up to two orders of magnitude greater than those of Cd, Ni, Li, and B (Figure 10c). The concentration profile of Li and B support that these elements are naturally sourced, as they remain similar down the Antequera River and increase after the confluence with the Pazña River due to inputs of thermal waters from the Urmiri River. Figure 10 shows how pH remains low (acidic) and concentrations of $SO_4$, Zn. Al, Ni, and Cd remains elevated downstream of the confluence of the Antequera and Urmiri River such that these elements are also elevated in the Pazña River (PAZR1). The highest contamination occurs between AVR2 – AVR3, as shown in Figure 11, which illustrates the magnitude of metal fluxes Zn, Al, Cd) in comparison to other surface sites in the area. Figure 11a shows how Zn is the major contaminate (~30-1500 kg/day) along the Antequera River, especially in the rainy season. The plots also further illustrate metal inputs into the Pazña River in so much as Urmiri sites have near zero or zero input but contribute naturally derived elements such as Li and B (Figure 11e,f). Anthropogenic sources of trace metal inputs (i.e., excluding naturally derived Li, B, F, Sb) in the upper catchment include the mining activities and associated and waste ponds of the Bolivar mine, which is reflected in part by the already high $SO_4$ and many metal concentrations at BODI1. Along the Totoral River and Avicaya sections of the Antequera River, influences include the mining activities of Totoral mine and tailing heaps, Avicaya mine and tailings, and artisanal mining.

| | |
|---|---|
| ***WQR:*** **TOTR1, TOTR2, AVR2, AVR1, AVR3** | **8** |

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked for grouped Antequera River sites: Zn (89-1920)> Fe (2-320)> Al (4-168)> **Cd** (31-99)> Mn (2-35)> **Cu** (0-30)> **As** (0-20)> **Ni** (0-4)> **Sb** (0-5.6)> **F** (0-2.6)> **Pb** (0-2)> Co (0-1.4).

***Limitations on use***

The Antequera River surface sites are unsuitable for human (or livestock) consumption or irrigation purposes due to extremely high concentrations of Zn (HQs up to 1900), Fe, Al and Cd (HQs >100), and high EC, Mn, Cu, As, Ni, Sb, F, Pb and $SO_4$ concentrations. Up to 100% of samples exceed 'A-D' criteria, WHO guidelines and FAO recommendations for these elements. These waters appear to be strongly affected by mining activity that should be controlled and mine waste contained such that they do not enter the river water to affect downstream locations or groundwater (refer to Table 6, and Sections 8.1.4 and 8.2.7).

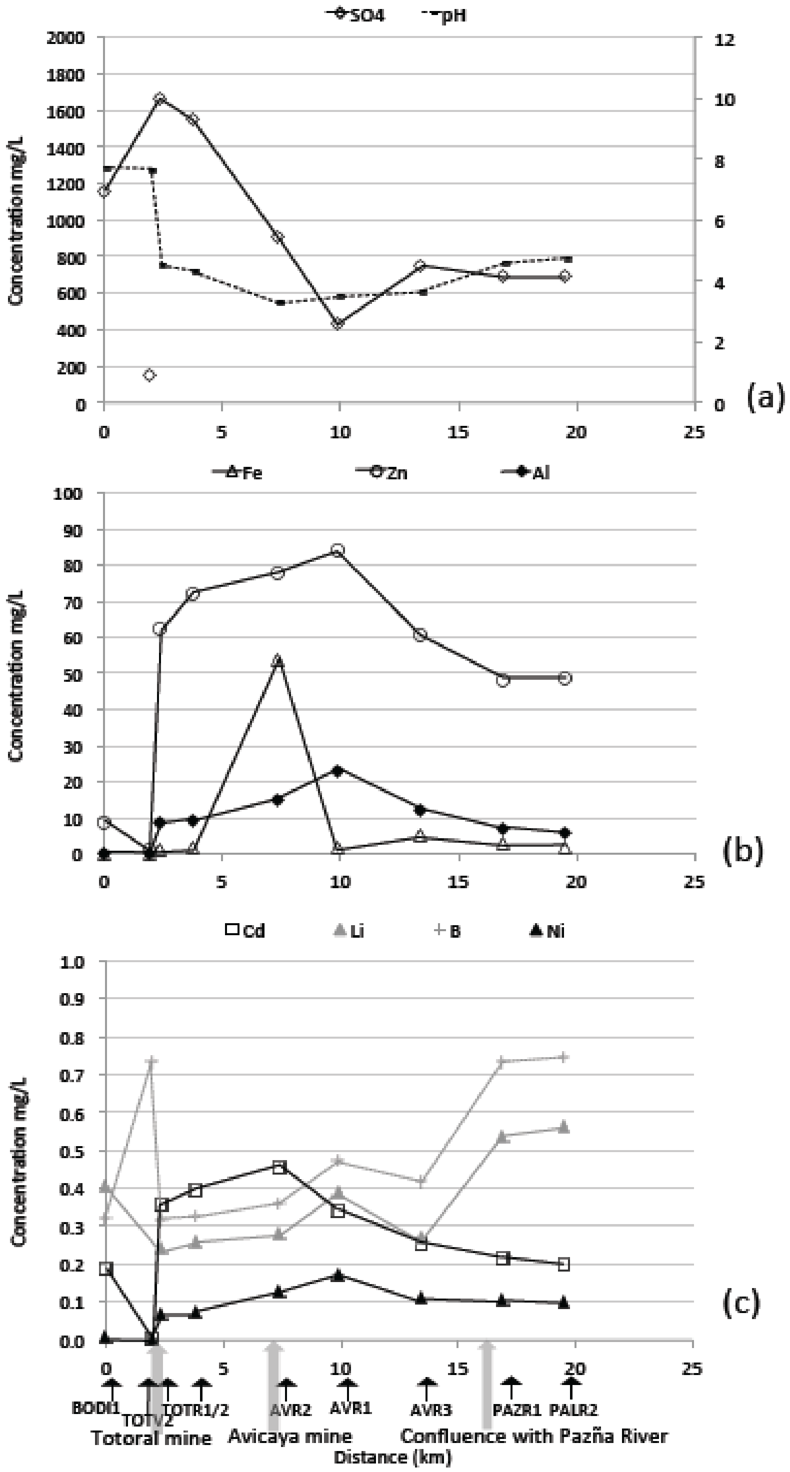


Figure 10 Graph showing concentrations (mg/L) of a) $SO_4$ (empty diamonds) and pH (dashed line), b) Zn (empty circles), and Fe (empty triangles), Al (solid diamonds) and pH (dashed line), c) Cd (empty square), Li (grey triangle), B (crosses), and Ni (solid triangles) against approximate distance down Antequera channel to Pazña River; from BODI1 (channel, 0 km), TOTV2 (slope, 1.9 km) TOTR1 (Antequera River, 2.4 km), TOTR2 (3.8 km), AVR2 (7.4 km), AVR1 (9.9 km), AVR3 (before confluence of Antequera and Pazña River 13.4 km), PAZR1 (Pazña River, 16.9 km), PALR2 (19.5 km) in April 2014.

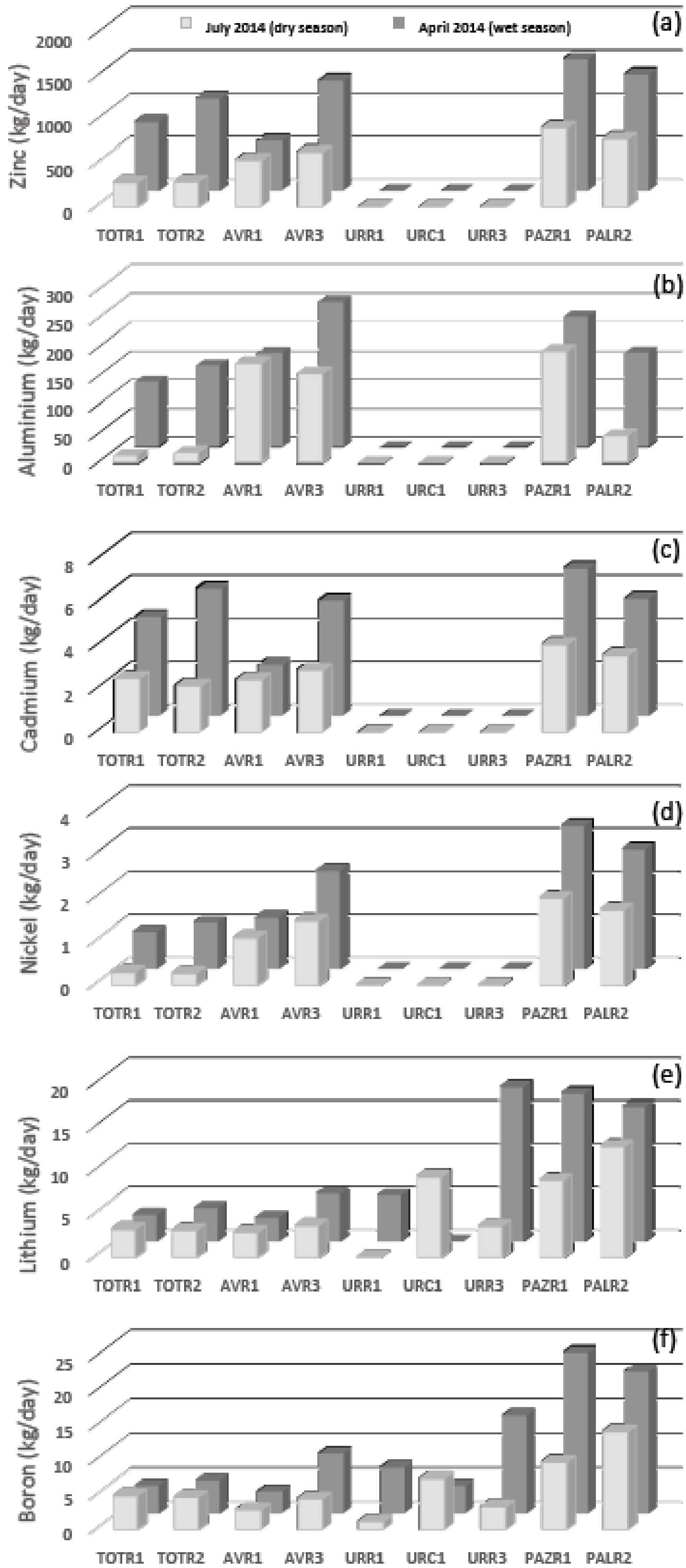


Figure 11 Graphs showing fluxes (kg/day) of a) zinc, b) aluminium, c) cadmium, d) nickel, e) lithium, and e) boron during April (wet season) and July (dry season) 2014 on the Antequera, Urmiri and Pazña Rivers (refer to Figure 1 for site code locations). Fluxes determined from site metal concentrations (mg/L) and river flows ($m^3/s$ converted to L/s).

## 6.2. Urmiri River/Village

### 6.2.1. Thermal water: URLT1

***Site description***

The URLT1 site (~3808 m a.s.l) is a thermal waterhole with bubbling water that passes through a stony channel. Thermal waters in Urmiri are used for recreational/bathing purposes.

***Water quality status***

Data from URLT1 thermal site in 2007 – 2009 and 2013 have high EC (~8 dS/m), very high SAR (60) values, and near zero DO. Temperatures can be up to ~60°C. Samples exceeded 'A-D' criteria and FAO recommendations for Na and Cl by one order of magnitude. 'A-D' criteria, FAO and WHO guidelines are exceeded for B (~7 mg/L), and Sb (~0.03 – 0.19 mg/L, no FAO) and usually for F (0.9 - 5.9 mg/L). Barium is also high. Lead often exceeds the WHO guideline (0.03 mg/L, meets 'A-D'). Iron (~0.5 mg/L) and $NO_3$ generally exceeds 'A-B' criteria. Lithium exceeds irrigation recommendations, and Sn exceeds UK EA non-statutory guideline for protection of aquatic life.

| | |
|---|---|
| ***WQR:* URLT1** | **9** |

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked at URLT1: **Sb** (0-19)> **B** (7)>*Li (4)*> **F** (0-4)> Fe (1.2-1.9).

***Limitations on use***

URLT1 thermal waters are unsuitable for human (or livestock) consumption or irrigation use due to very high EC, Cl and Na concentrations, high concentrations of Sb, Li and B and F. Like other thermal sites, high Sb, B, F and Li suggest these elements are naturally sourced in other/non-thermal waters (e.g., URR3 and PAZR1).

### 6.2.2. Water source sites: URV1, URC1

***Site description URV1***

URV1 is a slope site in Urmiri Village (~3809 m a.s.l, location in Figure 8) that feeds (a small volume of) water from the hillside into a small concrete tank that is covered by a wooden board. Water is used as a source of water for human consumption. There is a new water tank being constructed on the hillside.

***Water quality status URV1***

Data from 2007 – 2009 and 2013 - 2014 have EC values (~1.3 – 1.7 dS/m) that are higher than recommendations for drinking water (<0.9 dS/m, maximum 1.5 dS/m) or non-restricted irrigation. SAR values (~7.5) suggest some soil infiltration problems (depending on local soils) if used for irrigation (Table 1b). Levels of DO are low (<20% saturation) and therefore do not meet 'A-D' criteria. Concentrations of Na (~210 mg/L) are just over 'A-D' criteria. Between 2009 and 2013, concentrations of Cl and Fe reduced to meet 'A-D' criteria, and SAR values are also lower. In 2013 – 2014, B (~3 mg/L), Sb (0.03 - 0.04 mg/L) and usually F (0.8 - 4.5 mg/L) exceeded 'A-D' criteria, WHO and irrigation recommendations (no FAO for Sb). In August 2013, As (0.027 mg/L) exceeded the WHO guideline, and in April 2014, Fe (0.3 mg/L) exceeded 'A-B' criteria. Tin exceeds UK EA non-statutory guidelines for protection of aquatic life. The water is observed to be clear and transparent.

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|---|---|
| ***WQR:* URV1** | **5** |

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked at URV1: **Sb** (0-4.1)> **B** (3)> **F** (0-3)> Fe (1).

***Limitations on use and initial recommendations***

URV1 is unsuitable for human consumption due to EC values that are over the maximum recommended for drinking water, and also Sb, B, F, and sometimes As. Treatment for these elements is recommended (Section 8.1). Water at URV1 is not too bad for irrigation with the exception of B and F (i.e., maybe suitable for less sensitive/ higher tolerant crops), although soil infiltration maybe problematic. Water is chemically acceptable for livestock with the exception of high F concentrations. A water quality analysis should be made to assess microbial contamination in addition to basic treatment for potable water if this is in fact used for consumption despite the exceedances.

***Site description URC1***

URC1 is a channel site in Urmiri Village (~3787 m a.s.l) where river water feeds through a concrete channel (flow rate April 0.05 $m^3/s$, July 0.03 $m^3/s$, Figure 2a and 12) for domestic and agricultural use.

***Water quality status URC1***

Data from 2007 – 2009 and 2013 - 2014 show that EC values (2.4 - 2.9 dS/m) greatly exceed recommendations for drinking water or non-restricted irrigation use. SAR values are also high (14 - 28). TDS levels (~1400 mg/L) exceed 'A-B' criteria. 'A-D' criteria, FAO recommendations and WHO guidelines are exceeded for Na and Cl (>350 mg/L). Boron (~3 mg/L), F (~1.4 - 3.8 mg/L) and often Sb (up to 0.04 mg/L) exceed 'A-D' criteria and WHO guidelines. Lithium (~3.3 mg/L) exceeds FAO recommendations, and Sn exceeds UK EA non-statutory guidelines for protection of aquatic life. The water in the channel is generally clear.

| | |
|---|---|
| ***WQR:* URC1** | **7** |

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked for URC1: **B** (2.6-3.1)> **F** (0-2.7) > **Sb** (0-4)> *Li (1.3-1.6).*

***Limitations on use***

URC1 water is unsuitable for human consumption due to high EC, TDS, Na, and Cl, and also because of concentrations of B, F and Sb. It is not suitable for non-restricted irrigation (Table 1b) for these reasons and also Li concentrations. It is generally chemically acceptable for livestock with the exception of F. High Li and B suggests that thermal or other groundwater may be entering the channel, especially since the nearest upstream river site URR1 show a different chemical signature.

### 6.2.3. Urmiri River sites: URR2, URR1, URR3

***Site description URR2***

The URR2 site is located in the upper Urmiri River reach (~3995 m a.s.l, Figure 8 and 12) where the river passes through a small canyon. The river generally has quite a low flow (July 0.006 $m^3/s$, refer to Figure 12).

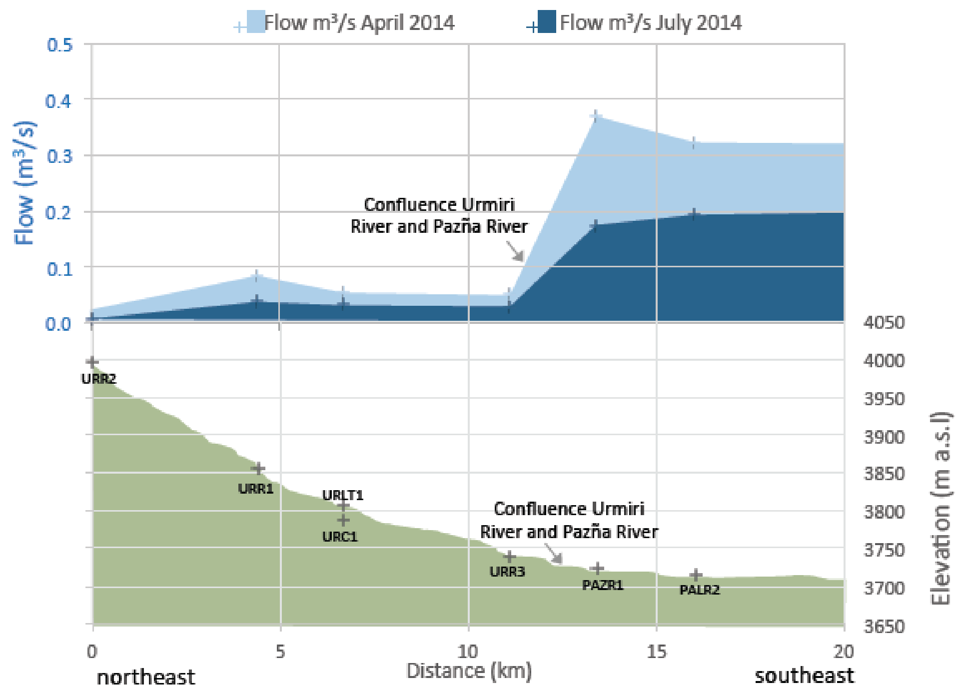


Figure 12 Conceptual elevation (m a.s.l. exaggerated by 20 relative to x axis) cross-section along the Urmiri – Pazña River (northeast to southwest, solid shaded area as land mass), including accretion profile from URR2 to PALP2 (flow, $m^3/s$) in April 2014 (dark and light shaded area) and July 2014 (light shaded area).

***Water quality status URR2***

The river water at URR2 is of good quality with the exception of DO (<40%), which does not meet 'A-D' criteria. EC is low (0.2 - 0.4 dS/m) and within recommendations for drinking water and irrigation. Low SAR values (0.6 – 1.8) suggest soil infiltration problems (depending on local soils) if used for irrigation (Table 1b). Data from 2007 – 2009 show that all measured parameters meet

'A' criteria, FAO and WHO guidelines. In 2013 - 2014, the only exceedances were for F (up to 3.4 mg/L), and in one sample Sb (up to 0.03 mg/L). Also, Sn concentrations are sometimes above UK EA non-statutory guidelines for protection of aquatic life. The water is observed to be clear.

| | |
|---|---|
| ***WQR:* URR2** | **3** |

***Limitations on use and initial recommendations***

There is no limitation on water use from URR2 with respect to chemical water quality status considered here except for F and sometimes Sb. Soil infiltration maybe problematic if used for irrigation. A water quality analysis is recommended to assess microbial contamination if used for human consumption.

***Site description URR1***

The URR1 site (~3856 m a.s.l) is located on the Urmiri River where construction of a large concrete water tank is taking place. Flow is quite low and seasonally variably (April, 0.08 $m^3/s$, July 0.04 $m^3/s$, Figures 2a and 12, Appendix B). There are generally algae in the river but the water is clear.

***Water quality status URR1***

Water in the river at URR1 is of relatively good quality with the exception of DO (<60%), which does not meet 'A-C' criteria. EC values (~0.3 – 0.4 dS/m) are within drinking water and irrigation recommendations. SAR values (0.8 – 2) suggest soil infiltration problems (depending on local soils) if used for irrigation (Table 1b). Data from 2007 – 2009 met all other 'A' criteria, FAO and WHO guidelines with the exception of some alkaline pH measurements (pH>8.5), one occasion of high Cl, and another with $SO_4$ that exceeded 'A' criteria. In 2013 – 2014. In December 2013, F (3.4 mg/L) exceeded all guidelines. Also, Sn concentrations are above UK EA non-statutory guidelines for protection of aquatic life.

| | |
|---|---|
| ***WQR:* URR1** | **3** |

***Limitations on use and initial recommendations***

URR1 is of generally good quality with the exception of occasionally elevated F. Basic treatment for potable water is recommended (Section 8.1) and a water quality analysis should be made to assess microbial contamination. Soil infiltration maybe problematic if the river water is used for irrigation depending on local soils. It is chemically acceptable for livestock.

***Site description URR3***

The URR3 site (~3740 m a.s.l) is located on the Urmiri River before the road that crosses to Pazña. The river has a low flow (April, 0.051 $m^3/s$, July 0.028 $m^3/s$, Figures 2a and 12) and generally many algae.

***Water quality status URR3***

Water in the river at URR3 has EC values (1.0 - 2.8 dS/m) that are above recommended values for drinking water or non-restricted irrigation (Table 1b). SAR values are ~7. Some samples exceed ‘A-B’ criteria for TDS (>1000 mg/L). Data from 2013 - 2014 (and generally in 2007 – 2009) often exceeded ‘A-D’ criteria and FAO recommendations for Na and Cl. Occasionally, alkaline pH exceeded ‘A’ criteria. Fluoride concentrations (1.2 – 4.4 mg/L) generally exceed all guidelines. Boron (1.4 – 1.8 mg/L) exceeds ‘A-D’ criteria and irrigation recommendations (meet WHO), and in December 2013 As (0.035 mg/L) exceeded the WHO guideline (met ‘A’). The water is observed to be clear with a lot of algae, and occasionally slightly turbid.

| | |
|---|---|
| ***WQR:*** **URR3** | **5** |

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked at URR3: **B** (1.4-1.8)> **F** (0-2.9).

***Limitations on use***

Water from URR3 is of fair quality but not really recommended for human consumption due to high EC, F, and sometimes As. It may be that there are inputs of high EC thermal waters that could possibly be prevented. Alternatively, treatment to reduce these parameters is recommended if used for human consumption, in addition to basic treatment for potable water (Section 8.1) and a water quality analysis to assess microbial contamination. Although B concentrations exceed ‘A’ criteria they are below WHO guidelines. Although it is not really recommended for non-restricted irrigation due to Na, Cl, B and F, it may be acceptable for restricted use (i.e., less sensitive/ higher tolerant crops, refer to Table 1b). It is chemically acceptable for livestock with the exception of F.

## 6.3. Pazña River/Village

### 6.3.1. Thermal water: PAZTE

***Site description***

The PAZTE site (~3738 m a.s.l) is a thermal waterhole with bubbling water. It is located on a slope and forms a shallow stream. A thermal pool for recreational use is nearby.

***Water quality status***

Data in 2007 – 2009 and 2013 - 2014 show that all samples have very high EC (~9.5 – 12.5 dS/m) and SAR (63) values. Temperatures can be up to ~60°C. Levels of DO are low (~20%) and do not meet ‘A-D’ criteria. Samples greatly exceed ‘A-D’ criteria, irrigation and WHO recommendations for Na and Cl (up to 2600 mg/L and 4300 mg/L, respectively). TDS levels (>4700 mg/L) greatly exceed ‘A-D’ criteria. Boron (>8 mg/L), F (~2.2 – 5.1 mg/L) and sometimes Sb (up to 0.03 mg/L) exceeds all guidelines. Iron (~0.4 – 1.0 mg/L) exceeds ‘A-B’ criteria. Occasionally Cd exceeds the WHO guidelines (meet ‘A-D’). Barium is also high. Lithium (~10 mg/L) exceeds irrigation recommendations, and Sn exceeds UK EA non-statutory guidelines for protection of aquatic life.

| ***WQR:* PAZTE** | **9** |
|---|---|

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked at PAZTE: **B** (8.3-9)> *Li (3.6-4.3)*> **F** (1.5-3.4)> **Sb** (0-3.2) >Fe (0-3.3).

***Limitations on use***

PAZTE thermal waters are unsuitable for human (or livestock) consumption or for irrigation purposes due to very high EC, TDS, Na, Cl, B, and Li and high F, Sb, F, and Fe.

6.3.2. Wells: VIP1, PALP7/8/9, PAZP3, PALP2, PALP3, PALP4, PALP5

***Site description VIP1***

The VIP1 well (~3734 m a.s.l) is an open, uncovered well that is situated in a mud-wall enclosure on a farm residence to the east of Pazña Village. The well has a lot of straw and appears grey, turbid and dirty. The well was only monitored in July 2014 when it was pumped prior to water sampling due to being visibly dirty.

***Water quality status VIP1***

The EC value in July 2014 (1.2 dS/m) is above recommendations for drinking water. Although it is also above recommendations for non-restricted irrigation, low SAR values (1.9) are acceptable for irrigation. 'A-D' criteria and WHO guidelines are exceeded for Cd (0.006 mg/L) and As (0.09 mg/L, only meets 'D' criteria). 'A-D' criteria are exceeded for Fe. 'A-B' criteria are exceeded for $SO_4$. Boron exceeds 'A-D' criteria and irrigation recommendations (1.3 mg/L, meets WHO). 'A' criteria, WHO and FAO recommendations are exceeded for Mn (0.9 mg/L). Tin exceeds UK non-statutory guidelines for protection of aquatic life.

| ***WQR:* VIP1** | **6** |
|---|---|

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQ>1 in July 2014 ranked at VIP1: Fe (7.2)>Mn (2.3)>**As** (1.8)> **Cd** (1.3)~**B** (1.3).

***Limitations on use and initial recommendations***

The water from the VIP1 well is not recommended for human consumption due to EC, concern over As and Cd which exceed health based WHO guidelines, and also Fe and Mn. It is acceptable for irrigation with the exception of B and Mn, which may be fine for less sensitive/higher tolerant crops. It is acceptable for livestock although biological assessment is recommended if used for human consumption despite exceedances, which tentatively suggest mine water migration affecting groundwater in this area. Covering the well is recommended, including for safety reasons.

***Site description PALP7/8/9***

The PALP7, 8 and 9 wells are located east - southeast of Pazña Village, proximate to each other (locations in Figure 8) and showing similar water chemistries. PALP7 (~3733 m a.s.l, ~4.5 m deep) and PALP9 (~3732 m a.s.l, ~5.6 m deep) wells have loose tin lids. PALP8 (~3730 m a.s.l) is a closed well with a hand pump and is situated next to a small pond. There is generally straw around all the wells, which are used for human consumption. Figure 4 shows water levels at PALP7 during the study period. The water level decreased by 0.71 m between mid-August (3.31 m b.d) and mid-December 2013 (4.02 m b.d), and subsequently varied little by mid-April (4.06 m b.d), and increased only slightly (0.13 m) by mid-July 2014 (3.93 m b.d) (Appendix B).

***Water quality status PALP7/8/9***

High EC values (~2.7 to 4.9 dS/m) greatly exceed drinking water and FAO recommendations for non-restricted irrigation. SAR values are high (~18 – 27). DO is also low (<40% saturation), particularly in December, and does not meet 'A-D' criteria. TDS ranges from 1371 – 2471 mg/L (higher in December), and exceeds 'A-B' (and 'C-D' when>1500 mg/L) criteria. In 2007 – 2009 and in 2013 - 2014, water in all wells exceeded 'A-D' criteria for Na (higher in December, >1000 mg/L), and exceeded 'A' criteria, irrigation and WHO guidelines for Cl (>600 mg/L) and B (3.0 - 5.8 mg/L). Nitrate concentrations often exceed 'A-B' criteria, and PALP7 in particular has consistently very high $NO_3$ (80 - 200 mg/L). Fluoride exceeds all guidelines (~1.5 - 4 mg/L) in all wells, and in December 2013 Pb exceeded WHO guidelines (up to 0.03 mg/L; meets 'A-D') at PALP7 and 9. Concentrations of As at PALP8 often exceed WHO guidelines (up to 0.045 mg/L; meet 'A-D' criteria). Lithium concentrations (2.7 – 5.4 mg/L) exceed irrigation recommendations. Tin exceeds UK EA non-statutory guidelines for protection of aquatic life. Water from all wells is observed as being generally clear.

| | |
|---|---|
| ***WQR:* PALP7/8/9** | **7** |

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked for grouped PALP7, 8, 9: **B** (2.7-5.8)> *Li (1.1-2.2)*> **F** (0-2.6).

***Limitations on use and initial recommendations***

PALP7, PALP8 and PALP9 are unsuitable for human consumption or non-restricted irrigation purposes due to high EC (2.7 and 4.9 dS/m), and high TDS, Na, and Cl, and due to concentrations of B, F, Li, and $NO_3$. Also, As exceeds health based WHO guidelines at PALP8. PALP7 should not be used for livestock due to very high $NO_3$. All are restricted for livestock (especially lower tolerant) due to high B and F and the higher EC values. All of the wells maybe stagnant and future sampling should pre-pump the wells. A water quality analysis should be made to assess microbial contamination at PALP8 and 9 if they are in fact used for consumption despite the exceedances. PALP7 should not be used without treatment due to $NO_3$. Improving the covers on the wells is recommended (Table 6).

***Site description PAZP3***

The PAZP3 well (3714 m a.s.l) is situated to the northwest of Pazña Village relatively close to the PAZTE thermal site (locations in Figure 8). It is a fairly shallow (~2.50 m) open well with a loose tin lid that sits on a wooden stand and stone cladding. The well is used for human consumption. The variations in water levels are shown in Figure 4. Between mid-August (1.63 m b.d) and mid-December 2013 (1.88 m b.d) the water level in the well decreased by 0.25 m, and was the same in mid-July 2014 (1.88 m b.d) (Appendix B).

***Water quality status PAZP3***

The well water has very high EC (~15.5 – 18.4 dS/m), TDS (~7700 – 9200 mg/L, higher in December), and SAR values (up to ~70), which all greatly exceed FAO recommendations for irrigation. TDS, Na and Cl concentrations greatly exceed 'A-D' criteria. Concentrations of Na (up to 3700 mg/L) and Cl (up to 6800 mg/L) are considerably higher than other Pazña well sites, and concentrations of B and Li are an order of magnitude greater than the other Pazña well sites. Concentrations of B (15 mg/L), F (~4 mg/L), As (up to 0.17 mg/L) and Mn (~0.8 mg/L) all exceed 'A-D' criteria, FAO and WHO guidelines (see HQ ranking below and Appendix A). Antimony often exceeds 'A-D' criteria and WHO guidelines (up to 0.056 mg/L). Lithium (~18 mg/L) greatly exceeds FAO recommendations. Tin exceeds UK EA non-statutory guidelines for protection of aquatic life. The water from the well is generally turbid with suspended particulate material. DO is very low (<30%), especially in December.

| | |
|---|---|
| ***WQR:* PAZP3** | **9** |

(despite not be having high temperature or SAR >30) (see Table 2).

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked for PAZP3: **B** (13.6-15.5)> *Li (5.3-7.6)*> **F** (2.2-2.8)> **As** (0-3.3)> **Sb** (0-5.6)> Mn (0-1.5).

***Limitations on use***

PAZP3 is of poor chemical quality and unsuitable for human (or livestock) consumption or irrigation purposes due to extremely high EC, Na, Cl and B concentrations, and high F, As, Sb, Mn and Li concentrations. Of particular concern are elements of health significance; B, F, As and Sb. The well maybe stagnant and future sampling should pre-pump the wells. The well water is brackish should not be used for consumption.

***Site description PALP2***

PALP2 is near PALP3, PALP4 and PALP5 (locations shown in Figure 8), all of which are near Santa Filomena and to the southwest of Pazña Village. The PALP2 well (~3710 m a.s.l,) is a relatively shallow (~3 m deep) large open-hole, with a broken cement cover and maybe semi-derelict although it is believed to be used for agricultural purposes. The water level in the well is similar to at PALP3/4, and decreased by 0.23 m between mid-August (2.05 m b.d) and mid-December 2013 (2.28 m b.d, Figure 4). The well was not monitored in April or July 2014.

***Water quality status PALP2***

EC values (2.5 – 3.2 dS/m) and Na and Cl concentrations (~200 – 300 mg/L) at PALP2 are similar to those at PALP4, and lower than PALP3 and PALP5, but generally exceed 'A' criteria. Although the EC is higher than that recommended for non-restricted irrigation water, SAR values are relatively low (~5 - 6) and suitable for irrigation. DO is low (<40% saturation) and does not meet 'A-D' criteria. TDS levels (~1250 – 1600 mg/L) exceed 'A-B' criteria. Sulphate (~850 mg/L), As (~0.1 mg/L), B (2.2 - 2.5 mg/L) and F (~3.4 mg/L) exceeds 'A-D' criteria, FAO and WHO guidelines. In August 2013, Sb concentrations (0.04 mg/L) exceeded 'A-D' criteria and WHO guidelines (see HQ ranking). Tin exceeds UK EA non-statutory guidelines for protection of aquatic life. The well water has algae or organic material and is cloudy.

| ***WQR:* PALP2** | **7** |
|---|---|

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked for PALP2: **F** (2.1-2.6)> **B** (2.2-2.5)> **As** (1.6-2.4)> **Sb** (0-4.1).

***Limitations on use and initial recommendations***

PALP2 is unsuitable for human consumption or non-restricted irrigation (Table 1b) due to high EC, $SO_4$, F, B, and As, and sometimes Sb. Treatment for these elements is recommended material if this is in fact used for consumption despite the poor quality and salinity, and basic potable water treatment apply. A water quality analysis should be made to assess microbial contamination if used for consumption, but the well should be pumped before sampling and use as it maybe stagnant. It is generally chemically acceptable for livestock with the exception of F. Improving the well cover is recommended.

***Site description PALP3***

PALP3 (~3710 m a.s.l) near Santa Filomena is also a relatively shallow (~3 m deep) open well, which is partially covered by wooden boards. The well water might be used for human consumption. Figure 4 shows the water level variations during the study period. Levels decreased slightly (0.12 m) between mid-August (2.25 m b.d) and December 2013 (2.37 m b.d), then increased by 0.43 m by April (1.94 m b.d) before decreasing by 0.16 m by July 2014 (2.10 m b.d) (Appendix B).

***Water quality status PALP3***

PALP3 has high EC (~3.7 – 5.6 dS/m) that greatly exceed recommendations for drinking water or non-restricted irrigation use. SAR values are high (up to 24). TDS (~1800 – 2800 mg/L) are also high and exceeds 'A-D' criteria. DO is very low (<20%). Sodium, Cl (both up to 1550 mg/L), B

(~3.3 – 5.3 mg/L), F (~1.1 – 4.2 mg/L), As (~0.06 mg/L) and $SO_4$ (>500 mg/L) exceed 'A-D' criteria, WHO guidelines and FAO recommendations (FAO not As). In April 2014, Sb (0.18 mg/L) greatly exceeded 'A-D' criteria and WHO guidelines (same at PALP4 nearby). Generally Mn (~1.6 mg/L) exceeds 'A-D' criteria, WHO and FAO guidelines (see HQ ranking). We tentatively propose the possibility of Mn indicating input of mine affected waters (infiltrated surface water) because only wells downstream (i.e., within a possible groundwater flow path) of mine affected rivers have high Mn (TOTP5, PAZP3, PALP3/4) and thermal waters do not suggest Mn (at concentrations over 'A' criteria) is naturally sourced. Other exceedances are for Ca that exceeds 'A' criteria, and some Li concentrations (2.0 – 3.9 mg/L) that exceed irrigation recommendations. Tin exceeds UK EA non-statutory guidelines for protection of aquatic life. The water from the well varies from clear (usually in summer/wet season) to turbid/cloudy (dry season).

| | |
|---|---|
| ***WQR:* PALP3** | **7** |

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked for PALP3: **B** (3.3-5.3)> **F** (1.1-2.8)>Mn (0-3.3)>**As** (1.1-1.3)> *Li (0-1.5)*> **Sb** (0-18, ranked last as there was one sample with a particularly high concentration, excluding this; HQ 0-1).

***Limitations on use and initial recommendations***

Water from the PALP3 well is unsuitable for human consumption and not recommended for irrigation purposes due primarily to high EC values (~5 dS/m), and high Na, Cl, $SO_4$, B, F, As, Mn, and Sb concentrations. The water is chemically acceptable for higher tolerant animals with the exception of F. The well maybe stagnant and future sampling should pre-pump the wells. Improving the well cover is recommended.

***Site description PALP4***

The PALP4 well (~3708 m a.s.l) near Santa Filomena is also relatively shallow (~2.6 m deep) and is covered with corrugated iron and wood. It is believed that the well is used for irrigation water and human consumption. The water level in the well shows similar seasonality to PALP3 (Figure 4), and decreased by 0.19 m between mid-August (2.08 m b.d) and mid-December 2013 (2.27 m b.d), before increasing by 0.44 m by mid-April 2014 (1.83 m b.d) and then reducing by 0.11 m by mid-July 2014 (1.94 m b.d) (Appendix B).

***Water quality status PALP4***

EC, SAR values, TDS, Cl and Na concentrations at the PALP4 well are considerably lower than at the adjacent PALP3 well and more similar to PALP2. Although SAR values (~6) are within recommendations for irrigation, EC values (2.2 – 2.5 dS/m) are quite high for non-restricted irrigation and greatly exceed drinking water recommendations. TDS (~1100 mg/L) exceed 'A-B' criteria but meets 'D-C' criteria. DO is very low (~0 – 10% saturation). Sulphate (>500 mg/L) exceeds 'A-D' criteria and FAO recommendations. Arsenic (~0.1 mg/L), F (1.8 - 4.5 mg/L), Mn (1.0 – 6.1 mg/L) concentrations exceed 'A-D' criteria, WHO guidelines and irrigation recommendations. Boron (~2 mg/L) exceeds 'A-D' and irrigation criteria (meets WHO) (see HQ ranking). Sodium and Cl (~300 mg/L) are a little higher than the 'A' criteria and general irrigation recommendations. In April 2014, Sb (0.16 mg/L) greatly exceeded 'A-D' criteria and WHO guidelines. Tin exceeds UK EA non-statutory guidelines for protection of aquatic life. The well water is generally clear but sometimes turbid.

| ***WQR:*** **PALP4** | **7** |
|---|---|

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked for PALP4: Mn (2.1-12.2)> **As** (1.8-2.5)> **B** (1.7-2.2)> *Li ()*> **F** (1.2-3)> **Sb** (0-16, ranked last as there was one sample with a particularly high concentration, excluding this; HQ 0-1.5).

***Limitations on use and initial recommendations***

Water from PALP4 is unsuitable for human consumption due to EC values, $SO_4$, Mn, As, B and F concentrations. Treatment for these elements is recommended if this well is in fact used for consumption despite the poor quality and salinity, and basic potable water treatment apply. A water quality analysis should be made to assess microbial contamination if used for consumption, but the well should be pumped before sampling and use as it maybe stagnant. It is not recommended for irrigation without restriction (Table 1b). It is generally chemically acceptable for livestock with the exception of F. Improving the well cover is recommended.

***Site description PALP5***

The PALP5 well (~3709 m a.s.l) is an open-hole (~3.9 m deep) covered with a loose wooden lid and corrugated iron. It is located on the property of an abandoned house so may not be in use. The well water contains straw. The water level in the well reduced by 0.14 m between mid-August (3.23 m b.d) and mid-December 2013 (3.37 m b.d) (Appendix B). The well was not monitored in April or July 2014 because it was visibly dirty.

***Water quality status PALP5***

High EC (4.3 – 6.7 dS/m) greatly exceed recommendations for drinking water or irrigation use. SAR values are high (up to 26). TDS (~2100 - 3300 mg/L), Na and Cl are also high (~1700 mg/L in December 2013) and exceed 'A-D' criteria. DO is low (<35% saturation) and does not meet 'A-D' criteria. Sulphate (~500 mg/L), B (~3.5 mg/L), F (3.4 – 4.3 mg/L) and As (0.26 mg/L) exceeds 'A-D' criteria, WHO guidelines and FAO recommendations. In August 2013, Sb concentrations (0.022 mg/L) exceeded 'A-D' criteria and WHO guidelines (see HQ ranking), and in December 2013 Li concentrations (up to 2.8 mg/L) exceed FAO recommendations. Calcium exceeds 'A' criteria. Tin exceeds UK EA non-statutory guidelines for protection of aquatic life.

| ***WQR:* PALP5** | **7** |
|---|---|

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked for PALP5: **As** (5.1)> **B** (3.1-3.6)> **F** (2.3-2.9)> **Sb** (0-2.2)> *Li (0-1.1)*.

***Limitations on use and initial recommendations***

PALP5 is unsuitable for human consumption or irrigation purposes due to very high EC, Na and Cl concentrations, and also high $SO_4$, As, B, F, and Sb. Particular concern relates to elements of health significance; As, B, F, and Sb. It is not recommended for livestock due to high As, and also F and higher EC values. The well maybe stagnant and future sampling should pre-pump the wells. Improving the well cover is recommended, although apparently this well has been abandoned.

### 6.3.3. Pazña River sites: PAZR1, PALR2

***Site description PAZR1 and PALR2***

PAZR1 (~3723 m a.s.l) and PALR2 (~3714 m a.s.l) are sites on the Pazña River (locations shown in Figure 8), which is formed at the confluence of the Antequera (>70% of input, i.e., assuming increase in flow after AVR3, April 0.25 $m^3$/s) and Urmiri Rivers (~15% input, Figure 12). The river flow varies seasonally (PAZR1; April 8th 0.37 $m^3$/s, July 12th 0.17 $m^3$/s, refer to Figures 2a, 8 and 12 and Appendix B) but varies little to the lower tributary reach before the river diverges (PALR2; April 9th 0.32 $m^3$/s, July 12th 0.19 $m^3$/s). River water can appear yellow-greenish and algae are present in some parts.

***Water quality status (grouped sites)***

Figures 10 and 11 illustrates the magnitude of contaminates at PAZR1 in December 2013 and the inputs from Antequera River. Figure 10e,f also indicate the contribution of naturally sourced elements such as B and Li from the Urmiri River. Data from 2007 – 2009 and 2013 - 2014 show that 100% of samples from Pazña River sites have acidic pH (<6) and EC (1.6 – 3 dS/m) that greatly exceed drinking water recommendations. DO levels are <50% saturation and do not meet 'A-D' criteria. TDS levels (~800 – 1500 mg/L) exceed 'A-B' criteria. 100% of samples exceed 'A-D' criteria, FAO and WHO guidelines (where applicable) for Zn, Al, Cd, Mn (see HQ ranking below and Appendix A), and $SO_4$. Most samples exceed all guidelines for F. Generally Fe exceeds 'A-D' criteria. 100% of samples exceed 'A' criteria for Cu but meet 'B' criteria and WHO guidelines. On some occasions Co exceeds 'A' criteria and FAO, Ni exceeds 'A-B' criteria and WHO guidelines (but meets FAO), and Sb often exceeds 'A-D' criteria and WHO guidelines. Some samples exceed 'A-B' criteria for Ca but many meet 'D' criteria. The river water can be turbid during high flow in the wet season. In the dry season it is generally clear but with algae in places.

| *WQR:* **PALR2, PAZR1** | **8** |
|---|---|

***HQ: metal ranking and concerns***[1]

Trace metals [1]HQs in 2013 – 2014 ranked for grouped Pazña River sites: Zn (240-506)>Al (14-124)>**Cd** (39-60)>Mn (10-29)>**Cu** (6-11)> **Sb** (0-13)> Fe (0-9)>**Ni** (2-3.4)> **F** (0-3)> Co (0-1.1).

***Limitations on use***

River water at PALR2 and PAZR1 is affected by mining activity on the Antequera River and is unsuitable for human (or livestock) consumption or irrigation use due to extremely high Zn, Al, Cd and Mn concentrations, and high $SO_4$, Cu, Fe, Ni, Sb and Co. Control of mining activities and containment of waste upstream in the Antequera River is recommended (refer to Table 6).

## 7. SUMMARY OF WATER QUALITY STATUS

Figure 13 provides a map summarising the current WQR of the 45 sites sampled in this study (site codes in Figure 1). Here we summarise the status with respect to human consumption and recommend any necessary treatment for potable quality. Table 5 gives generalised recommended actions based on WQR. Table 6 summarises each sites WQR, acceptability for human consumption, livestock and irrigation and also gives site-specific recommended actions. In all situations i) microbial assessment is required for sources used for human consumption, ii) wells should be pre-pumped and covers improved where possible, iii) rainwater harvesting is recommended (Section 8.2.2).

Thirteen sites (29% of total) were classified as WQR <6 (refer to Figure 13). Only one (PUNP1), the school tap water in Puñaca, was determined as WQR 2 and chemically acceptable for human consumption without restriction or concern for the elements assessed (pending microbial assessment). Five sites were classified as WQR 3; upstream Poopó River (POR4) and storage tank (CABT1), upstream Urmiri River (URR2 and URR1), and an irrigation channel in Kuchi-Avicaya (CUCC1). Four wells were classified as WQR 4; in Tolapampa (TOLAP1), Callipampa (CALLP3), Morochi (PMO1), and near Vilaque (PALP10). Three sites were classified as WQR 5 (PUNP2 well in Puñaca, URV1 slope above Urmiri Village, and downstream Urmiri River URR3) (Figures 13 and 1, Appendix A for data).

For all WQR 3 sites cautions are is for F and/or (non-excessive) Sb concentrations, and sometime low dissolved oxygen and/or algae suggest potentially poor bacterial quality. Sites with WQR 4 are considered to be of slightly poorer quality because of these reasons but also either because of the presence of an additional element of health significance (e.g., As or Cd) that exceeds 'A' criteria, or because higher EC that is at the upper threshold of recommendations for drinking water (i.e., ~0.8 dS/m). Water from WQR 5 sites also appear to be affected by natural contamination

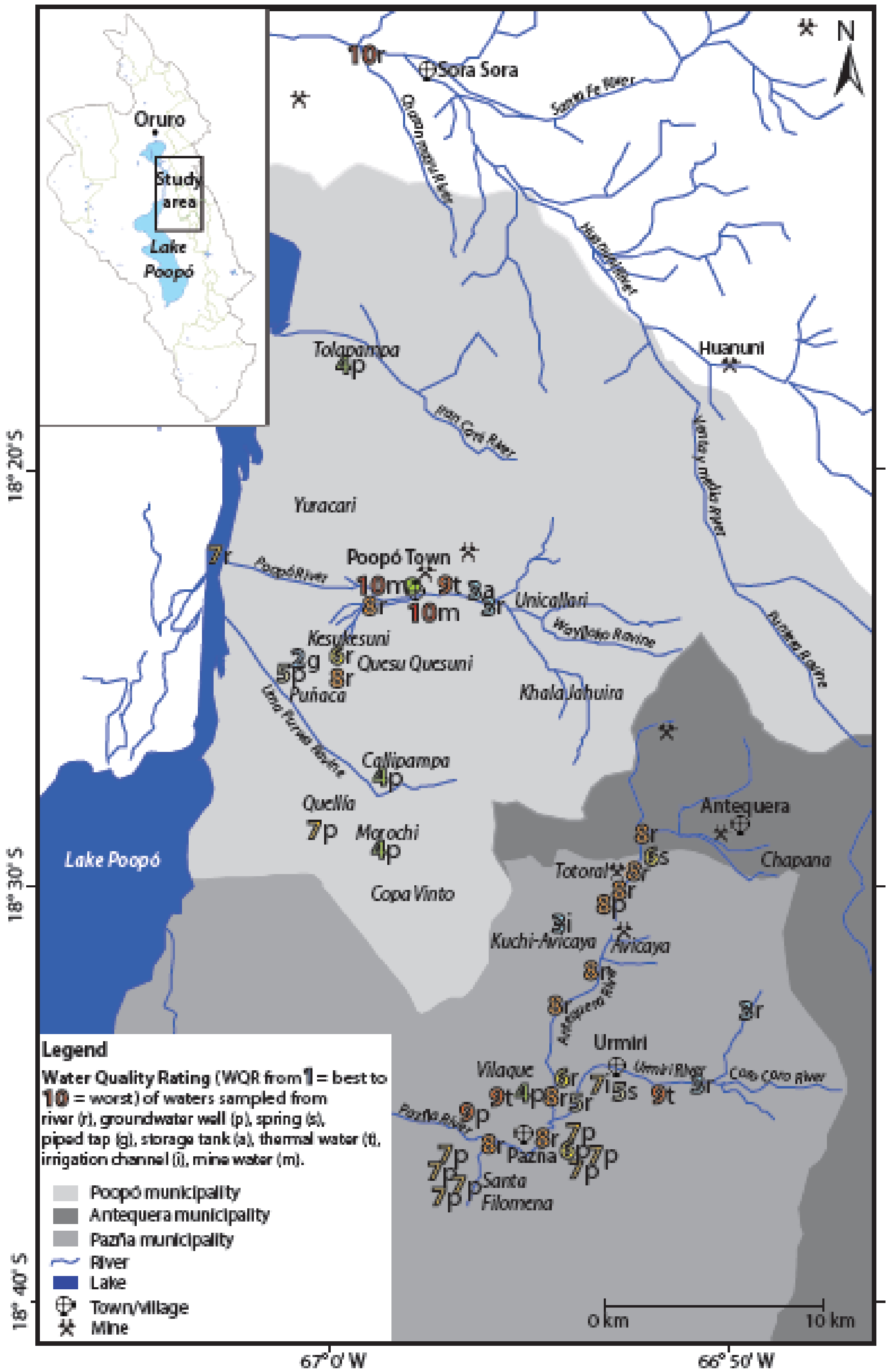


Figure 13 Map of study area showing WQR for each site in 2013-2014 (refer to Figure 1 for site codes and Tables 4 and 5 for summary WQR and recommended actions), where WQR refers to the chemical water quality status from best (1) to worse (10) (see Table 2 for WQR description).

(including exceedance of 'A' criteria for B), and have higher EC values that exceed that recommended for drinking water (i.e., 1 - 2 dS/m). Chemical signatures from local thermal waters (see later) suggest many of the elements and salts exceeding in WQR 3, 4 and 5 sites are naturally sourced (especially F and Sb). The relatively good quality of the upstream Poopó and Urmiri River sites (POR4 and URR2/URR1, respectively) sites, especially in comparison to downstream river sites (POR3 and PAZR1, see later), illustrates the natural state of the rivers without the influence of mining activity. The possibility of obtaining more water from near these sources should be investigated, especially in the case of rivers because upstream abstraction can prevent waters from passing through mine affected areas and becoming contaminated. Rainwater harvesting is also recommended to supplement water demand. Table 5 summarises recommended actions for each site. Overall, WQR 3 and 4 sites require water quality assessment for microbial contamination, and treatment is recommended for reducing concentrations of elements of health significance F, Sb and sometimes As and Cd (refer to Section 8.1.2), along with standard treatment for potable water if used for human consumption (Section 8.1.1). Whereas WQR 5 additionally have EC values above that recommended for use as potable water use.

Four sites were classified as WQR 6; a farm well (VIP1) to the west of Pazña Village, and a spring/slope runoff site near Totoral (TOTV2), KER1 on the Kesukesuni River, and the LCR1 on the Laca Laca River (Figure 13). The water quality at these sites is poorer than lower WQR sites because of exceedance of 'A' criteria for elements of health significance (e.g., F, As, Sb and in some cases Cd), but also due to the exceedance of criteria for several other elements (e.g., Mn, Zn, Al and/or Fe) that may suggest some infiltration/migration of mine affected water. Treatment is not initially recommended because source input may continue (and possibly worsen), hence, identification of contaminate source then prevention and control (e.g., of upstream mining) is recommended. Hence, recommendations are for rain-watering harvesting or sourcing potable water from elsewhere over use of these sources.

Ten sites were classified as WQR 7; RYU1 at Lake Poopó, URC1 irrigation channel in Urmiri Village, the PQUE1 well near Quellía, and the PALP2/3/4/5/7/8/9 wells near Santa Filomena and Pazña Village (Figure 13). These sites are considered to have a naturally high salt content; EC >2 dS/m, high Na, Cl, B, and sometimes Li. Additionally, these sites often exceed 'A' criteria for health risk elements F, Sb or Cd. Concentrations of $NO_3$ are very high in the PALP7 well. The PALP2/3/4/5 wells also exceed 'A' criteria for As and $SO_4$, and PALP3 and PALP4 have high Mn, which tentatively suggests the possibility of mine water migration in groundwater in this area. Hence, WQR 7 sites would require any necessary pre-treatment with subsequent desalination in order to be of potable quality. All wells should be pumped before use and sampling, and improving the covers on wells where applicable is recommended (Section 8 for actions). A water quality analysis should be made to assess microbial contamination at any wells used for any consumption despite the exceedances of guidelines. PALP7 in particular should not be used without treatment for very high $NO_3$, and PALP2/3/4/5 for As.

Eleven sites were categorised as WQR 8; mine affected water that is high in $SO_4$ and with very high concentrations of many metals and metalloids. This includes i) downstream River Poopó (POR3), which has very high EC (8 dS/m), Zn, Cd, and Na, and high Cl, Fe, B, and Mn, ii) Kesukesuni River (KER2), very high Zn, Cd and Fe, and high EC, B, Mn, Sb, F, Li, Na, Cl, and $SO_4$, iii) all Antequera River sites (BODI1 channel, TOTR1, TOTR2, AVR2, AVR1, AVR3 and one well TOTP5), with extremely high concentrations of Zn, Fe, Al and Cd (HQ's >100), and high EC, Mn, Cu, Ni, F, and $SO_4$ concentrations (AVR2 also has high As) and sometimes Sb and Pb, and iv) the continuation of the Antequera River to sites on the Pazña River (PAZR1, PALR2), which have extremely high Zn, Al, Cd and Mn concentrations, and high $SO_4$, Cu, Fe, Ni, Sb and Co. Control of mine activity upstream (and artisanal practices throughout the river reaches) including removal/containment of mine waste and tailings to prevent contact with water (prevent initial/continued generation of AMD) and containment of AMD/minewater for treatment are necessary to prevent high metal loadings to the rivers that may also infiltrate groundwater. Treatment of mine-affected water is discussed in Sections 8.1.4 and 8.2.7.

The three thermal sites (CABTE, PAZTE, and URLT1) and one well (PAZP3) sampled in the study were classified as WQR 9, all showing a similar chemical signature; extremely high EC (6 - 18 dS/m), TDS, Na, Cl, and very high B, and high Li, F and Sb, and sometimes high Fe. PAZP3 well also has high As and Mn concentrations. This suggests that B, Li, F and Sb are naturally sourced in other waters in the region, and that these elements are naturally sourced in other/non-thermal waters. These waters are highly mineralised, and only suitable for bathing purposes.

Mine water sites (MAD1 and TID1) and the river at SORR1 were classified as WQR 10. Water that is strongly contaminated by acid mine drainage are unsuitable for any use due to metal and metalloids HQs>10, acidic pH and EC>10. Such waters should be contained to prevent consequential contamination of local groundwater or surface waters, and mining operations should adhere to environmental legislation and improved environmental management practice. Remediation of mine waste and affected water, as mentioned previously, requires significant treatment (refer to Sections 8.1.4 and 8.2.7).

Table 5 Generalised recommended actions for different WQR (1 = best, 10 = worst).

<table>
<tr><th rowspan="2">PRIORITISED RECOMMENDED ACTION</th><th colspan="10">WQR</th></tr>
<tr><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th></tr>
<tr><td>1st</td><td>N/A</td><td colspan="4">Microbial assessment of water sources for human consumption and livestock</td><td colspan="5" rowspan="4">Not for human consumption without significant treatment (see below)</td></tr>
<tr><td>2nd</td><td>N/A</td><td colspan="4">Covering, cleaning and replacement of tanks, pipes, channels etc.</td></tr>
<tr><td>3rd</td><td>N/A</td><td colspan="4">Standard treatment for potable water (disinfection, filtration etc.)</td></tr>
<tr><td>4th</td><td>N/A</td><td>N/A</td><td colspan="3">Treatment for F (As and Sb in some cases)</td></tr>
<tr><td>5th</td><td colspan="10">Rainwater harvesting to supplement water supply (requires some treatment after collection)</td></tr>
<tr><td>6th</td><td colspan="10">Investigate sources (e.g., additional supply from upstream locations) and improve capture of runoff and spring discharge prior to source of anthropogenic (e.g., mining activity) and natural contamination (e.g., high salt areas)</td></tr>
<tr><td>7th</td><td colspan="10">Hydrogeological investigation to better characterise and assess groundwater dynamics and quality (e.g., better regional coverage of borehole levels for piezometry, pump test to determine yields, quality at depth)</td></tr>
<tr><td>8th</td><td>N/A</td><td>N/A</td><td>N/A</td><td>N/A</td><td colspan="3">Desalination for potable water (and livestock if WQR >6)</td><td colspan="3">N/A unless undergone remediation for mine water</td></tr>
<tr><td>9th</td><td>N/A</td><td>N/A</td><td>N/A</td><td>N/A</td><td>N/A</td><td>Low level mine water remediation</td><td>N/A</td><td>Mine water remediation</td><td>N/A</td><td>Intensive Mine water remediation</td></tr>
</table>

Table 6 Summary of chemical status for use and recommended actions based on 2013 – 2014 water chemical data (refer to Appendix A for individual site data).

✓ Chemically acceptable for use. Meets Bolivian 'A' criteria (see Table 1a) and indicates Electrical conductivity (EC) <0.9 dS/m.
+ Chemically acceptable for use with caution of noted metals (occasional occurrence of elements in brackets) as they exceed 'A' criteria in samples 2013 – 2014. SAR reference used to indicate potential soil infiltration problems (refer to Table 1b). Treatment recommended for noted elements. Tin (Sn) not included as Bolivian criteria are not known to exist.
× Not acceptable for use without treatment. Exceeds 'A' criteria in >75% samples 2013 – 2014, and generally EC >1.5 dS/m (see Appendix A for individual site data).
✖ Not acceptable for use. Exceeds 'A' criteria by a factor of at least 10 (i.e., HQ>10) for many elements and generally EC >8 dS/m. Requires significant treatment to be of potable quality.

| **Site (type)** | **Location** | **WQR** (2013 – 2014) | **Chemical acceptability for use** (limitations given for WQR<5 by noted metals and electrical conductivity (EC) as salt content (brackets occasional). | | | **Action 1** | **Action 2** | **Action 3** |
|---|---|---|---|---|---|---|---|---|
| | | | Human consumption | Livestock watering | Irrigation (non-restricted) | | | |
| SORR1 (river) | Sora Sora | 10 | ✖ | ✖ | ✖ | Contain minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. |
| TOLAP1 (well) | Tolapampa | 4 | + F, Sb (Cd) | + F | + F, SAR | Microbial assessment (pre-pump well before sampling). Use rainwater harvesting to supplement water demand. | Improve the cover on the well. Pump well before use, and filter all well water before consumption. | Treatment for F, Sb (and Cd) for human consumption. Standard potable water treatment required. |
| POR4 (river) | Poopó | 3 | + Sb | ✓ | + SAR | Use rainwater harvesting to supplement water demand. | Microbial assessment. Standard treatment for potable water, and treatment for Sb. | Pump water from the river (or drill/pump boreholes) prior to water becoming contaminated downstream. |
| CABT1 (storage tank) | Poopó | 3 | + F (Sb) | + F | + F, SAR | Microbial assessment. Clean tank, new tank/pipes if necessary. | Investigate additional water in this area and use rainwater harvesting. | Standard treatment for potable water, and treatment for F (and Sb). |
| CABTE (thermal) | Poopó | 9 | ✖ | ✖ | ✖ | Bathing use only. | Prevent influx of thermal waters to rivers. | --- |
| MAD1 (mine water) | Poopó | 10 | ✖ | ✖ | ✖ | Contain minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. |
| TID1 (mine water) | Poopó | 10 | ✖ | ✖ | ✖ | See MAD1 | See MAD1 | See MAD1 |
| POR3 (river) | Poopó | 8 | ✖ | ✖ | ✖ | See MAD1 | See MAD1 | See MAD1.<br>Possible upstream groundwater pumping to lower the water table and thus river flow. |
| RYU1 (river/lake) | Lake Poopó | 7 | × | × | × | Desalination (to include reduction of B, Sb, Cd, F). | --- | --- |

Table 6 continues on next 4 pages.

| **Site (type)** | **Location** | **WQR** (2013 – 2014) | **Chemical acceptability for use** (limitations given for WQR<5 by noted metals and electrical conductivity (EC) as salt content (brackets occasional). | | | **Action 1** | **Action 2** | **Action 3** |
|---|---|---|---|---|---|---|---|---|
| | | | Human consumption | Livestock watering | Irrigation (non-restricted) | | | |
| KER1 (river) | Kesukesuni | **6** | × | + F | × | Rainwater harvesting. Note: concern over poor quality of water at adjacent KER2 and lack of data for KER1. | Investigate possible mine water migration. | Desalination and treatment for Sb, F, B, and Zn, and standard potable water treatment required for human consumption. |
| KER2 (river) | Kesukesuni | **8** | ✖ | ✖ | ✖ | Contain minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. |
| PUNP1 (tap) | Puñaca | **2** | ✓ | ✓ | ✓ | Microbial assessment. | Use rainwater harvesting to supplement water demand. | --- |
| PUNP2 (well) | Puñaca | **5** | × | ✓ | + F, B, Mn | Use rainwater harvesting to supplement water demand. | Treatment for F, Mn, Sb and As (rainy season). Microbial assessment (pre-pump well before sampling) and standard potable water treatment required. | Investigate other groundwater in the area and at depth. |
| CALLP3 (well) | Callipampa | **4** | + (F, B) | ✓ | + (F, B) SAR | Use rainwater harvesting to supplement water demand. | Treatment for F. Microbial assessment (pre-pump well before sampling) and standard potable water treatment required. | Investigate other groundwater in the area and at depth. |
| PQUE1 (well) | Quellía | **7** | × | ✓ | × | Use rainwater harvesting to supplement water demand. | Desalination and treatment for F, As and B. If Used for supply, microbial assessment (pre-pump well before sampling) and standard potable water treatment required. | Investigate other groundwater in the area and at depth. |
| PMO1 (well) | Morochi | **4** | + (As, F, Sb) | ✓ | + (F) SAR | Use rainwater harvesting to supplement water demand. | Treatment for F, As and Sb. Microbial assessment (pre-pump well before sampling) and standard potable water treatment required. | Investigate other groundwater in the area and at depth. |
| BODI1 (mine water) | Antequera - Bolivar | **8** | ✖ | ✖ | ✖ | Contain minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. |
| TOTV2 (spring/ slope) | Antequera – Totoral Martha | **6** | × | + F | + F, SAR | Use rainwater harvesting to supplement water demand. | Diversion of mine affected water to prevent infiltration to groundwater etc. | If used for potable water, treatment for F, As. Sb, Cd, and Zn. Microbial assessment and standard potable water treatment. |

| **Site (type)** | **Location** | **WQR** (2013 – 2014) | **Chemical acceptability for use** (limitations given for WQR<5 by noted metals and electrical conductivity (EC) as salt content (brackets occasional). | | | **Action 1** | **Action 2** | **Action 3** |
|---|---|---|---|---|---|---|---|---|
| | | | Human consumption | Livestock watering | Irrigation (non-restricted) | | | |
| TOTR1 (river) | Antequera – Totoral Martha | **8** | ✖ | ✖ | ✖ | Contain minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. Possible upstream groundwater pumping to lower the water table and thus river flow. |
| TOTR2 (river) | Antequera – Totoral | **8** | ✖ | ✖ | ✖ | Contain minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. Possible upstream groundwater pumping to lower the water table and thus river flow. |
| TOTP5 (well) | Antequera – Totoral Martha | **8** | ✖ | ✖ | ✖ | Contain minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. |
| CUCC1 (irrigation channel /pool) | Kuchi Avicaya | **3channel pool not sampled** | + F | ✓ | + F, SAR | Use rainwater harvesting to supplement water demand. | Clean the pool of algae and install a roll-back cover to prevent evaporation losses. Treatment for F if used for human consumption. | Investigate upstream water sources that supply the channel that feeds the pool. |
| AVR2 (river) | Antequera - Avicaya | **8** | ✖ | ✖ | ✖ | Contain minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. |
| AVR1 (river) | Antequera - Avicaya | **8** | ✖ | ✖ | ✖ | Contain minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. |
| AVR3 (river) | Antequera - Avicaya | **8** | ✖ | ✖ | ✖ | Contain minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. |

| **Site (type)** | **Location** | **WQR** (2013 – 2014) | **Chemical acceptability for use** (limitations given for WQR<5 by noted metals and electrical conductivity (EC) as salt content (brackets occasional). | | | **Action 1** | **Action 2** | **Action 3** |
|---|---|---|---|---|---|---|---|---|
| | | | Human consumption | Livestock watering | Irrigation (non-restricted) | | | |
| PALP10 (well) | Vilaque (Antequera – Avicaya) | **4** | × | + F | + F, Mn | Microbial assessment (pre-pump well before sampling). | Improve cover on well, install a pump to obtain deeper water and deal with stagnation. | Treatment for F and Mn if used for human consumption. High Fe may affect taste. Standard potable water treatment required. |
| LCR1 (river) | Laca Laca | **6** | × | + Zn | × | Use rainwater harvesting as an alternative to supplement water demand. | Determine the source of high Zn, Ni and Cd. Source/migration control. | Treatment for very high concentrations of Zn, and treatment for Ni and Cd if used for human consumption followed by standard potable treatment. |
| URR2 (river) | Urmiri - Talaco | **3** | + (F, Sb) | + F | + SAR, F | Microbial assessment if used for human consumption. | Treatment for F and Sb if used for human supply. | Investigate groundwater in this area. |
| URR1 (river) | Urmiri | **3** | + (F) | + (F) | + SAR, F | Microbial assessment if used for human consumption. | Treatment for F if used for human supply. | Investigate groundwater in this area. |
| URLT1 (thermal) | Urmiri | **9** | ✖ | ✖ | ✖ | Bathing use only. | Prevent influx of thermal waters to rivers. | --- |
| URV1 (spring/ slope) | Urmiri | **5** | × | + F | + SAR, F, B | Use rainwater harvesting to supplement water demand. | Microbial assessment, and desalination and treatment for F, B, and Sb if used for human consumption. | Use upstream sources unaffected by thermal inputs. |
| URC1 (irrigation channel) | Urmiri | **7** | × | + F | × | Use rainwater harvesting to supplement water demand. | Microbial assessment, and desalination and treatment for F, B, and Sb if used for human consumption. | Use upstream sources unaffected by thermal inputs. |
| URR3 (river) | Urmiri | **5** | × | + F | + F (EC) | Use rainwater harvesting to supplement water demand. | Microbial assessment, and desalination and treatment for F if used for human consumption. | Use upstream sources unaffected by thermal inputs. |
| VIP1 (well) | Pazña | **6** | × | ✓ | + B, Mn | Avoid use of this well due to possible mine water migration. | Use alternate water sources and rain-water harvesting. | Treatment for Cd, As and Mn, and standard potable water treatment required in addition to microbial assessment if used for human consumption. |
| PALP7 (well) | Pazña | **7** | × | + B, F | × | Use rainwater harvesting to supplement water demand. Improve the cover on the well. | Desalination and treatment for $NO_3$, F and B if used for human consumption or animals ($NO_3$ especially). | Microbial assessment (pre-pump well before sampling) and standard potable water treatment required if used for human consumption. |
| PALP8 (well) | Pazña | **7** | × | + B, F | × | Use rainwater harvesting to supplement water demand. | Desalination and treatment for F and B if used for human consumption. | Microbial assessment (pre-pump well before sampling) and standard potable water treatment required if used for human consumption. |

| **Site (type)** | **Location** | **WQR** (2013 – 2014) | **Chemical acceptability for use** (limitations given for WQR<5 by noted metals and electrical conductivity (EC) as salt content (brackets occasional). | | | **Action 1** | **Action 2** | **Action 3** |
|---|---|---|---|---|---|---|---|---|
| | | | Human consumption | Livestock watering | Irrigation (non-restricted) | | | |
| PALP9 (well) | Pazña | **7** | × | + B, F | × | Use rainwater harvesting to supplement water demand. Improve the cover on the well. | Desalination and treatment for F and B if used for human consumption. | Microbial assessment (pre-pump well before sampling) and standard potable water treatment required if used for human consumption. |
| PAZR1 (river) | Pazña | **8** | ✖ | ✖ | ✖ | Contain upstream minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. |
| PALR2 (river) | Pazña | **8** | ✖ | ✖ | ✖ | Contain minewater for future treatment. Control mine water discharges or infiltration away from rivers (via ditches/channels). | Remove and/or contain mine waste and tailings, isolate from all water sources (including rainfall) to prevent infiltration and generation of AMD. | Minewater remediation for contained AMD and continued AMD from mine exits. Treatment of continued AMD from non-isolated tailings/spoils. |
| PAZTE (thermal) | Pazña | **9** | ✖ | ✖ | ✖ | Bathing use only. | Prevent influx of thermal waters to rivers. | --- |
| PAZP3 (well) | Pazña | **9** | ✖ | ✖ | ✖ | Use other wells and rainwater harvesting to supplement water demand. | Like thermal waters, EC>15. Significant desalination and treatment to reduce B, F, As, Li, Mn, Pb, Sb. | --- |
| PALP2 (well) | Pazña | **7** | × | + F | × | Improve the cover on the well and pump before use. Use rainwater harvesting to supplement water demand. | Desalination and treatment for F, B, As and Sb if used for human consumption. | Microbial assessment (pre-pump well before sampling) and standard potable water treatment required if used for human consumption. |
| PALP3 (well) | Pazña | **7** | × | × | × | Improve the cover on the well and pump before use. Use rainwater harvesting to supplement water demand. | Desalination and treatment for F, B, As, Mn, Sb and Cd if used for human consumption. | Microbial assessment (pre-pump well before sampling) and standard potable water treatment required if used for human consumption. |
| PALP4 (well) | Pazña | **7** | × | + F | × | Improve the cover on the well and pump before use. Use rainwater harvesting to supplement water demand. | Desalination and treatment for F, B, As, Mn and Cd if used for human consumption. | Microbial assessment (pre-pump well before sampling) and standard potable water treatment required if used for human consumption. |
| PALP5 (well) | Pazña | **7** | × | × | × | Cover on the well and pump before use. Use rainwater harvesting to supplement water demand. | Desalination and treatment for As, F, B and Sb if used for human consumption. Particularly high arsenic. | Microbial assessment (pre-pump well before sampling) and standard potable water treatment required if used for human consumption. |

## 8. ACTIONS: OPTIONS & RECOMMENDATIONS

The WHO (2011a) recommends that in situations where short-term exposure is not likely to lead to health impairment, efforts may be better concentrated on finding and eliminating the source of contamination as oppose to installing expensive drinking-water treatment to remove chemical constituents. This is a principle that should be at the core of considering any actions or treatment, and although it is within the context of human health risk, it can be used to express the need to prioritise human health over environmental concerns. Even for environmental concerns within the context of the study area, source protection by controlling and containing mining waste is a priority albeit complicated due poor enforcement of legislation. Environmental legacy of mining, however, is also complicated even if they are not directly contaminating water sources, because of possible livestock watering in mine affected rivers and other food chain implications (e.g., fish) where mine contaminated waters enter rivers and lakes. The need for environmental remediation of mine affected waters is dealt with separately to potable water (Section 8.1.4 and 8.2.7) as these waters contain very high metal concentrations, and any remediation is a long-term, costly, and often politically complicated issue for Lake Poopó region.

In this report we have emphasised health risk chemicals, and in the following sub-section we provide information on general options for potable water quality treatment quality, focussing on those most applicable for rural locations. All of the options detailed require in-situ testing if after obtaining further, more specific information on individual treatments, a treatment is considered feasible. We then make general recommendations in Section 8.2 for the study area based on data and observations obtained during this study as summarised in Section 7; these include recommended actions for quality and quantity issues as suggestions for increased potable water. We do not focus on irrigation water management.

### 8.1. OPTIONS FOR TREATMENT

#### 8.1.1. Standard treatments for potable water

Standard treatment for potable water generally involves some or all of the following processes depending on the source water and level of treatment required, i) pre-chlorination for algae etc., ii) aeration (to remove dissolved Fe and Mn), iii) chemical coagulation, iv) sedimentation, v) filtration to remove particulate material, vi) desalination, and vii) disinfection against microbes. Other treatments include lime softening. There are various techniques that involve different levels of scale, complexity, and cost and with varying affectivity. Detailed information is beyond the scope of this report and reference material such as Cheremisinoff (2002) should be consulted. Although many are listed here because the principle of some has been extended for small-scale use, we focus on treatments applicable for rural areas and point-of-use (i.e., small-scale/household level) treatment (and temporary methods such as those used by travellers). All methods require field-testing.

***Chemical coagulation***

Coagulates such as aluminium or iron salts (e.g., aluminium or ferric sulphate) are added to water in order to form a metal hydroxide flocculent that facilitates bonding between particulates, which then either settle out over a period of ~ 1 week or are removed by flotation or pressure gravity filtration prior to subsequent additional filtration (see below). Coagulation removes suspended particles, many low-solubility organic compounds, inorganic precipitates such as Fe, and has been approved by the US Environmental Protection Agency (US EPA) for removing Cd and Sb. For point-of-use applications, a coagulation-flocculation method followed by chlorination uses packets of powdered ferrous sulphate and calcium hypochlorite.

***Filtration***

*Point-of-use methods:*

- *Membrane filters* include micro-filters, ultra-filters, nano-filters and reverse osmosis cartridges. All are common in developing countries. Filters must be ≤1 μm to remove pathogens. Micro-filters may not remove viruses but are effective for removing organic chemicals (WHO, 2011a). More basic filtration in developing countries also uses cloth or fibre filters in the absence of other methods or in conjunction with other method.
- *Ceramic filters* involve gravity driven filtration through porous ceramic material, which is effective for removal of microbes such as *E. coli* especially in areas where boiling or chemical disinfection is not practical or effective. A widely used method is the ceramic “candle” filter (Clasen et al., 2006) that has been shown to be effective for use at the household level in reducing diarrhoea in rural Bolivia. Ceramic filter have also been developed with impregnated silver nanoparticles (Kallman et al., 2011). Filters generally require a minimum water input of 20 L/day (WHO, 2011b).
- *Carbon block filters* must have pore size ≤1 μm to remove pathogens. This is a point-of-use/household method that can remove chlorine, organic compounds, *cryptosporidium* and other contaminants through adsorption and de-ionisation. Carbon is also used in granulated activated carbon and powdered activated carbon adsorption treatments generally at larger scale than point-of-use. Different types of activated carbon have different affinities for various contaminants (refer to WHO, 2011a for details).
- *Granular media filters* involve the filtration of water through sand or other particulate material that is in tanks or beds, and effectively retain particulate material, algae, microbes and sometimes organics through filtration, sedimentation and adsorption. A household scale method is the BioSand filter (Stauber et al., 2011) that is understood to be effective in reducing microbes.

Other, larger scale filtration methods include the following (refer to Cheremisinoff (2002) or WHO (2011a) for details):

- *Rapid gravity filters* involve the relatively quick filtration of water through open tanks (0.6 – 2.0 m deep) containing sand (0.5 – 1.0 mm), generally used to treat wastewater and the floc from coagulated water. This method can also reduce turbidity and oxidised iron and manganese.
- *Slow sand filters* are tanks (0.5 – 1.5 m deep) packed with sand (0.15 – 0.3 mm). Input water percolates slowly down though the sand, removing algae, microbes, turbidity and some organics. An upper biological layer ("schmutzdecke") develops and is effective at removing microbes. Sand filters are generally used to treat wastewater, and have also been used in conjunction with iron filters for removal of cations, anions, organic matter and microorganisms (Noubactep, 2010).
- *Bank filtration* often involves abstracting water from boreholes next to a surface water source. Sediments act as a filter and biofilter, and can remove particles, pathogens, heavy metals and easily biodegradable compounds (WHO, 2011a).

***Boiling***

Boiling water is effective in killing pathogens but does not provide residual chemical disinfection to protect against contamination. Pasteurisation temperatures are typically >63 $^{o}$C and requires 30 minutes. Boiling can destroy microbes, but does not reduce sediment or turbidity, and must be cooled and subsequently contained.

***Chemical disinfection***

Chemical disinfection against pathogenic microorganisms is often used for surface waters and groundwater subject to faecal contamination (animal and human). Attention should be made in highly turbid waters as these can protect microorganisms from the effects of disinfection (WHO, 2011a).

*Point-of-use methods:*

- *Chlorine compounds:* The most widely used method in developing countries and for point-of-use is using free chlorine (hypoclorous acid), which is quite effective, widely available, inexpensive and has ease of use (WHO, 2011b). Travellers use household bleach (sodium hypochlorite, 4 drops/litre), sodium dichloroisocyanurate tablets, or calcium hypochlorite (4 drops/litre) which are effective in killing most bacteria and viruses, but ineffective against *cryptosporidium* and less effective than iodine for turbid waters (WHO, 2011a).
- *Flocculant-chlorine tablets or sachets* (powdered ferrous sulphate and calcium hypochlorite) are used by travellers or as point-of-use method (sachet added to ~10 L water), and are effective at killing or removing most waterborne pathogens (coagulant-flocculants partially remove *cryptosporidium*). After treatment, water should be filtered (through fabric) into a clean container (WHO, 2011a).

- *Iodine* tincture solutions, tablets and resins are sometimes used by travellers. Iodine treatment is not recommended for extended use due to certain toxic biological effects. It is also difficult to prepare, handle and deliver. However, it can be used in emergency or short-term situations (WHO, 2011b). This method is not effective against *cryptosporidium*.
- *Silver and copper* use for disinfection is uncertain (WHO, 2011b).

*Other chemical disinfection (refer to WHO, 2001a for information):*

- *Ozonation* is not recommended for household/point-of-use treatment, as it is expensive and not straightforward.
- *Chloramination*
- *Chlorine dioxide*
- *Bromine*

***Solar disinfection***

The use of solar irradiation for microbial disinfection has been well studied and is discussed in WHO (2011b). On example is the SODIS system, which used clear plastic containers where the contained water is affected by penetrating UV radiation in combination with oxidative activity due to heat and dissolved oxygen. Performance is dependent on the geographical location and environmental conditions and requires field-testing.

***Ultra-violet light disinfection***

UV lights can also be used for treating drinking water and is proven to be effective against chlorine-resistant pathogens such as *Cryptosporidium* and *Giardia*. Point-of-use treatment generally uses low-pressure mercury arc lamps that produce monochromatic UV radiation at a wavelength of 254 nm, which must be field-tested (WHO, 2011b).

***Lime softening – cation exchange***

Lime softening (using calcium hydroxide) is used for reducing Ca and Mg (i.e., hardness), which causes scaling. Water softening is achieved by cation exchange using a bed of catonic resin, whereby Ca and Mg ions in water are replaced by Na. It can also be effective in reducing many microorganisms, dissolved organic matter, and some trace metals such as Cd, As, Cr, Fe and radon (see below).

### 8.1.2. Treatments for specific elements or chemicals

Various treatments are effective in reducing elements of health significance and chemicals, including F, As, Sb, Cr, Cd, Pb and $NO_{3.}$

- *Fluoride* in drinking water and defluoridation is reviewed by Jagtap et al. (2012). Fluoride concentrations can be reduced by activated alumina, precipitation with aluminium sulphate and lime (“Nalgonda” method used in India) or calcium and phosphate compounds, through the use of membrane processes such as reverse osmosis or electrodialysis, by ion-exchange resins, by adsorption using materials other than activated alumina such as activated carbon (Jagtap et al., 2012), or bone-char (Medellin-Castillo et al., 2007). Point-of-use/household method for F reduction can use activated alumina, reverse osmosis cartridges and the Nalgonda method.

- *Arsenic* can be reduced by anion exchange, and activated alumina filtration methods have been tested. However, there are no proven methods for use at wells, hand-pumps and springs. Point-of-use/household method for As reduction is reverse osmosis. Membrane-based nanofiltration has also been investigated (Harisha et al., 2010). Rainwater harvesting is a good alternative to avoid using water contaminated by As (and other contaminates).
- *Antimony* removal by coagulation/filtration or reverse osmosis have both been approved by the US EPA.
- *Chromium* removal by coagulation/filtration, ion exchange, reverse osmosis or lime softening has been approved by the US EPA.
- *Cadmium* removal by coagulation/filtration, ion exchange, reverse osmosis or lime softening has been approved by the US EPA.
- *Lead* can be reduced by corrosion control. Possibly Pb may be removed at the household level by reverse osmosis cartridges, carbon filters, ion exchange resins, activated alumina.
- *Nitrates and nitrites* require source-protection management, as they are often associated with sewage or agricultural runoff. Nitrite is more toxic and can be oxidised to nitrate ($NO_3$) by disinfection. The US EPA has approved ion-exchange, reverse osmosis and electrodialysis (see desalination below) for removing nitrates/nitrites.

#### 8.1.3. Desalination

Desalination processes involve the removal of high salt content from water and can be catagorised into two main types i) phase-change/thermal (e.g., multi-stage flash, vapour compression, freezing, solar stills), and ii) membrane processes (e.g., reverse osmosis, membrane distillation, and electrodialysis). Many of these have been well developed in recent years, including the use of renewable energies for powering desalination (Charcosset, 2009; Gnaneswar Gude et al., 2010; Qiblawey and Banat, 2008). Methods (and scale) vary considerably in cost (Karagiannis and Soldatos, 2008) and applicability to different locations and levels of water salinity. Desalination of brackish waters is significantly cheaper than for saline/seawater. Much research has been undertaken on rural desalination using renewable energy (e.g., Banasiak and Schäfer, 2009; Richards et al., 2011). Desalinated water has a very low total organic carbon content and low disinfection demand (WHO, 2011a). Membrane and distillation methods are very efficient at removing high molecular weight organic carbon and inorganic chemicals. Desalination can also include removal of some trace metals, for example, reverse osmosis can also remove Cd, F, As, Sb, and $NO_3$. Membrane processes such as reverse osmosis may not be highly effective in removing boron because it is present as boric acid at normal operational pH (Öztürk at el., 2008).

Reference material such as Cotruvo et al. (2010) review issues associated with desalination (technology, management, water quality issues etc.), and should be consulted for detailed information on desalination for drinking water. The WHO also provides information on the principal health risks related to different desalination processes and guidance on appropriate risk assessment and risk management procedures (http://www.who.int/water_sanitation_health/publications/en/index.html).

### 8.1.4. Remediation of mine affected water

When sulphide-bearing material is exposed to oxygen and water, sulphide minerals oxidise to form acidic, sulphate rich drainage. The resultant acid mine drainage (AMD) is generally of low pH, high specific conductivity and high concentrations of Fe, Al, Mn and other metals and metalloids. The chemistry of AMD is described by Kalin et al. (2006) and Akcil and Koldas (2006), who summarise that AMD formation involves iron sulphide ($FeS_2$) oxidation (Eq.1), ferrous iron ($Fe^{2+}$) oxidation (Eq.2), ferric iron ($Fe^{3+}$) hydrolysis at pH 2.3 – 3.5 (Eq.3), and the enhanced oxidation of ferric sulphide ions (Eq.4):

$$FeS_2 + 7/2O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad \text{(Eq.1)}$$

$$Fe^{2+} + 1/4O_2 + H^+ \rightarrow Fe^{3+} + 1/2H_2O \qquad \text{(Eq.2)}$$

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3\,(s) + 3H^+ \qquad \text{(Eq.3)}$$

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad \text{(Eq.4)}$$

Primary sources of AMD include mine rock dumps, tailing impoundments, underground and open pit mine workings, pumped discharge underground water, and diffuse seepage. Secondary sources include treatment sludge ponds, rock cuts, concentrated load-out, and stockpiles (Akcil and Koldas, 2006).

The environmental impact of mining can be minimised through 1) prevention of AMD generation, 2) migration control/prevention, and 3) collection and treatment of minewater and waste. Johnson and Hallberg (2005) discuss how it is generally preferable, although not always pragmatic, to prevent the formation of AMD through "source control". Prevention generally relates to controlling water entry to sites of AMD formation, for example, flooding and sealing of old underground mines, underwater storage of mine tailings, diversion of surface water, prevention of groundwater infiltration, and controlled placement and more appropriate containment of acid-generating waste material (from rainfall as well as surface water and groundwater) using land-based storage in sealed waste heaps (see Johnson and Hallberg, 2005).

Treatment of minewater (i.e., "migration control"), on the other hand, first requires either i) interception to collect surface run-off (e.g., ditches) and groundwater flow (e.g., cut-off walls or trenches) for treatment, or ii) re-routing (e.g., for wetland treatment, see below). Minewater can then be remediated via abiotic or biological methods that can be “active” (i.e., generally required continual application of alkaline material) or “passive” (i.e., not a source of secondary pollution and ideally self-renewing, e.g., wetlands). Treatment selection is dependent on many factors, including the chemical characteristics of the AMD, the volume of water requiring treatment, sludge waste characteristics, local environmental conditions (climate, terrain, hydrology etc.), projected life span, and cost.

Figure 14 summarises available AMD remediation techniques, which include following:

a) *Neutralization treatment* by chemical dosing (with hydrated lime, calcium carbonate, sodium carbonate, sodium hydroxide, kiln dust, fly ash etc.) and sedimentation is the most widespread method to mitigate AMD. This effectively increases the pH, accelerates the rate of oxidation of ferrous iron, and causes many metals to precipitate as hydroxides and carbonates (Johnson and Hallberg, 2005). There are high operating costs and the process produces a voluminous sludge/secondary waste, which are the subject of environmental concern and requires costly disposal (reduced by creating “high-density sludge”). Lime treatment can also produce hard water that can be detrimental to the receiving environment (Kalin et al., 2006), and additionally, valuable metal resources are not recovered (Ňancucheo and Johnson, 2012).

b) *Anoxic limestone drains (ALD)*, limestone ponds or open limestone channels. The basic principle involved is the addition of alkalinity whilst maintaining Fe in a reduced form to avoid oxidation of ferrous iron and precipitation of ferric hydroxide. However, in reality these systems have been found to become coated by Fe and Al hydroxides within 6 months (Johnson and Hallberg, 2005), which reduces limestone dissolution and requires it to be renewed. Hence, it is not truly passive or sustainable (Kalin et al., 2006). Although ALD are considered to be lower cost options than constructed compost wetland treatment, ALD are not suitable for all AMD water and still do not offer the potential to recover metals. They are, however, generally used in association with aerobic and/or compost wetland systems (Johnson and Hallberg, 2005).

c) *Sulphidogenic bioreactors* utilize inoculants of sulphate-reducing bacteria (SRB), whereby an optimised biogenic production of hydrogen sulphide generates alkalinity to remove metals as insoluble sulphides. Systems require the addition of biodegradable organic material to provide a source of carbon, and studies have reported a tendency for the carbon resource of lactate, acetate/ethanol, glucose and molasses, which increase the fraction of SRB and improve sulphate removal efficiency, and also reduces starting-up duration (Zhao et al., 2010). Bioreactors and the biosulphide process also offer economic recovery through the capture of commercial grade metals (Ňancucheo and Johnson, 2012, also see references within Johnson and Hallberg, 2005, and Kalin et al., 2006).

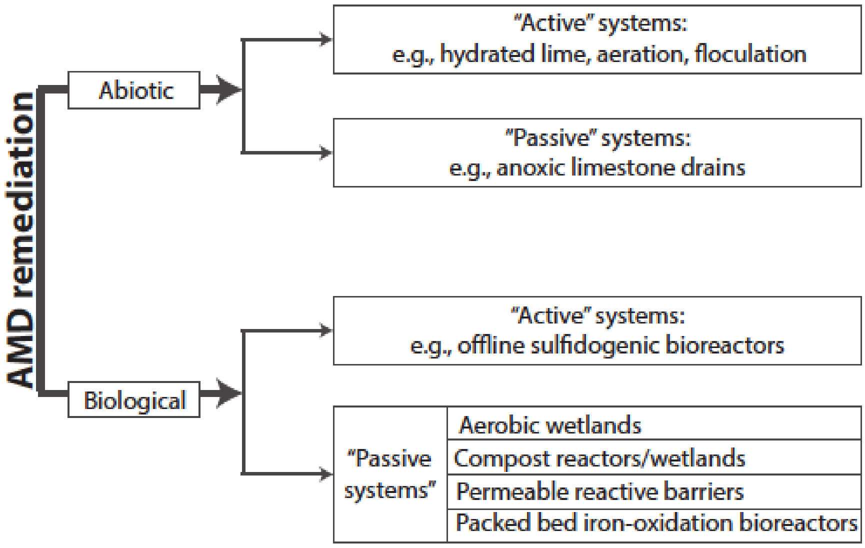


Figure 14 Flow chart showing main AMD remediation methods (after Johnson and Hallberg, 2006).

d) *Anaerobic "wetlands" (compost bioreactors)* are often confined below ground and use microbial reductive processes and the generation of alkalinity to immobilize metals from acidic, metal-rich AMD. These methods also require the addition of bulky biodegradable organic material (usually straw, sawdust, animal manure) to provide a source of carbon, the demand for replacement of this in addition to the lack of recovery of metals (that are effectively locked up within compost and usually categorised as toxic) are disadvantageous (Ňancucheo and Johnson, 2012).

e) *Permeable reactive barriers* (PRBs, e.g., Blowes et al., 2000) operate on the same basic principles as compost. PRBs are constructed trench or pits containing organic materials (and sometimes limestone) where groundwater affected by AMD is intercepted. Alkalinity is generated in the sub-surface system by microbial reduction to remove metals as sulphides, hydroxides, and carbonates (chemical and biological processes are described in Sheoran and Sheoran, 2006).

f) *Aerobic wetlands* (constructed or natural) are shallow systems operated by surface flow, which are generally used to treat minewater that is net alkaline (Johnson and Hallberg, 2005) and act as biological filters (see Sheoran and Sheoran, 2006). The primary reaction occurring is oxidation of ferrous iron ($Fe^{2+}$) (Eq. 2) and subsequent hydrolysis of the ferric ion ($Fe^{3+}$) produced (Eq. 3). ALD can be incorporated to control the acidity generated if there is insufficient alkalinity (Johnson and Hallberg, 2005) (chemical and biological processes are described in Sheoran and Sheoran, 2006).

g) *Composite aerobic and anaerobic "wetlands"*, for example, Acid Reduction Using Microbiology (ARUM; Kalin, 1993), which has been successfully applied at sites in

Canada and Brazil (see references within Kalin et al., 2006). The ARUM system consists of treatment cells containing sediments constructed from organic materials and floating cattail/vegetation rafts, and has been demonstrated to result in the removal of metals, acidity and sulphur through sulphate reduction.

Comprehensive review of minewater treatment is given in Brown et al. (2002), who detail available methods for treatment and also assess applicability, efficiency and cost-effectiveness of minewater treatment schemes. Generally, conventional “active” treatments are considered to be expensive in terms of operating and capital costs. Although “passive” systems are usually thought of as requiring relatively lower recurring cost and maintenance in comparison to active methods, they might be i) expensive to set up, ii) impractical to set up, iii) require more land than is available or suitable. In reality all “passive” treatment require a certain amount of maintenance costs. Furthermore, performance is considered less predictable than chemical treatment and the long-term fate of accumulated deposits are uncertain (Johnson and Hallberg, 2005). However, “passive” systems may foster community responsibility (Sheoran and Sheoran, 2006), and advancing techniques might promise ecological engineered systems as a sustainable approach for dealing with AMD (Kalin et al., 2006).

## 8.2. RECOMMENDED ACTIONS

The general recommendations presented below relate to the discussion in Section 7 and summarised actions in Tables 4 and 5 for each site, and include actions for quality and quantity issues of varying scales across the study area. We stress the importance of prioritising needs for action and treatment based on immediate concerns, health risks, and also on feasibility, complexity and cost of actions for this rural area. Hence, the actions are presented in a general order from concerns requiring immediate attention to long-term, expensive remediation. As previously stated, we do not focus on irrigation water management issues.

### 8.2.1. Immediate actions (relatively low cost)

***Cleaning and covering***

- Tanks, pools and weirs should be cleaned (e.g., of algae).
- Open tanks and pools should be covered (e.g., with rolling covers to allow ease of access), such that evaporation losses are reduced and protection is given to contamination.
- All wells should be covered both for safety reasons and to prevent input of material (e.g., straw) and contamination (e.g., animal droppings). Existing covers that are of poor condition should be replaced, ideally such that wells have concrete stands, sealable lids and (manual and/or electrical) pumps (to allow pre-pumping before use).
- New tanks, pipes, plastic casings etc. for existing water sources to improve storage/quality.

- Rivers should be cleaned of general refuse.
- Wastewater should not be discharged directly to surface waters without treatment. Suggestions for treating organic waste include systems such as 'biobolsa' (http://sistemabiobolsa.com/home/), which can be effective for fertilizer and energy production.

***Microbial assessment***

For all water sources, microbial assessment for pathogens including bacteria, viruses and protozoa should be prioritised. This is a very important issue for human and animal health, particularly relating to gastrointestinal infections. The WHO (2011a, b) provides guidance on microbial contaminants, assessment, health-based targets for pathogens, and treatment (discussed previously). They also suggest literature for guidance (Annex 1 of WHO, 2011a). Management strategies should prioritise preventing or reducing the entry of pathogens into water sources, and the greatest microbial risks are associated with water that is contaminated with faeces. Other microbial hazards include *Legionella*.

Additionally, in situation where algae is present, analysis might be made for microcystin-LR; an organic toxin of health concern that is produced by cyanobacteria or blue-green algae, which are often present in lakes, ponds, and slow flowing rivers. Control and prevention of algae blooms is recommended, e.g., by controlling nutrient loadings.

### 8.2.2. Rainwater Harvesting

Rainwater harvesting (RWH) is used widely in areas requiring supplementary water supply, especially rural communities and as an adaptation step to climate change (Mwenge Kahinda et al., 2010). Systems are based on local skills, materials and equipment, and often offer a practical, low cost, relatively easily installed and low maintenance means of supplementing local water demand.

RWH systems comprise a catchment area (e.g., rooftop) and storage facility (e.g., under- or over-ground tank or cistern) and settling tank. Because microbial and vector disease are often a concern, and the quality of the water collected depends both on the local conditions (e.g., climate and any pollution sources affecting rainwater) and storage and handling of collected water, filtration systems may also be incorporated. For example, silver-ion based purification system (Adler et al., 2014), slow sand filtration, solar technologies and membrane technologies may also be used (Helmreich and Horn, 2009). Also, unpublished studies have explored the potential of RWH as an instrument to reduce poverty (Lehmann and Tsukada, 2011).

In order to consider implementing rainwater harvesting (developed as a trial system that if successful could be extended), or expanding existing schemes, a scoping phase should first be conducted. This ideally should first involve a community workshop to ascertain i) willingness to participate both in construction and system maintenance, ii) locally available labour and materials (e.g., guttering, cisterns, pumps, tools) for construction, iii) potential sites for installation of a

RWH system (e.g., local school). At this stage local information on water usage and existing potable sources should also be gathered.

The second step of the scoping phase prior to undertaking a RWH trial project should involve surveys of potential sites, whereby photographs of the building and surrounding ground (e.g., for possible building materials), and measurements and sketches are made (e.g., roof angle and dimensions). Other information such as materials the roof is made of, availability of electric supply, and existing guttering/tanks/pumps should also be gathered. The potential amount of water that can be collected from the system can then be determined using methods such as the "Dropcount calculator" (see http://node01.geospatial.ucl.ac.uk/teaching/user25/test/home.php).

#### 8.2.3. Treatment for fluoride, arsenic and antimony

The majority of chemical concern other than salt content in water sources in this study was for health-risk elements F and Sb (and in some cases As, Cd; see Table 6 and Appendix A for individual site information). These elements often consistently exceed Bolivian 'A' and WHO guidelines, and treatment is recommended for the following sites sampled in this study as they may be used for human consumption or feed into water sources: TOLAP well, POR4 river, CABT1 tank, PUNP2 well, CALLP3 well, PMO1 well, CUCC1 pool, PALP10 well, URR1/2/3 river, and URV1 slope (refer to Figure 1 for locations). Other sites, with the exception of the PUNP1 tap, not mentioned should not be used for human consumption as they have poorer quality requiring additional treatment. The following sites also require desalination, which may remove some of the aforementioned elements: PQUE1 well, URC1 channel, PALP2/3/4/5/8/9 wells (PALP7 not included as this well also requires treatment for $NO_3$). See Table 6 for specific element exceedances and other recommended actions, and Section 8.1.2 for treatment options.

#### 8.2.4. Investigating sources

The possibility of obtaining additional water to meet demand for domestic use and agriculture should be prioritised by considering and investigating exiting good sources. This might include investigating the naturally occurring artesian springs on the sides of hills/mountains that maintain the river flow in the dry season, and building more channels, pools and tanks (as well as improving existing systems) for more efficient and effective capturing and storage of water resources. Examples include reducing losses to evaporation (covering pools/using closed tanks), intercepting water prior to contact with mine waste (by pumping upstream), and more channels to transport upstream water to holding tanks.

#### 8.2.5. Hydrogeological assessment

There are many literatures on groundwater that detail hydrogeological principles and investigations (e.g., Domenico and Schwartz, 1990). Essentially there is a need to assess regional groundwater resources through a comprehensive hydrogeological investigation by experienced Hydrogeologists in order to build a more accurate understanding of the local and regional aquifer systems. This might include:

a) Using existing boreholes and wells to obtain an up to date temporal and spatial database of groundwater levels that can be used to more accurately determine flow paths and flow direction, and create potentiometric/piezometric maps and cross-sections.
b) Characterisation of aquifer properties such as hydraulic conductivity.
c) Pumping from depth to ascertain the groundwater quality at deeper levels than already accessed.
d) Pumping tests to determine yield.
e) Drilling of new, deeper boreholes may also be required for determining regional flow field in addition to groundwater in areas not assessed to date.

#### 8.2.6. Desalination

A significant number of water sources, especially wells ( PQUE1, PALP2/3/4/5/8/9 wells), were found in this study to have electrical conductivities exceeding the maximum recommended for drinking water (1.5 dS/m). Desalination is (e.g., point-of-use) recommended to treat these waters (refer to Section 8.1.3), especially as this can also be effective in reducing other chemical elements as well as microbial contaminates.

#### 8.2.7. Environmental remediation: mine waste and AMD

As well as known sites of contained minewater (TID1, MAD1), many rivers in the study area (excluding the Urmiri River and upstream Poopó River) have been found to be significantly contaminated by mine waste (Sections 4 – 7, Table 6; POR3, KER2, AVR1/2/3, BOD1, TOTR1/2, PALR2, PAZR1). There are also a number of sites that are suspect for being affected by mine water migration (TOTP5, TOTV2, KER1, LCR1, and VIP1). As discussed in Section 8.1.4 numerous treatment options are available with advantages and disadvantages, primarily relating to cost, time, effectiveness, sustainability and environmental acceptability. Although treatment of mine affected water is necessary due to the significant environmental legacy of mining in the study area, improved environmental management practice and prevention by "source control" is important for reducing impacts to surface water and groundwater. Long-term environmental remediation though ecologically engineered systems that have advanced over recent years and promise a sustainable means of treatment (e.g. ARUM) and possible recovery of metals (e.g., sulphidogenic bioreactors, section 8.1.4) from mine-affected water, however, desalination may still be required for potable quality. In the study area, and within the context of climate change adaption, a balance needs to be made with respect to supplying potable water to the communities (e.g., by implementing rainwater harvesting and investigating upstream locations and groundwater) over long-term environmental remediation of mine waste and AMD.

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**Appendix A1:** August 2013 **c**hemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| AUGUST 13 – 16th 2013 | | Site code: | | AVR1 | AVR2 | AVR3 | BODI1 | CABT1 | CABTE | CALLP3 | CUCC1 | MAD1 | PALP2 | PALP3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type: | | River | River | River | Channel | Tank | Thermal | Well | Irrigation channel /pool | Mine water | Well | Well |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: | WQR | 8 | 8 | 8 | 8 | 3 | 9 | 4 | 3 channel (pool not sampled) | 10 | 7 | 7 |
| pH | N/A | 6.0 - 8.5 | | 3.2 | 3.4 | 4.3 | 9.3 | 7.7 | 7.0 | 7.7 | 7.1 | 2.7 | 7.2 | 7.8 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | | 2.75 | 3.26 | 2.22 | 3.50 | 0.32 | 16.55 | 0.84 | 0.22 | 10.85 | 2.50 | 3.70 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | | 29.9% | 40.1% | 38.1% | 47.6% | 46.3% | 46.9% | 12.6% | 48.8% | 38.8% | 1.5% | 12.6% |
| Sodium adsorption ratio (SAR)** | N/A | --- | | 0.8 | 0.8 | 0.9 | 0.9 | 1.4 | 58.7 | 3.5 | 0.1 | 9.2 | 6.2 | 8.8 |
| Total dissolved solids (TDS) | N/A | 1000.0 | | 1376.0 | 1628.0 | 1110.0 | 1751.0 | 158.0 | 8271.0 | 419.0 | 111.0 | 5424.0 | 1250.0 | 1847.0 |
| Total alkalinity (mg/L) | N/A | --- | | --- | --- | --- | 22.6 | 75.2 | 350.0 | 132.2 | 48.0 | --- | 111.0 | 265.0 |
| Cl, chloride | | 250.0 | | 152.8 | 231.1 | 126.5 | 289.0 | 40.0 | 5350.5 | 142.8 | 10.4 | 1545.0 | 293.1 | 853.1 |
| F, fluoride | | 0.6 - 1.7 | | 2.26 | 3.67 | 4.17 | 4.56 | 1.51 | 5.05 | 3.62 | 3.30 | 4.48 | 3.13 | 3.52 |
| NO3, nitrate | | 20.0 | | 3.12 | 4.40 | 3.18 | 18.18 | 2.60 | 16.81 | 9.91 | 3.31 | --- | 6.87 | 20.76 |
| SO4, sulphate | | 300.0 | | 1440.0 | 1730.9 | 1131.2 | 1594.3 | 46.6 | 202.3 | 99.4 | 64.6 | 4039.2 | 875.1 | 513.2 |
| Al, aluminium | 0.0312 | 0.2 | | --- | 18.466 | 22.803 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | 86.958 | <0.0312 | <0.0312 |
| As, arsenic | 0.0248 | 0.05 | | <0.0248 | 0.297 | <0.0248 | <0.0248 | 0.028 | <0.0248 | <0.0248 | <0.0248 | 4.010 | 0.121 | 0.057 |
| B, boron | 0.0266 | 1.0 | | 0.42 | 0.42 | 0.48 | 0.37 | 0.42 | 12.82 | 1.21 | 0.28 | 1.98 | 2.51 | 3.31 |
| Ba, barium | 0.0003 | 0.7^ | | --- | --- | --- | --- | 0.020 | --- | 0.059 | 0.020 | --- | --- | --- |
| Ca, calcium | 0.0054 | 200.0 | | 486.5 | 712.3 | 406.5 | 990.1 | 23.1 | 106.6 | 50.4 | 20.2 | 292.3 | 199.6 | 227.9 |
| Cd, cadmium | 0.0011 | 0.005 | | 0.399 | 0.239 | 0.323 | 0.027 | 0.002 | <0.0011 | <0.0011 | <0.0011 | 3.893 | <0.0011 | <0.0011 |
| Co, cobalt | 0.0035 | 0.1 | | 0.118 | 0.061 | 0.100 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | 0.332 | <0.0035 | <0.0035 |
| Cr, chromium | 0.0052 | 0.05 | | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | 0.036 | <0.0052 | <0.0052 |
| Cu, copper | 0.0044 | 0.05 | | 0.525 | 0.592 | 0.490 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | 0.377 | <0.0044 | <0.0044 |
| Fe, iron | 0.0019 | 0.3 | | 1.781 | 48.286 | 0.906 | 0.026 | 0.014 | 0.050 | 0.022 | 0.006 | 2018.659 | 0.009 | 0.015 |
| K, potassium | 0.0298 | N/A | | 9.4 | 13.7 | 9.6 | 14.5 | 2.5 | 227.1 | 24.7 | 1.5 | 43.9 | 36.1 | 47.7 |
| Li, lithium | 0.0029 | 2.5^^ | | 0.33 | 0.19 | 0.37 | 0.14 | 0.01 | 13.54 | 0.29 | <0.029 | 1.91 | 2.08 | 2.02 |
| Mg, magnesium | 0.0010 | 100.0 | | 27.5 | 18.2 | 30.6 | 9.0 | 8.5 | 24.4 | 9.0 | 7.3 | 199.7 | 39.3 | 35.4 |
| Mn, manganese | 0.0004 | 0.50 | | --- | 3.730 | 12.350 | 0.174 | 0.003 | 0.342 | 0.005 | 0.004 | 21.376 | 0.026 | 0.341 |
| Mo, molybdenum | 0.0083 | 0.02^ | | --- | --- | --- | --- | <0.0083 | --- | <0.0083 | <0.0083 | --- | --- | --- |
| Na, sodium | 0.0047 | 200.0 | | 68.8 | 82.0 | 66.5 | 98.5 | 31.5 | 2576.4 | 102.6 | 15.8 | 834.0 | 362.7 | 537.4 |
| Ni, nickel | 0.0074 | 0.05 | | 0.190 | 0.124 | 0.208 | <0.0074 | 0.019 | <0.0074 | <0.0074 | <0.0074 | 0.939 | <0.0074 | <0.0074 |
| Pb, lead | 0.0251 | 0.05 | | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | 0.495 | <0.0251 | <0.0251 |
| Sb, antimony | 0.0192 | 0.01 | | <0.0192 | 0.025 | <0.0192 | <0.0192 | 0.026 | 0.022 | <0.0192 | <0.0192 | <0.0192 | 0.041 | <0.0192 |
| Si, silica | 0.0263 | N/A | | 26.0 | 7.4 | <0.0263 | 0.2 | 7.7 | 29.4 | --- | 7.3 | 22.4 | 12.2 | 9.9 |
| Sn, tin | 0.0353 | 0.025^^^ | | <0.0353 | <0.0353 | <0.0353 | <0.0353 | <0.0353 | <0.0353 | 0.045 | <0.0353 | <0.0353 | 0.058 | <0.0353 |
| Zn, zinc | 0.0026 | 0.2 | | --- | 61.906 | 91.454 | 0.138 | 0.021 | 0.078 | 0.023 | 0.005 | 972.548 | 0.016 | 0.005 |

* Generally, recommended drinking water EC <0.9 dS/m (<600 ppm TDS) and maximum 1.5 dS/m (1000 ppm TDS; recommended by the WHO (2011a) for taste and palatability).
EC >2.5 dS/m is not recommended for consumption and that with >10 dS/m is considered unfit for any consumption (livestock included).

** SAR = [Na meq/l]/({[Ca meq/l]+[Mg meq/l])/2})1/2

^ WHO guideline (2011a).

^^ FAO (1985) recommendation for non-restricted irrigation use.

^^^ UK Environment Agency non-statutory guideline for the protection of aquatic life (surface waters).

**Appendix A1:** August 2013 **c**hemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| **AUGUST 13 - 16th 2013** | | Site code: | PALP4 | PALP5 | PALP7 | PALP8 | PALP9 | PALP10 | PALR2 | PAZP3 | PAZR1 | PAZTE | POR3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type: | Well | Well | Well | Well | Well | Well | River | Well | River | Thermal | River |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: WQR | 7 | 7 | 7 | 7 | 7 | 4 | 8 | 9 | 8 | 9 | 8 |
| pH | N/A | 6.0 - 8.5 | 8.0 | 8.5 | 8.1 | 7.4 | 8.0 | 7.4 | 5.0 | 7.9 | 4.7 | 6.8 | 6.8 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | 2.20 | 4.34 | 3.43 | 4.24 | 2.74 | 0.77 | 2.13 | 15.63 | 2.08 | 9.62 | 9.42 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | 0.0% | 34.3% | 40.1% | 20.2% | 32.9% | 0.0% | 47.5% | 22.9% | 41.1% | 24.5% | 48.6% |
| Sodium adsorption ratio (SAR)** | N/A | --- | 5.9 | 9.8 | 7.1 | 10.4 | 9.1 | 1.2 | 1.7 | 42.5 | 1.2 | 42.5 | 27.7 |
| Total dissolved solids (TDS) | N/A | 1000.0 | 1099.0 | 2172.0 | 1705.0 | 2121.0 | 1371.0 | 386.0 | 1063.0 | 7814.0 | 1042.0 | 4808.0 | 4711.0 |
| Total alkalinity (mg/L) | N/A | --- | 165.4 | 398.2 | 280.0 | 418.6 | 338.2 | 192.2 | --- | 447.6 | --- | 382.8 | 75.7 |
| Cl, chloride | | 250.0 | 284.5 | 979.3 | 763.2 | 1016.6 | 593.5 | 44.2 | 226.4 | 4855.7 | 156.7 | 2890.4 | 2480.2 |
| F, fluoride | | 0.6 - 1.7 | 4.51 | 4.30 | 2.83 | 3.23 | 3.97 | 2.85 | 4.50 | 4.16 | 4.33 | 4.95 | 3.59 |
| NO3, nitrate | | 20.0 | 6.70 | 3.74 | 207.11 | 16.58 | 17.78 | 11.05 | 3.39 | 81.63 | 0.10 | 22.78 | 3.79 |
| SO4, sulphate | | 300.0 | 650.9 | 399.6 | 183.6 | 106.0 | 83.1 | 183.4 | 944.4 | 157.2 | 971.1 | 61.3 | 828.6 |
| Al, aluminium | 0.0312 | 0.2 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | 13.282 | <0.0312 | 18.530 | <0.0312 | <0.0312 |
| As, arsenic | 0.0248 | 0.05 | 0.126 | 0.254 | <0.0248 | 0.027 | <0.0248 | <0.0248 | <0.0248 | 0.076 | <0.0248 | <0.0248 | <0.0248 |
| B, boron | 0.0266 | 1.0 | 2.05 | 3.12 | 2.98 | 4.04 | 3.20 | 0.78 | 0.87 | 15.56 | 0.62 | 8.95 | 5.32 |
| Ba, barium | 0.0003 | 0.7^ | 0.020 | --- | --- | 0.320 | --- | 0.030 | --- | --- | --- | --- | --- |
| Ca, calcium | 0.0054 | 200.0 | 160.8 | 256.7 | 221.6 | 193.2 | 105.8 | 81.1 | 323.4 | 193.0 | 355.3 | 103.0 | 231.5 |
| Cd, cadmium | 0.0011 | 0.005 | <0.0011 | <0.0011 | <0.0011 | 0.001 | <0.0011 | <0.0011 | 0.227 | <0.0011 | 0.268 | <0.0011 | 0.170 |
| Co, cobalt | 0.0035 | 0.1 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | 0.064 | <0.0035 | 0.081 | <0.0035 | 0.015 |
| Cr, chromium | 0.0052 | 0.05 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 |
| Cu, copper | 0.0044 | 0.05 | 0.007 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | 0.315 | <0.0044 | 0.383 | <0.0044 | <0.0044 |
| Fe, iron | 0.0019 | 0.3 | 0.098 | 0.006 | 0.006 | 0.011 | 0.009 | 0.035 | 0.267 | 0.011 | 0.518 | 0.936 | 4.026 |
| K, potassium | 0.0298 | N/A | 29.6 | 49.5 | 59.0 | 64.8 | 50.1 | 10.7 | 14.2 | 290.5 | 11.7 | 155.9 | 109.8 |
| Li, lithium | 0.0029 | 2.5^^ | 1.72 | 2.17 | 3.33 | 4.45 | 2.67 | 0.08 | 0.67 | 19.09 | 0.57 | 10.31 | 4.01 |
| Mg, magnesium | 0.0010 | 100.0 | 25.3 | 32.3 | 41.1 | 49.8 | 26.2 | 16.7 | 29.3 | 30.1 | 30.7 | 12.0 | 29.4 |
| Mn, manganese | 0.0004 | 0.50 | 4.115 | 0.010 | <0.0004 | 0.002 | 0.003 | 0.646 | 9.763 | 0.003 | 11.572 | 0.360 | 2.221 |
| Mo, molybdenum | 0.0083 | 0.02^ | <0.0083 | --- | --- | <0.0083 | --- | <0.0083 | --- | --- | --- | --- | --- |
| Na, sodium | 0.0047 | 200.0 | 305.7 | 626.7 | 439.6 | 627.6 | 402.0 | 43.6 | 117.9 | 2397.4 | 84.4 | 1704.3 | 1675.9 |
| Ni, nickel | 0.0074 | 0.05 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | 0.148 | <0.0074 | 0.169 | <0.0074 | 0.035 |
| Pb, lead | 0.0251 | 0.05 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 |
| Sb, antimony | 0.0192 | 0.01 | <0.0192 | 0.022 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | 0.023 | 0.032 | 0.133 | <0.0192 | <0.0192 |
| Si, silica | 0.0263 | N/A | 18.0 | 14.5 | 15.4 | 15.8 | 16.6 | --- | 23.3 | 15.1 | 23.6 | 33.3 | 8.0 |
| Sn, tin | 0.0353 | 0.025^^^ | 0.040 | <0.0353 | 0.066 | 0.046 | <0.0353 | 0.070 | 0.051 | <0.0353 | 0.059 | <0.0353 | <0.0353 |
| Zn, zinc | 0.0026 | 0.2 | 0.046 | 0.004 | <0.0026 | <0.0026 | 0.024 | 0.015 | 72.877 | 0.006 | 86.825 | 0.011 | 20.244 |

**Appendix A1:** August 2013 **c**hemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| **AUGUST 13 – 16th 2013** | | Site code: | SORR1 | TID1 | TOLAP1 | TOTR1 | TOTR2 | TOTV2 | URC1 | URLT1 | URR1 | URR3 | URV1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type: | River | Mine water | Well | River | River | Spring/ slope | Irrigation channel | Thermal | River | River | Spring/ slope |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: WQR | 10 | 10 | 4 | 8 | 8 | 6 | 7 | 9 | 3 | 5 | 5 |
| pH | N/A | 6.0 - 8.5 | 3.6 | 7.1 | 8.2 | 4.5 | 4.5 | 8.2 | 8.0 | 6.8 | 8.2 | 9.0 | 7.7 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | 1.92 | 9.95 | 0.33 | 3.00 | 2.94 | 0.42 | 2.60 | 5.93 | 0.30 | 1.40 | 1.31 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | 56.2% | 46.2% | 22.4% | 33.0% | 42.1% | 29.1% | 53.8% | 25.1% | 50.9% | 54.3% | 15.6% |
| Sodium adsorption ratio (SAR)** | N/A | --- | 0.6 | 25.0 | 0.8 | 0.9 | 0.9 | 1.2 | 15.4 | 30.1 | 0.8 | 7.6 | 7.9 |
| Total dissolved solids (TDS) | N/A | 1000.0 | 957.0 | 4978.0 | 166.0 | 1499.0 | 1472.0 | 210.0 | 1301.0 | 2962.0 | 150.0 | 700.0 | 653.0 |
| Total alkalinity (mg/L) | N/A | --- | --- | 76.6 | 104.0 | --- | --- | 51.6 | 232.8 | 442.0 | 107.0 | 151.6 | 336.6 |
| Cl, chloride | | 250.0 | 37.5 | 2869.3 | 16.1 | 211.0 | 217.0 | 16.6 | 605.3 | 1612.5 | 11.5 | 336.6 | 228.5 |
| F, fluoride | | 0.6 - 1.7 | 7.47 | 5.15 | 0.72 | 3.45 | 3.95 | 3.06 | 4.03 | 5.89 | 1.15 | 4.41 | 3.97 |
| NO3, nitrate | | 20.0 | 2.73 | 2.74 | 8.39 | 6.27 | 7.29 | 3.42 | 17.03 | 24.48 | 6.20 | 22.52 | 12.34 |
| SO4, sulphate | | 300.0 | 1212.7 | 934.3 | 61.1 | 1578.9 | 1678.3 | 148.1 | 44.8 | 30.0 | 54.2 | 40.6 | 73.6 |
| Al, aluminium | 0.0312 | 0.2 | 67.206 | <0.0312 | <0.0312 | 18.141 | 16.072 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 |
| As, arsenic | 0.0248 | 0.05 | 0.253 | <0.0248 | <0.0248 | <0.0248 | 0.048 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | 0.027 |
| B, boron | 0.0266 | 1.0 | 0.38 | 6.29 | 0.37 | 0.39 | 0.37 | 0.75 | 3.15 | 6.61 | 0.36 | 1.51 | 3.04 |
| Ba, barium | 0.0003 | 0.7^ | --- | --- | 0.030 | --- | --- | --- | 0.270 | --- | 0.020 | --- | 0.040 |
| Ca, calcium | 0.0054 | 200.0 | 112.1 | 301.7 | 28.1 | 686.2 | 672.7 | 35.5 | 46.0 | 78.9 | 25.2 | 39.5 | 30.2 |
| Cd, cadmium | 0.0011 | 0.005 | 1.071 | 0.126 | <0.0011 | 0.496 | 0.426 | 0.002 | <0.0011 | <0.0011 | <0.0011 | <0.0011 | <0.0011 |
| Co, cobalt | 0.0035 | 0.1 | 0.423 | 0.013 | <0.0035 | 0.054 | 0.054 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 |
| Cr, chromium | 0.0052 | 0.05 | 0.013 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 |
| Cu, copper | 0.0044 | 0.05 | 2.375 | <0.0044 | 0.006 | 0.131 | 0.115 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 |
| Fe, iron | 0.0019 | 0.3 | 312.742 | 0.114 | 0.004 | 0.477 | 0.756 | 0.003 | 0.032 | 0.575 | 0.035 | 0.012 | 0.003 |
| K, potassium | 0.0298 | N/A | 13.1 | 120.5 | 2.9 | 12.9 | 12.9 | 2.9 | 47.3 | 114.4 | 2.4 | 21.5 | 10.7 |
| Li, lithium | 0.0029 | 2.5^^ | 0.31 | 4.09 | <0.029 | 0.18 | 0.16 | <0.029 | 3.28 | 9.80 | <0.029 | 1.46 | 1.58 |
| Mg, magnesium | 0.0010 | 100.0 | 59.6 | 26.8 | 9.2 | 21.7 | 20.5 | 11.2 | 10.1 | 11.0 | 10.3 | 9.7 | 16.8 |
| Mn, manganese | 0.0004 | 0.50 | 24.169 | 1.742 | 0.001 | 4.755 | 4.403 | 0.002 | 0.070 | 0.169 | 0.030 | 0.003 | 0.022 |
| Mo, molybdenum | 0.0083 | 0.02^ | --- | --- | <0.0083 | --- | --- | --- | <0.0083 | --- | <0.0083 | --- | <0.0083 |
| Na, sodium | 0.0047 | 200.0 | 33.1 | 1680.4 | 19.3 | 84.4 | 83.5 | 31.7 | 441.6 | 1074.8 | 18.4 | 205.1 | 217.4 |
| Ni, nickel | 0.0074 | 0.05 | 0.631 | 0.029 | <0.0074 | 0.099 | 0.085 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 |
| Pb, lead | 0.0251 | 0.05 | 0.036 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 |
| Sb, antimony | 0.0192 | 0.01 | 0.030 | 0.031 | 0.049 | 0.053 | 0.034 | <0.0192 | 0.040 | <0.0192 | <0.0192 | <0.0192 | 0.039 |
| Si, silica | 0.0263 | N/A | <0.0263 | 15.6 | 15.1 | 13.9 | 11.9 | 23.6 | 13.2 | 13.3 | 15.7 | 10.0 | 8.9 |
| Sn, tin | 0.0353 | 0.025^^^ | <0.0353 | 0.080 | 0.050 | 0.051 | <0.0353 | 0.082 | <0.0353 | 0.038 | <0.0353 | <0.0353 | <0.0353 |
| Zn, zinc | 0.0026 | 0.2 | 56.910 | 13.671 | 0.006 | 100.413 | 95.291 | 0.364 | 0.003 | 0.006 | <0.0026 | <0.0026 | 0.030 |

**Appendix A2:** December 2013 **c**hemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| **DECEMBER 16 - 20th 2013** | | Site code: | AVR1 | AVR2 | AVR3 | BODI1 | CABT1 | CUCC1 | KER1 | MAD1 | PALP2 | PALP3 | PALP4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type: | River | River | River | Channel | Tank | Irrigation channel/ pool | River | Mine water | Well | Well | Well |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: / WQR | 8 | 8 | 8 | 8 | 3 | 3 (channel), pool not sampled | 6 | 10 | 7 | 7 | 7 |
| pH | N/A | 6.0 - 8.5 | 3.2 | 3.0 | 3.3 | 6.3 | 7.0 | 7.7 | 7.4 | 2.9 | 7.1 | 7.2 | 7.5 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | 3.27 | 3.11 | 2.80 | 3.91 | 0.26 | 0.15 | 1.69 | 13.03 | 3.19 | 5.60 | 2.52 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | 12.1% | 57.1% | 30.5% | 44.1% | 33.0% | 12.8% | 28.6% | 0.0% | 39.5% | 0.9% | 10.6% |
| Sodium adsorption ratio (SAR)** | N/A | | 1.5 | 1.1 | 1.5 | 1.4 | 2.2 | 1.6 | 8.7 | 20.7 | 4.9 | 25.2 | 5.2 |
| Total dissolved solids (TDS) | N/A | 1000.0 | 1634.0 | 1556.0 | 1398.0 | 1954.0 | 127.0 | 74.0 | 843.0 | 6532.0 | 1586.0 | 2795.0 | 1258.0 |
| Total alkalinity (mg/L) | N/A | | --- | --- | --- | 15.0 | 87.8 | 53.2 | 52.1 | --- | 89.0 | 206.0 | 103.0 |
| Cl, chloride | | 250.0 | 130.3 | 71.1 | 110.0 | 221.4 | 12.4 | 8.2 | 331.5 | 1461.0 | 238.0 | 906.5 | 238.3 |
| F, fluoride | | 0.6 - 1.7 | 3.53 | 3.35 | 3.55 | 3.14 | 3.08 | 1.94 | 3.26 | 4.05 | 3.60 | 3.79 | 3.16 |
| NO3, nitrate | | 20.0 | 4.19 | 3.35 | 4.72 | 8.46 | 3.31 | 2.85 | 4.39 | --- | 6.03 | 10.35 | 6.23 |
| SO4, sulphate | | 300.0 | 1363.4 | 1178.90 | 1129.7 | 1528.3 | 31.2 | 17.4 | 96.0 | 5652.3 | 797.4 | 465.0 | 479.5 |
| Al, aluminium | 0.0312 | 0.2 | 33.728 | 34.785 | 25.532 | 0.052 | 0.083 | 0.077 | <0.0312 | 85.120 | <0.0312 | <0.0312 | <0.0312 |
| As, arsenic | 0.0248 | 0.05 | 0.030 | 1.020 | <0.0248 | <0.0248 | <0.0248 | 0.029 | 0.033 | 1.580 | 0.078 | 0.067 | 0.105 |
| B, boron | 0.0266 | 1.0 | 0.39 | 0.460 | 0.36 | 0.43 | 0.32 | 0.39 | 1.11 | 2.10 | 2.22 | 3.40 | 1.73 |
| Ba, barium | 0.0003 | 0.7^ | --- | --- | --- | --- | 0.020 | 0.010 | --- | --- | --- | --- | 0.029 |
| Ca, calcium | 0.0054 | 200.0 | 425.9 | 347.3 | 359.6 | 749.4 | 16.0 | 10.0 | 30.5 | 246.0 | 183.4 | 238.2 | 118.5 |
| Cd, cadmium | 0.0011 | 0.005 | 0.321 | 0.359 | 0.276 | 0.103 | 0.002 | <0.0011 | 0.005 | 1.965 | <0.0011 | 0.002 | <0.0011 |
| Co, cobalt | 0.0035 | 0.1 | 0.138 | 0.086 | 0.108 | 0.005 | <0.0035 | <0.0035 | <0.0035 | 0.349 | <0.0035 | <0.0035 | <0.0035 |
| Cr, chromium | 0.0052 | 0.05 | <0.0052 | 0.014 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | 0.020 | <0.0052 | <0.0052 | <0.0052 |
| Cu, copper | 0.0044 | 0.05 | 0.622 | 1.515 | 0.522 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | 0.033 | <0.0044 | <0.0044 | <0.0044 |
| Fe, iron | 0.0019 | 0.3 | 2.685 | 95.879 | 1.872 | 0.144 | 0.069 | 0.059 | 0.015 | 1201.154 | 0.008 | 0.005 | 0.033 |
| K, potassium | 0.0298 | N/A | 9.4 | 5.8 | 8.3 | 14.6 | 1.8 | 1.2 | 15.3 | 42.2 | 36.7 | 53.2 | 30.2 |
| Li, lithium | 0.0029 | 2.5^^ | 0.37 | 0.11 | 0.33 | 0.20 | 0.01 | <0.029 | 0.72 | 2.16 | 2.09 | 2.44 | 1.63 |
| Mg, magnesium | 0.0010 | 100.0 | 28.3 | 19.2 | 26.4 | 12.3 | 5.8 | 3.9 | 8.4 | 221.9 | 40.1 | 41.4 | 23.4 |
| Mn, manganese | 0.0004 | 0.50 | 17.248 | 3.402 | 13.264 | 0.984 | 0.003 | 0.004 | 0.253 | 30.909 | 0.024 | 1.648 | 1.035 |
| Mo, molybdenum | 0.0083 | 0.02^ | --- | --- | --- | --- | <0.0083 | <0.0083 | --- | --- | --- | --- | <0.0083 |
| Na, sodium | 0.0047 | 200.0 | 114.7 | 80.2 | 105.6 | 136.1 | 40.3 | 22.9 | 209.3 | 1854.6 | 280.8 | 1597.9 | 236.5 |
| Ni, nickel | 0.0074 | 0.05 | 0.160 | 0.132 | 0.150 | 0.008 | <0.0074 | <0.0074 | <0.0074 | 0.779 | <0.0074 | <0.0074 | <0.0074 |
| Pb, lead | 0.0251 | 0.05 | <0.0251 | 0.065 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | 0.427 | <0.0251 | <0.0251 | <0.0251 |
| Sb, antimony | 0.0192 | 0.01 | <0.0192 | 0.056 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | 0.025 | 0.186 | <0.0192 | <0.0192 | <0.0192 |
| Si, silica | 0.0263 | N/A | 23.8 | 11.0 | 22.5 | 0.5 | 7.6 | 7.4 | 7.5 | 21.3 | 14.1 | 9.8 | 14.0 |
| Sn, tin | 0.0353 | 0.025^^^ | 0.036 | <0.0353 | <0.0353 | 0.095 | 0.037 | <0.0353 | 0.053 | 0.065 | 0.079 | 0.057 | 0.062 |
| Zn, zinc | 0.0026 | 0.2 | 384.088 | 390.348 | 92.983 | 13.861 | 0.010 | <0.0026 | 0.967 | 3692.586 | 0.023 | 0.009 | 0.033 |

* Generally, recommended drinking water EC <0.9 dS/m (<600 ppm TDS) and maximum 1.5 dS/m (1000 ppm TDS; recommended by the WHO (2011a) for taste and palatability).

EC >2.5 dS/m is not recommended for consumption and that with >10 dS/m is considered unfit for any consumption (livestock included).

** SAR = [Na meq/l]/({[Ca meq/l]+[Mg meq/l]})/2})1/2

^ WHO guideline (2011a).

^^ FAO (1985) recommendation for non-restricted irrigation use.

^^^ UK Environment Agency non-statutory guideline for the protection of aquatic life (surface waters).

**Appendix A2:** December 2013 **c**hemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| DECEMBER 16 - 20th 2013 | | Site code: | PALP5 | PALP7 | PALP8 | PALP9 | PALP10 | PALR2 | PAZP3 | PAZR1 | PAZTE | POR3 | SORR1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type: | Well | Well | Well | Well | Well | River | Well | River | Thermal | River | River |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: WQR | 7 | 7 | 7 | 7 | 4 | 8 | 9 | 8 | 9 | 8 | 10 |
| pH | N/A | 6.0 - 8.5 | 8.4 | 7.4 | 7.1 | 7.2 | 6.8 | 3.6 | 8.2 | 3.4 | 6.7 | 7.1 | 3.3 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | 6.56 | 3.74 | 4.94 | 3.61 | 0.97 | 2.99 | 18.35 | 3.08 | 12.64 | 0.82 | 1.24 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | 17.7% | 12.5% | 11.5% | 28.4% | 0.0% | 38.4% | 7.5% | 31.8% | 20.6% | 4.5% | 6.2% |
| Sodium adsorption ratio (SAR)** | N/A | | 26.1 | 18.6 | 27.4 | 21.2 | 2.3 | 1.7 | 13.6 | 1.6 | 64.0 | 9.6 | 1.0 |
| Total dissolved solids (TDS) | N/A | 1000.0 | 3281.0 | 1866.0 | 2471.0 | 1802.0 | 483.0 | 1497.0 | 9169.0 | 1543.0 | 6304.0 | 402.0 | 620.0 |
| Total alkalinity (mg/L) | N/A | | 337.0 | 387.2 | 366.0 | 283.0 | 173.6 | --- | 536.0 | --- | 364.0 | 39.0 | --- |
| Cl, chloride | | 250.0 | 1092.1 | 591.7 | 962.3 | 656.3 | 38.2 | 127.3 | 3912.2 | 126.2 | 2665.9 | 128.8 | 11.9 |
| F, fluoride | | 0.6 - 1.7 | 2.62 | 3.26 | 3.03 | 3.03 | 3.22 | 3.45 | 3.37 | 3.58 | 3.89 | 6.51 | 4.93 |
| NO3, nitrate | | 20.0 | 11.30 | 108.81 | 28.92 | 13.15 | 8.13 | 3.65 | 0.19 | 4.44 | 16.36 | 4.11 | 4.08 |
| SO4, sulphate | | 300.0 | 481.4 | 102.3 | 99.2 | 71.3 | 172.2 | 1079.9 | 59.0 | 1149.8 | 54.2 | 64.4 | 446.3 |
| Al, aluminium | 0.0312 | 0.2 | <0.0312 | 0.045 | 0.005 | <0.0312 | <0.0312 | 16.935 | 0.032 | 24.883 | 0.054 | 0.149 | 26.251 |
| As, arsenic | 0.0248 | 0.05 | 0.257 | <0.0248 | 0.045 | <0.0248 | 0.800 | <0.0248 | 0.166 | <0.0248 | <0.0248 | <0.0248 | 0.170 |
| B, boron | 0.0266 | 1.0 | 3.57 | 3.07 | 4.09 | 3.33 | 0.80 | 0.50 | 14.70 | 0.45 | 8.27 | 0.47 | 0.14 |
| Ba, barium | 0.0003 | 0.7^ | --- | --- | 0.274 | --- | 0.039 | --- | --- | --- | --- | --- | --- |
| Ca, calcium | 0.0054 | 200.0 | 283.2 | 162.3 | 160.4 | 120.7 | 88.2 | 372.6 | 145.3 | 396.9 | 105.8 | 16.7 | 45.0 |
| Cd, cadmium | 0.0011 | 0.005 | <0.0011 | 0.001 | <0.0011 | <0.0011 | <0.0011 | 0.279 | <0.0011 | 0.299 | <0.0011 | <0.0011 | 0.429 |
| Co, cobalt | 0.0035 | 0.1 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | 0.107 | <0.0035 | 0.111 | <0.0035 | <0.0035 | 0.165 |
| Cr, chromium | 0.0052 | 0.05 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | 0.006 |
| Cu, copper | 0.0044 | 0.05 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | 0.523 | <0.0044 | 0.542 | 0.019 | 0.009 | 1.642 |
| Fe, iron | 0.0019 | 0.3 | 0.008 | 0.005 | 0.009 | 0.007 | 0.035 | 1.797 | 0.102 | 1.904 | 0.376 | 0.202 | 85.083 |
| K, potassium | 0.0298 | N/A | 56.0 | 54.2 | 62.0 | 54.3 | 11.7 | 10.9 | 227.4 | 11.0 | 150.3 | 13.9 | 3.7 |
| Li, lithium | 0.0029 | 2.5^^ | 2.81 | 3.43 | 4.24 | 3.20 | 0.10 | 0.43 | 13.16 | 0.43 | 8.92 | 0.21 | 0.08 |
| Mg, magnesium | 0.0010 | 100.0 | 44.3 | 35.2 | 39.6 | 33.5 | 19.9 | 28.7 | 25.4 | 30.5 | 13.6 | 4.6 | 23.1 |
| Mn, manganese | 0.0004 | 0.50 | 0.035 | 0.002 | 0.043 | 0.002 | 0.506 | 9.054 | 0.775 | 14.262 | 0.386 | 0.044 | 8.628 |
| Mo, molybdenum | 0.0083 | 0.02^ | --- | --- | <0.0083 | --- | <0.0083 | --- | --- | --- | --- | --- | --- |
| Na, sodium | 0.0047 | 200.0 | 1785.6 | 999.7 | 1489.9 | 1018.5 | 92.1 | 125.3 | 674.4 | 121.1 | 2623.2 | 170.7 | 33.7 |
| Ni, nickel | 0.0074 | 0.05 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | 0.153 | <0.0074 | 0.160 | <0.0074 | 0.017 | 0.189 |
| Pb, lead | 0.0251 | 0.05 | <0.0251 | 0.031 | <0.0251 | 0.027 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 |
| Sb, antimony | 0.0192 | 0.01 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | 0.032 | <0.0192 | <0.0192 |
| Si, silica | 0.0263 | N/A | 14.6 | 16.9 | 16.5 | 14.7 | 16.5 | 23.1 | 17.5 | 24.5 | 33.8 | 6.0 | 11.6 |
| Sn, tin | 0.0353 | 0.025^^^ | 0.068 | 0.056 | 0.053 | 0.118 | 0.041 | 0.095 | 0.083 | <0.0353 | 0.043 | <0.0353 | <0.0353 |
| Zn, zinc | 0.0026 | 0.2 | 0.005 | <0.0026 | <0.0026 | 0.003 | 0.063 | 62.857 | 0.047 | 101.259 | 0.010 | 0.071 | 17.992 |

**Appendix A2:** December 2013 **c**hemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| **DECEMBER 16 - 20th 2013** | | Site code: | | TID1 | TOLAP1 | TOTP5 | TOTR1 | TOTR2 | TOTV2 | URC1 | URLT1 | URR1 | URR2 | URR3 | URV1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type: | | Mine water | Well | Well | River | River | Spring/ slope | Irrigation canal | Thermal | River | River | River | Spring/ slope |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: | WQR | 10 | 4 | 8 | 8 | 8 | 6 | 7 | 9 | 3 | 3 | 5 | 5 |
| pH | N/A | 6.0 - 8.5 | | 6.1 | 7.6 | 4.1 | 2.9 | 2.9 | 6.3 | 8.3 | 6.6 | 8.2 | 7.6 | 8.3 | 7.5 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | | 7.77 | 0.42 | 0.52 | 2.28 | 2.67 | 0.35 | 2.93 | 7.79 | 0.39 | 0.33 | 2.84 | 1.71 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | | 0.0% | 12.0% | 20.1% | 41.8% | 45.3% | 40.1% | 70.2% | 0.0% | 45.5% | 34.3% | 72.0% | 16.3% |
| Sodium adsorption ratio (SAR)** | N/A | | | 42.5 | 1.9 | 2.4 | 1.1 | 1.2 | 2.1 | 28.8 | 60.4 | 1.9 | 1.7 | 6.5 | 7.4 |
| Total dissolved solids (TDS) | N/A | 1000.0 | | 3888.0 | 210.0 | 259.0 | 1138.0 | 1333.0 | 177.0 | 1465.0 | 3920.0 | 192.0 | 167.0 | 1421.0 | 850.0 |
| Total alkalinity (mg/L) | N/A | | | 58.8 | 83.0 | --- | --- | --- | 34.3 | 190.0 | 391.0 | 78.8 | 76.1 | 131.2 | 292.0 |
| Cl, chloride | | 250.0 | | 1307.1 | 17.8 | 22.8 | 39.7 | 62.3 | 12.3 | 550.8 | 1633.9 | 12.2 | 12.2 | 605.9 | 211.6 |
| F, fluoride | | 0.6 - 1.7 | | 3.13 | 2.45 | 3.54 | 3.29 | 2.94 | 3.05 | 3.46 | 3.90 | 3.16 | 3.15 | 3.58 | 4.14 |
| NO3, nitrate | | 20.0 | | 3.57 | 5.64 | 3.87 | 5.74 | 4.76 | 4.16 | 21.57 | 18.06 | 5.99 | 5.01 | 7.80 | 13.16 |
| SO4, sulphate | | 300.0 | | 773.4 | 39.2 | 134.5 | 811.3 | 1047.8 | 73.3 | 45.6 | 29.7 | 46.5 | 42.8 | 40.6 | 73.8 |
| Al, aluminium | 0.0312 | 0.2 | | 0.114 | <0.0312 | 3.608 | 23.958 | 29.661 | 0.202 | <0.0312 | 0.033 | <0.0312 | <0.0312 | <0.0312 | <0.0312 |
| As, arsenic | 0.0248 | 0.05 | | 0.062 | <0.0248 | 0.046 | 0.068 | 0.120 | 0.050 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | 0.035 | <0.0248 |
| B, boron | 0.0266 | 1.0 | | 3.38 | 0.42 | 0.49 | 0.26 | 0.42 | 0.50 | 2.79 | 6.98 | 0.36 | 0.36 | 1.84 | 2.97 |
| Ba, barium | 0.0003 | 0.7^ | | --- | 0.030 | --- | --- | --- | --- | 0.233 | --- | 0.020 | --- | --- | 0.049 |
| Ca, calcium | 0.0054 | 200.0 | | 186.7 | 31.9 | 20.6 | 171.3 | 261.8 | 24.5 | 47.9 | 82.6 | 28.5 | 25.3 | 72.2 | 32.9 |
| Cd, cadmium | 0.0011 | 0.005 | | 1.548 | <0.0011 | 0.028 | 0.389 | 0.361 | 0.003 | <0.0011 | <0.0011 | 0.002 | <0.0011 | 0.002 | <0.0011 |
| Co, cobalt | 0.0035 | 0.1 | | 0.074 | <0.0035 | 0.084 | 0.054 | 0.065 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | 0.004 | <0.0035 |
| Cr, chromium | 0.0052 | 0.05 | | <0.0052 | <0.0052 | <0.0052 | 0.013 | 0.013 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 |
| Cu, copper | 0.0044 | 0.05 | | 0.313 | <0.0044 | 0.287 | 0.279 | 0.315 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 |
| Fe, iron | 0.0019 | 0.3 | | 8.372 | 0.003 | 5.709 | 85.843 | 91.530 | 0.130 | 0.026 | 0.396 | 0.049 | 0.008 | 0.011 | 0.216 |
| K, potassium | 0.0298 | N/A | | 65.4 | 3.2 | 17.4 | 4.8 | 6.3 | 2.6 | 44.1 | 115.0 | 2.7 | 2.1 | 35.7 | 12.3 |
| Li, lithium | 0.0029 | 2.5^^ | | 3.09 | 0.01 | 0.40 | 0.06 | 0.09 | <0.029 | 3.30 | 9.02 | <0.029 | <0.029 | 2.38 | 1.81 |
| Mg, magnesium | 0.0010 | 100.0 | | 10.8 | 10.8 | 5.4 | 16.7 | 19.5 | 8.0 | 11.6 | 12.5 | 12.3 | 11.6 | 20.7 | 19.4 |
| Mn, manganese | 0.0004 | 0.50 | | 1.433 | 0.007 | 0.622 | 2.288 | 2.384 | 0.009 | 0.033 | 0.180 | 0.072 | 0.001 | 0.012 | 0.035 |
| Mo, molybdenum | 0.0083 | 0.02^ | | --- | 0.010 | --- | --- | --- | --- | <0.0083 | --- | <0.0083 | --- | --- | <0.0083 |
| Na, sodium | 0.0047 | 200.0 | | 2198.9 | 48.6 | 47.8 | 55.9 | 74.0 | 47.5 | 853.3 | 2220.0 | 47.6 | 42.0 | 242.6 | 216.9 |
| Ni, nickel | 0.0074 | 0.05 | | 0.089 | <0.0074 | 0.079 | 0.110 | 0.112 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 |
| Pb, lead | 0.0251 | 0.05 | | <0.0251 | <0.0251 | <0.0251 | 0.095 | 0.083 | <0.0251 | <0.0251 | 0.036 | <0.0251 | <0.0251 | <0.0251 | <0.0251 |
| Sb, antimony | 0.0192 | 0.01 | | 0.027 | <0.0192 | 0.038 | <0.0192 | <0.0192 | 0.031 | 0.020 | 0.042 | <0.0192 | <0.0192 | <0.0192 | <0.0192 |
| Si, silica | 0.0263 | N/A | | 3.6 | 11.6 | 5.6 | 8.7 | 9.6 | 9.7 | 12.0 | 24.2 | 2.6 | 8.7 | 7.8 | 8.2 |
| Sn, tin | 0.0353 | 0.025^^^ | | <0.0353 | 0.041 | <0.0353 | <0.0353 | 0.046 | <0.0353 | 0.093 | <0.0353 | 0.043 | 0.043 | <0.0353 | 0.060 |
| Zn, zinc | 0.0026 | 0.2 | | 1283.080 | 0.014 | 1.524 | 83.222 | 84.718 | 0.281 | <0.0026 | 0.014 | <0.0026 | <0.0026 | <0.0026 | <0.0026 |

**Appendix A3:** April 2014 **c**hemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| **APRIL 7 - 12th 2014** | | Site code: | AVR1 | AVR2 | AVR3 | BODI1 | CABTE | CALLP3 | CUCC1 | KER2 | MAD1 | PALP3 | PALP4 | PALP7 | PALP8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type: | River | River | River | Channel | Thermal | Well | Irrigation channel/ pool | River | Mine water | Well | Well | Well | Well |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: WQR | 8 | 8 | 8 | 8 | 9 | 4 | 3 (channel), pool not sampled | 8 | 10 | 7 | 7 | 7 | 7 |
| pH | N/A | 6.0 - 8.5 | 3.5 | 3.3 | 3.6 | 7.7 | 6.8 | 7.5 | 7.1 | 6.5 | 2.2 | 7.0 | 7.8 | 8.2 | 7.0 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | 2.21 | 3.13 | 1.79 | 4.26 | 17.10 | 0.69 | 0.22 | 6.45 | 15.71 | 5.62 | 2.28 | 2.89 | 3.93 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sodium adsorption ratio (SAR)** | N/A | | 0.8 | 0.8 | 0.8 | 0.8 | --- | 3.3 | 0.6 | 30.8 | 6.8 | 13.0 | 7.3 | 7.2 | 8.5 |
| Total dissolved solids (TDS) | N/A | 1000.0 | 1104.0 | 1564.0 | 896.0 | 2130.0 | 8555.0 | 329.0 | 112.0 | 3224.0 | 7855.0 | 2806.0 | 1138.0 | 1444.0 | 1985.0 |
| Total alkalinity (mg/L) | N/A | | --- | --- | --- | 25.0 | 316.0 | 106.8 | 60.8 | 12.0 | --- | 294.0 | 151.0 | 314.0 | 420.4 |
| Cl, chloride | | 250.0 | 91.1 | 140.2 | 83.0 | 252.8 | 3814.7 | 95.6 | 11.2 | 903.4 | 1024.3 | 1181.9 | 278.3 | 758.4 | 1124.6 |
| F, fluoride | | 0.6 - 1.7 | 1.65 | 1.69 | 1.84 | 2.52 | 5.33 | 1.52 | 1.11 | 1.58 | 6.05 | 1.70 | 1.82 | 1.55 | 1.38 |
| NO3, nitrate | | 20.0 | --- | 7.50 | --- | 15.10 | 40.00 | 7.20 | 4.40 | 6.30 | --- | 21.30 | 14.50 | 82.60 | 25.70 |
| SO4, sulphate | | 300.0 | 428.3 | 905.7 | 748.3 | 1158.1 | 187.2 | 67.1 | 41.5 | 533.4 | 10675.6 | 646.0 | 604.9 | 93.4 | 80.4 |
| Al, aluminium | 0.0312 | 0.2 | 23.190 | 15.136 | 11.913 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | 281.536 | 0.041 | <0.0312 | <0.0312 | <0.0312 |
| As, arsenic | 0.0248 | 0.05 | <0.0248 | 0.199 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | 8.999 | 0.055 | 0.123 | <0.0248 | <0.0248 |
| B, boron | 0.0266 | 1.0 | 0.47 | 0.36 | 0.42 | 0.32 | 13.19 | 0.91 | 0.34 | 4.09 | 1.48 | 5.30 | 2.17 | 2.73 | 5.78 |
| Ba, barium | 0.0003 | 0.7^ | --- | --- | --- | --- | --- | 0.059 | 0.019 | --- | --- | --- | 0.048 | --- | 0.262 |
| Ca, calcium | 0.0054 | 200.0 | 310.6 | 557.8 | 260.3 | 1306.2 | 112.6 | 37.2 | 21.0 | 111.6 | 216.5 | 272.4 | 137.4 | 144.6 | 207.3 |
| Cd, cadmium | 0.0011 | 0.005 | 342.000 | 0.455 | 0.255 | 0.188 | 0.003 | 0.003 | 0.002 | 0.269 | 14.007 | <0.0011 | 0.002 | <0.0011 | <0.0011 |
| Co, cobalt | 0.0035 | 0.1 | 0.101 | 0.051 | 0.054 | 0.007 | <0.0035 | <0.0035 | 0.004 | 0.005 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 |
| Cr, chromium | 0.0052 | 0.05 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | 0.111 | <0.0052 | <0.0052 | <0.0052 | <0.0052 |
| Cu, copper | 0.0044 | 0.05 | 0.617 | 1.411 | 0.478 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | 4.586 | <0.0044 | <0.0044 | <0.0044 | <0.0044 |
| Fe, iron | 0.0019 | 0.3 | 1.638 | 53.719 | 5.031 | <0.0019 | 0.219 | <0.019 | 0.009 | 12.134 | 3888.354 | 0.009 | 0.012 | 0.006 | 0.018 |
| K, potassium | 0.0298 | N/A | 7.5 | 11.9 | 6.9 | 36.0 | 243.4 | 8.8 | 1.7 | 76.8 | 32.4 | 84.3 | 31.9 | 48.2 | 76.6 |
| Li, lithium | 0.0029 | 2.5^^ | 0.39 | 0.28 | 0.27 | 0.41 | 14.04 | 0.36 | <0.029 | 3.88 | 1.59 | 3.85 | 1.93 | 3.28 | 5.41 |
| Mg, magnesium | 0.0010 | 100.0 | 28.2 | 23.4 | 21.4 | 155.0 | 28.2 | 8.1 | 8.1 | 24.8 | 209.3 | 59.1 | 26.2 | 31.9 | 53.6 |
| Mn, manganese | 0.0004 | 0.50 | 13.332 | 4.939 | 6.338 | 1.258 | 0.451 | 0.001 | 0.001 | 1.566 | 33.679 | 1.632 | 5.270 | 0.001 | 0.159 |
| Mo, molybdenum | 0.0083 | 0.02^ | --- | --- | --- | --- | --- | <0.0083 | <0.0083 | --- | --- | --- | 0.010 | --- | <0.0083 |
| Na, sodium | 0.0047 | 200.0 | 53.2 | 71.8 | 46.4 | 100.0 | --- | 84.6 | 13.0 | 1374.2 | 586.3 | 905.6 | 353.0 | 366.6 | 527.8 |
| Ni, nickel | 0.0074 | 0.05 | 0.171 | 0.128 | 0.109 | 0.008 | <0.0074 | <0.0074 | <0.0074 | 0.041 | 2.340 | <0.0074 | <0.0074 | <0.0074 | <0.0074 |
| Pb, lead | 0.0251 | 0.05 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | 0.665 | <0.0251 | <0.0251 | <0.0251 | <0.0251 |
| Sb, antimony | 0.0192 | 0.01 | <0.0192 | <0.0192 | <0.0192 | 0.021 | 0.027 | <0.0192 | <0.0192 | <0.0192 | --- | 0.182 | 0.162 | <0.0192 | <0.0192 |
| Si, silica | 0.0263 | N/A | 28.9 | 16.0 | 15.8 | 0.2 | 30.5 | 17.9 | 9.3 | 8.4 | 24.1 | 13.4 | 18.1 | 13.6 | 17.2 |
| Sn, tin | 0.0353 | 0.025^^^ | <0.0353 | <0.0353 | 0.058 | 0.046 | 0.068 | <0.0353 | <0.0353 | <0.0353 | 0.039 | 0.095 | 0.053 | 0.036 | 0.066 |
| Zn, zinc | 0.0026 | 0.2 | 84.131 | 77.978 | 60.730 | 8.783 | 0.205 | 0.015 | <0.0026 | 45.329 | 2570.371 | 0.005 | 0.018 | <0.0026 | <0.0026 |

* Generally, recommended drinking water EC <0.9 dS/m (<600 ppm TDS) and maximum 1.5 dS/m (1000 ppm TDS; recommended by the WHO (2011a) for taste and palatability).
EC >2.5 dS/m is not recommended for consumption and that with >10 dS/m is considered unfit for any consumption (livestock included).

** SAR = [Na meq/l]/({[Ca meq/l]+[Mg meq/l]}/2})1/2

^ WHO guideline (2011a).

^^ FAO (1985) recommendation for non-restricted irrigation use.

^^^ UK Environment Agency non-statutory guideline for the protection of aquatic life (surface waters).

**Appendix A3:** April 2014 chemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| **APRIL 7 - 12th 2014** | | Site code: | PALP10 | PALR2 | PAZP3 | PAZR1 | PAZTE | PMO1 | POR3 | POR4 | PQUE1 | PUNP1 | PUNP2 | RYU1 | SORR1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type: | Well | River | Well | River | Thermal | Well | River | River | Well | Tap | Well | River/ Lake | River |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: WQR | 4 | 8 | 9 | 8 | 9 | 4 | 8 | 3 | 7 | 2 | 5 | 7 | 10 |
| pH | N/A | 6.0 - 8.5 | 6.8 | 4.7 | 8.3 | 4.6 | 6.5 | 7.6 | 6.6 | 7.5 | 7.8 | 7.9 | 8.3 | 7.6 | 3.1 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | 0.71 | 1.65 | 15.62 | 1.61 | 9.49 | 0.43 | 5.51 | 0.35 | 2.34 | 0.27 | 0.99 | 3.20 | 1.79 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sodium adsorption ratio (SAR)** | N/A | | 1.2 | 1.7 | 71.1 | 1.4 | 47.8 | 1.0 | 27.8 | 0.9 | 21.5 | 0.8 | 2.4 | 10.8 | 0.6 |
| Total dissolved solids (TDS) | N/A | 1000.0 | 352.0 | 827.0 | 7815.0 | 807.0 | 4791.0 | 214.0 | 2912.0 | 179.0 | 1169.0 | 135.0 | 494.0 | 1597.0 | 895.0 |
| Total alkalinity (mg/L) | N/A | | 148.2 | --- | 434.0 | --- | 400.4 | 172.2 | 87.0 | 66.4 | 181.2 | 283.2 | 72.4 | 166.2 | --- |
| Cl, chloride | | 250.0 | 31.6 | 134.1 | 1885.3 | 107.6 | 2707.9 | 16.7 | 1381.5 | 19.6 | 604.4 | 18.1 | 161.5 | 750.8 | 26.7 |
| F, fluoride | | 0.6 - 1.7 | --- | 1.21 | 3.32 | 1.69 | 2.24 | 1.15 | 1.91 | 0.46 | 1.21 | 0.90 | 2.18 | 1.05 | 4.57 |
| NO3, nitrate | | 20.0 | --- | --- | 41.30 | --- | 31.80 | 9.10 | 5.30 | 4.90 | 40.30 | 5.80 | 20.30 | 18.30 | 8.10 |
| SO4, sulphate | | 300.0 | 237.0 | 686.7 | 26.4 | 689.3 | 61.0 | 40.0 | 451.2 | 36.5 | 113.0 | 35.3 | 21.0 | 368.0 | 800.8 |
| Al, aluminium | 0.0312 | 0.2 | <0.0312 | 5.891 | <0.0312 | 7.067 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | 0.080 | 35.561 |
| As, arsenic | 0.0248 | 0.05 | <0.0248 | <0.0248 | 0.153 | <0.0248 | <0.0248 | 0.085 | <0.0248 | <0.0248 | 0.096 | <0.0248 | 0.080 | <0.0248 | 0.726 |
| B, boron | 0.0266 | 1.0 | 0.77 | 0.75 | 13.57 | 0.73 | 8.44 | 0.78 | 3.63 | 0.37 | 2.63 | 0.35 | 1.12 | 2.65 | 0.44 |
| Ba, barium | 0.0003 | 0.7^ | 0.038 | --- | --- | --- | --- | 0.057 | --- | 0.019 | 0.039 | 0.019 | 0.171 | --- | --- |
| Ca, calcium | 0.0054 | 200.0 | 81.4 | 214.0 | 152.0 | 231.8 | 108.1 | 53.2 | 111.8 | 22.8 | 26.1 | 22.2 | 81.3 | 104.7 | 99.6 |
| Cd, cadmium | 0.0011 | 0.005 | 0.001 | 0.197 | <0.0011 | 0.215 | <0.0011 | 0.003 | 0.171 | 0.002 | <0.0011 | <0.0011 | <0.0011 | 0.003 | 0.836 |
| Co, cobalt | 0.0035 | 0.1 | <0.0035 | 0.036 | 0.004 | 0.050 | <0.0035 | <0.0035 | 0.009 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | 0.157 |
| Cr, chromium | 0.0052 | 0.05 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | 0.006 |
| Cu, copper | 0.0044 | 0.05 | <0.0044 | 0.454 | <0.0044 | 0.391 | 0.008 | <0.0044 | 0.005 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | 0.007 | 2.159 |
| Fe, iron | 0.0019 | 0.3 | 1.921 | 1.939 | 0.133 | 2.770 | 0.986 | 0.002 | 0.393 | 0.008 | <0.019 | 0.079 | 0.068 | 0.061 | 121.276 |
| K, potassium | 0.0298 | N/A | 9.5 | 10.2 | 290.4 | 11.1 | 156.7 | 3.8 | 71.5 | 3.9 | 15.5 | 2.2 | 12.5 | 30.1 | 12.1 |
| Li, lithium | 0.0029 | 2.5^^ | 0.12 | 0.56 | 18.16 | 0.54 | 10.77 | 0.03 | 3.51 | 0.01 | 0.59 | 0.01 | 0.19 | 0.54 | 0.22 |
| Mg, magnesium | 0.0010 | 100.0 | 18.9 | 22.2 | 32.3 | 23.0 | 14.0 | 10.8 | 18.0 | 9.0 | 6.3 | 8.9 | 23.8 | 50.5 | 50.9 |
| Mn, manganese | 0.0004 | 0.50 | 0.345 | 4.926 | 0.528 | 5.645 | 0.391 | 0.009 | 0.681 | 0.012 | 0.006 | 0.005 | 3.240 | 0.018 | 10.798 |
| Mo, molybdenum | 0.0083 | 0.02^ | <0.0083 | --- | --- | --- | --- | <0.0083 | --- | <0.0083 | <0.0083 | <0.0083 | <0.0083 | --- | --- |
| Na, sodium | 0.0047 | 200.0 | 44.4 | 98.5 | 3684.9 | 80.2 | 1980.9 | 29.5 | 1196.8 | 19.3 | 468.8 | 18.3 | 96.2 | 534.5 | 30.9 |
| Ni, nickel | 0.0074 | 0.05 | <0.0074 | 0.100 | <0.0074 | 0.104 | <0.0074 | <0.0074 | 0.022 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | 0.336 |
| Pb, lead | 0.0251 | 0.05 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | 0.049 |
| Sb, antimony | 0.0192 | 0.01 | <0.0192 | <0.0192 | 0.056 | 0.035 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | <0.0192 |
| Si, silica | 0.0263 | N/A | 17.3 | 14.6 | 18.9 | 21.4 | 32.6 | 27.5 | 7.5 | 9.4 | 19.9 | 7.1 | 29.0 | 0.2 | 27.0 |
| Sn, tin | 0.0353 | 0.025^^^ | 0.050 | 0.054 | 0.095 | 0.043 | 0.062 | <0.0353 | 0.040 | 0.037 | 0.052 | <0.0353 | <0.0353 | 0.078 | <0.0353 |
| Zn, zinc | 0.0026 | 0.2 | 0.004 | 48.750 | 0.017 | 48.084 | 0.008 | 0.011 | 19.618 | 0.084 | 0.015 | 0.126 | <0.0026 | 0.018 | 32.948 |

**Appendix A3:** April 2014 chemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| APRIL 7 - 12th 2014 | | | Site code: | TID1 | TOLAP1 | TOTP5 | TOTR1 | TOTR2 | TOTV2 | URC1 | URLT1 | URR1 | URR2 | URR3 | URV1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Type: | Mine water | Well | Well | River | River | Spring/ slope | Irrigation canal | Thermal | River | River | River | Spring/ slope |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: | WQR | 10 | 4 | 8 | 8 | 8 | 6 | 7 | 9 | 3 | 3 | 5 | 5 |
| pH | N/A | 6.0 - 8.5 | | 7.2 | 7.2 | 3.6 | 4.5 | 4.3 | 7.6 | 8.3 | 6.7 | 8.8 | 8.5 | 8.8 | 7.7 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | | 11.71 | 0.44 | 1.26 | 3.04 | 3.16 | 0.46 | 2.60 | 6.09 | 0.28 | 0.23 | 1.04 | 1.33 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sodium adsorption ratio (SAR)** | N/A | | | 41.4 | 0.8 | 3.1 | 0.8 | 0.8 | 0.8 | 13.8 | 34.6 | 0.8 | 0.6 | 6.7 | 7.8 |
| Total dissolved solids (TDS) | N/A | 1000.0 | | 5860.0 | 269.0 | 632.0 | 1521.0 | 1573.0 | 232.0 | 1302.0 | 3045.0 | 141.0 | 115.0 | 522.0 | 665.0 |
| Total alkalinity (mg/L) | N/A | | | 90.2 | 66.0 | --- | --- | --- | 48.4 | 224.2 | 376.0 | 94.8 | 76.0 | 159.0 | 388.4 |
| Cl, chloride | | 250.0 | | 1435.0 | 22.4 | 34.3 | 151.6 | 152.9 | 10.0 | 650.2 | 1344.8 | 11.3 | 9.0 | 213.4 | 205.0 |
| F, fluoride | | 0.6 - 1.7 | | 2.19 | 1.72 | 3.55 | 1.70 | 2.02 | 0.95 | 1.40 | 2.39 | 1.43 | 1.09 | 2.11 | 2.30 |
| NO3, nitrate | | 20.0 | | --- | 6.50 | --- | 10.90 | 10.30 | 2.40 | 9.20 | 30.90 | 6.40 | 5.10 | 16.50 | 22.70 |
| SO4, sulphate | | 300.0 | | 357.2 | 50.7 | 521.6 | 1664.4 | 1544.7 | 152.9 | 34.9 | 32.2 | 37.6 | 27.4 | 38.8 | 74.6 |
| Al, aluminium | 0.0312 | 0.2 | | <0.0312 | <0.0312 | 25.679 | 8.708 | 9.408 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 | <0.0312 |
| As, arsenic | 0.0248 | 0.05 | | 0.030 | <0.0248 | 0.033 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 |
| B, boron | 0.0266 | 1.0 | | 6.38 | 0.43 | 1.45 | 0.32 | 0.33 | 0.73 | 3.11 | 6.73 | 0.57 | 0.35 | 1.55 | 2.98 |
| Ba, barium | 0.0003 | 0.7^ | | --- | 0.019 | --- | --- | --- | --- | 0.267 | --- | 0.019 | --- | --- | 0.048 |
| Ca, calcium | 0.0054 | 200.0 | | 291.2 | 36.2 | 89.4 | 679.2 | 710.6 | 49.5 | 50.3 | 86.3 | 35.1 | 21.7 | 32.5 | 33.1 |
| Cd, cadmium | 0.0011 | 0.005 | | 0.073 | <0.0011 | 0.092 | 0.357 | 0.394 | 0.004 | <0.0011 | 0.002 | <0.0011 | 0.002 | 0.002 | 0.003 |
| Co, cobalt | 0.0035 | 0.1 | | <0.0035 | <0.0035 | 0.359 | 0.029 | 0.032 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 |
| Cr, chromium | 0.0052 | 0.05 | | <0.0052 | <0.0052 | 0.009 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 |
| Cu, copper | 0.0044 | 0.05 | | <0.0044 | <0.0044 | 1.833 | 0.066 | 0.079 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 |
| Fe, iron | 0.0019 | 0.3 | | 0.012 | <0.019 | 14.082 | 0.908 | 1.702 | <0.0019 | 0.015 | 0.491 | 0.030 | <0.0019 | 0.014 | 0.301 |
| K, potassium | 0.0298 | N/A | | 125.9 | 3.8 | 21.9 | 16.6 | 17.2 | 3.2 | 46.6 | 117.7 | 3.3 | 1.8 | 17.5 | 10.8 |
| Li, lithium | 0.0029 | 2.5^^ | | 6.03 | 0.01 | 3.50 | 0.24 | 0.26 | <0.029 | 3.91 | 9.68 | <0.029 | <0.029 | 1.25 | 1.79 |
| Mg, magnesium | 0.0010 | 100.0 | | 28.9 | 12.5 | 22.5 | 20.1 | 21.1 | 15.2 | 11.4 | 13.2 | 14.7 | 9.5 | 8.3 | 19.4 |
| Mn, manganese | 0.0004 | 0.50 | | 1.031 | 0.001 | 0.895 | 3.563 | 3.787 | <0.0004 | 0.067 | 0.189 | 0.061 | 0.001 | 0.016 | 0.030 |
| Mo, molybdenum | 0.0083 | 0.02^ | | --- | <0.0083 | --- | --- | --- | --- | <0.0083 | --- | <0.0083 | --- | --- | <0.0083 |
| Na, sodium | 0.0047 | 200.0 | | 2758.1 | 21.4 | 126.0 | 76.2 | 76.7 | 26.1 | 414.0 | 1302.3 | 23.4 | 13.8 | 164.6 | 227.6 |
| Ni, nickel | 0.0074 | 0.05 | | 0.015 | <0.0074 | 0.414 | 0.067 | 0.073 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 |
| Pb, lead | 0.0251 | 0.05 | | 0.028 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 |
| Sb, antimony | 0.0192 | 0.01 | | <0.0192 | 0.031 | <0.0192 | 0.021 | <0.0192 | <0.0192 | <0.0192 | 0.194 | <0.0192 | <0.0192 | <0.0192 | 0.026 |
| Si, silica | 0.0263 | N/A | | 6.7 | 13.6 | 23.7 | 11.5 | 12.1 | 14.2 | 16.0 | 26.6 | 9.7 | 9.5 | 12.2 | 9.2 |
| Sn, tin | 0.0353 | 0.025^^^ | | 0.056 | 0.057 | 0.043 | 0.067 | 0.070 | 0.045 | 0.041 | 0.043 | 0.036 | <0.0353 | <0.0353 | 0.090 |
| Zn, zinc | 0.0026 | 0.2 | | 4.968 | 0.006 | 2.655 | 62.012 | 71.833 | 1.354 | <0.0026 | 0.010 | <0.0026 | <0.0026 | <0.0026 | <0.0026 |

**Appendix A4:** July 2014 chemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| **JULY 9 - 13th 2014** | | Site code: | AVR1 | AVR2 | AVR3 | BODI1 | CABT1 | CABTE | CALLP | CUCC1 | KER2 | LCR1 | MAD1 | PALP3 | PALP4 | PALP7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type: | River | River | River | Channel | Tank | Thermal | Well | Irrigation channel | River | River | Mine water | Well | Well | Well |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: WQR | 8 | 8 | 8 | 8 | 3 | 9 | 4 | 3 (channel), pool not sampled | 8 | 6 | 10 | 7 | 7 | 7 |
| pH | N/A | 6.0 - 8.5 | 3.3 | 4.1 | 4.1 | 10.4 | 8.0 | 6.8 | 7.4 | 6.8 | 7.6 | 7.3 | 2.5 | 7.2 | 7.5 | 7.5 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | 2.60 | 3.26 | 1.91 | 2.59 | 0.33 | 16.71 | 0.69 | 0.23 | 9.22 | 1.54 | 12.29 | 5.23 | 2.35 | 3.44 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sodium adsorption ratio (SAR)** | N/A | | 0.8 | 1.0 | 0.8 | 0.9 | 1.0 | 77.7 | 2.9 | 0.5 | 29.2 | 1.2 | 8.3 | 9.7 | 5.5 | 6.5 |
| Total dissolved solids (TDS) | N/A | 1000.0 | 1301.0 | 1629.0 | 957.0 | 1758.0 | 164.0 | 8358.0 | 346.0 | 117.0 | 4608.0 | 767.0 | 6140.0 | 2611.0 | 1176.0 | 1720.0 |
| Total alkalinity (mg/L) | N/A | | --- | --- | --- | 24.4 | 62.0 | 326.8 | 115.2 | 47.0 | 75.2 | 45.2 | --- | 272.2 | 179.6 | 334.0 |
| Cl, chloride | | 250.0 | 124.7 | 224.9 | 98.6 | 237.9 | 30.4 | 4932.5 | 98.3 | 10.9 | 5061.4 | 89.0 | 1197.5 | 1083.9 | 297.8 | 716.0 |
| F, fluoride | | 0.6 - 1.7 | 0.58 | 4.23 | 1.79 | 0.60 | 1.42 | 1.30 | 1.57 | 2.46 | 0.96 | 1.44 | 3.43 | 3.74 | 3.73 | 0.58 |
| NO3, nitrate | | 20.0 | --- | 10.00 | 3.00 | 13.40 | 5.40 | 21.90 | 9.00 | 3.30 | --- | 3.10 | --- | 18.70 | 13.80 | 115.40 |
| SO4, sulphate | | 300.0 | 1207.4 | 1647.5 | 909.7 | 1823.5 | 50.7 | 171.8 | 78.0 | 53.8 | 1255.9 | 653.9 | 6670.7 | 533.3 | 693.2 | 127.0 |
| Al, aluminium | 0.0312 | 0.2 | 28.563 | 15.783 | 16.414 | 0.091 | 0.050 | 0.035 | <0.0312 | 0.035 | 0.061 | 0.074 | 164.302 | 0.069 | <0.031 | <0.031 |
| As, arsenic | 0.0248 | 0.05 | <0.024 | 0.128 | <0.024 | <0.0248 | <0.024 | <0.0248 | <0.0248 | <0.0248 | <0.024 | <0.024 | 2.364 | 0.058 | 0.088 | <0.024 |
| B, boron | 0.0266 | 1.0 | 0.49 | 0.40 | 0.48 | 0.32 | 0.35 | 11.25 | 0.96 | 0.26 | 5.58 | 0.91 | 1.78 | 4.24 | 2.02 | 3.11 |
| Ba, barium | 0.0003 | 0.7^ | 0.010 | 0.027 | 0.010 | 0.084 | 0.020 | 0.280 | 0.051 | 0.015 | 0.140 | 0.037 | 0.033 | 0.039 | 0.046 | 0.162 |
| Ca, calcium | 0.0054 | 200.0 | 370.8 | 628.7 | 285.4 | 837.6 | 23.7 | 91.9 | 39.2 | 20.3 | 174.2 | 173.4 | 227.0 | 268.4 | 140.2 | 194.1 |
| Cd, cadmium | 0.0011 | 0.005 | 0.407 | 0.328 | 0.308 | 0.005 | <0.001 | <0.0011 | 0.002 | 0.002 | 0.265 | 0.006 | 9.876 | 0.005 | 0.005 | 0.002 |
| Co, cobalt | 0.0035 | 0.1 | 0.123 | 0.058 | 0.074 | <0.0035 | <0.003 | <0.0035 | <0.0035 | <0.0035 | 0.013 | 0.004 | 0.437 | <0.003 | <0.003 | <0.003 |
| Cr, chromium | 0.0052 | 0.05 | <0.005 | <0.005 | <0.005 | <0.0052 | <0.005 | 0.006 | <0.0052 | <0.0052 | <0.005 | <0.005 | 0.052 | <0.005 | <0.005 | <0.005 |
| Cu, copper | 0.0044 | 0.05 | 0.606 | 0.457 | 0.410 | <0.0044 | <0.004 | <0.0044 | <0.0044 | <0.0044 | <0.004 | <0.004 | 1.012 | <0.004 | <0.004 | <0.004 |
| Fe, iron | 0.0019 | 0.3 | 1.715 | 27.668 | 1.503 | <0.0019 | 0.005 | 0.264 | 0.003 | 0.006 | 0.159 | 0.048 | 2349.60 | 0.009 | 0.025 | 0.003 |
| K, potassium | 0.0298 | N/A | 8.1 | 13.2 | 7.9 | 15.8 | 2.1 | 225.3 | 7.8 | 1.7 | 110.8 | 18.5 | 35.3 | 64.5 | 31.9 | 61.5 |
| Li, lithium | 0.0029 | 2.5^^ | 0.49 | 0.34 | 0.40 | 0.25 | 0.03 | 12.96 | 0.31 | <0.029 | 5.32 | 1.00 | 1.99 | 3.42 | 1.92 | 3.82 |
| Mg, magnesium | 0.0010 | 100.0 | 30.4 | 21.7 | 28.3 | 10.3 | 9.6 | 25.5 | 8.6 | 7.7 | 31.9 | 51.6 | 202.9 | 50.7 | 26.1 | 42.8 |
| Mn, manganese | 0.0004 | 0.50 | 16.667 | 3.550 | 8.856 | 0.005 | 0.001 | 0.285 | 0.002 | 0.003 | 1.504 | 0.232 | 27.853 | 1.568 | 6.103 | 0.0005 |
| Mo, molybdenum | 0.0083 | 0.02^ | <0.008 | <0.008 | <0.008 | 0.009 | <0.008 | <0.0083 | <0.0083 | <0.0083 | <0.008 | <0.008 | <0.0083 | <0.008 | <0.008 | <0.008 |
| Na, sodium | 0.0047 | 200.0 | 58.9 | 91.2 | 53.2 | 92.2 | 21.6 | 3257.0 | 77.2 | 11.1 | 1592.7 | 67.7 | 712.2 | 657.6 | 270.5 | 380.1 |
| Ni, nickel | 0.0074 | 0.05 | 0.183 | 0.093 | 0.159 | <0.0074 | <0.007 | <0.0074 | <0.0074 | <0.0074 | 0.029 | 0.204 | 1.407 | <0.007 | <0.007 | <0.007 |
| Pb, lead | 0.0251 | 0.05 | <0.025 | 0.026 | <0.025 | <0.0251 | <0.025 | 0.030 | <0.0251 | <0.0251 | <0.025 | <0.025 | 0.524 | <0.025 | <0.025 | <0.025 |
| Sb, antimony | 0.0192 | 0.01 | <0.019 | <0.019 | <0.019 | 0.020 | <0.019 | <0.0192 | <0.0192 | <0.0192 | 0.034 | <0.019 | 0.377 | <0.019 | <0.019 | <0.019 |
| Si, silica | 0.0263 | N/A | 30.1 | 12.2 | 25.2 | 0.1 | 7.1 | 26.4 | 17.2 | 9.3 | 8.1 | 30.5 | 28.3 | 13.6 | 23.0 | 22.2 |
| Sn, tin | 0.0353 | 0.025^^^ | 0.059 | 0.106 | <0.035 | 0.052 | 0.042 | <0.0353 | <0.0353 | 0.044 | 0.080 | 0.075 | 0.066 | 0.137 | 0.078 | 0.109 |
| Zn, zinc | 0.0026 | 0.2 | 90.769 | 51.279 | 67.928 | 0.051 | <0.002 | <0.0026 | 0.004 | <0.0026 | 19.465 | 39.113 | 1582.88 | 0.018 | 0.012 | <0.002 |

* Generally, recommended drinking water EC <0.9 dS/m (<600 ppm TDS) and maximum 1.5 dS/m (1000 ppm TDS; recommended by the WHO (2011a) for taste and palatability).
EC >2.5 dS/m is not recommended for consumption and that with >10 dS/m is considered unfit for any consumption (livestock included).
** SAR = [Na meq/l]/({[Ca meq/l]+[Mg meq/l]}/2})1/2
^ WHO guideline (2011a).
^^ FAO (1985) recommendation for non-restricted irrigation use.
^^^ UK Environment Agency non-statutory guideline for the protection of aquatic life (surface waters).

**Appendix A4:** July 2014 chemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| **JULY 9 - 13th 2014** | | Site code: | PALP8 | PALP10 | PALR2 | PAZP3 | PAZR1 | PAZTE | PMO1 | POR3 | POR4 | PQUE1 | PUNP1 | PUNP2 | RYU1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type: | Well | Well | River | Well | River | Thermal | Well | River | River | Well | Tap | Well | River/ Lake |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: WQR | 7 | 4 | 8 | 9 | 8 | 9 | 4 | 8 | 3 | 7 | 2 | 5 | 7 |
| pH | N/A | 6.0 - 8.5 | 7.0 | 6.7 | 5.4 | 8.3 | 4.7 | 6.7 | 8.3 | 8.6 | 8.2 | 8.3 | 8.3 | 7.8 | 8.2 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | 3.95 | 0.68 | 1.96 | 15.52 | 1.97 | 12.36 | 0.45 | 8.60 | 0.33 | 2.59 | 0.33 | 0.87 | 3.66 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sodium adsorption ratio (SAR)** | N/A | | 10.4 | 1.0 | 2.0 | 63.3 | 1.2 | 41.5 | 0.9 | 30.9 | 0.9 | 18.4 | 1.0 | 1.9 | 10.0 |
| Total dissolved solids (TDS) | N/A | 1000.0 | 1976.0 | 338.0 | 979.0 | 7755.0 | 986.0 | 5172.0 | 224.0 | 1308.0 | 163.0 | 1293.0 | 164.0 | 437.0 | 1829.0 |
| Total alkalinity (mg/L) | N/A | | 350.4 | 136.2 | --- | 628.6 | --- | 401.8 | 172.4 | 74.8 | 60.8 | 184.2 | 69.2 | 159.0 | 186.4 |
| Cl, chloride | | 250.0 | 944.0 | 36.2 | 194.0 | 4802.8 | 128.3 | 2935.3 | 21.2 | 2350.4 | 29.5 | 603.1 | 30.8 | 151.5 | 760.0 |
| F, fluoride | | 0.6 - 1.7 | 2.47 | 3.60 | 0.49 | 3.49 | 1.98 | 5.14 | 2.96 | 3.56 | 0.77 | 2.38 | 0.80 | 3.19 | 3.43 |
| NO3, nitrate | | 20.0 | 25.00 | --- | --- | 44.90 | --- | 34.90 | 11.90 | 1.20 | 7.30 | 17.10 | 5.40 | 11.60 | 21.50 |
| SO4, sulphate | | 300.0 | 112.7 | 164.9 | 706.6 | 51.7 | 834.7 | 66.8 | 33.9 | 469.0 | 46.0 | 117.0 | 53.1 | 77.3 | 491.4 |
| Al, aluminium | 0.0312 | 0.2 | 0.036 | 0.041 | 2.826 | <0.0312 | 12.950 | 0.051 | 0.072 | <0.0312 | 0.054 | <0.0312 | 0.055 | <0.0312 | 0.062 |
| As, arsenic | 0.0248 | 0.05 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | 0.063 | <0.0248 | <0.0248 | <0.0248 |
| B, boron | 0.0266 | 1.0 | 4.27 | 0.79 | 0.86 | 14.14 | 0.66 | 8.41 | 0.75 | 5.81 | 0.34 | 2.90 | 0.36 | 0.93 | 3.00 |
| Ba, barium | 0.0003 | 0.7^ | 0.260 | 0.042 | 0.030 | 0.312 | 0.020 | HIGH | 0.053 | 0.123 | 0.020 | 0.050 | 0.020 | 0.120 | 0.030 |
| Ca, calcium | 0.0054 | 200.0 | 146.4 | 77.9 | 232.1 | 138.0 | 283.1 | 101.1 | 50.7 | 129.6 | 23.9 | 30.1 | 24.2 | 71.0 | 117.0 |
| Cd, cadmium | 0.0011 | 0.005 | <0.0011 | 0.003 | 0.216 | <0.0011 | 0.273 | 0.003 | 0.003 | 0.100 | 0.002 | 0.002 | <0.0011 | 0.003 | 0.002 |
| Co, cobalt | 0.0035 | 0.1 | <0.0035 | <0.0035 | 0.049 | <0.0035 | 0.063 | <0.0035 | <0.0035 | 0.010 | <0.0035 | <0.0035 | <0.0035 | <0.0035 | <0.0035 |
| Cr, chromium | 0.0052 | 0.05 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 |
| Cu, copper | 0.0044 | 0.05 | <0.0044 | <0.0044 | 0.254 | <0.0044 | 0.346 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | 0.011 |
| Fe, iron | 0.0019 | 0.3 | 0.028 | 1.523 | 0.645 | 0.074 | 1.884 | 0.913 | 0.005 | 0.010 | 0.007 | 0.002 | 0.004 | 0.002 | 0.014 |
| K, potassium | 0.0298 | N/A | 62.1 | 8.7 | 13.8 | 271.3 | 11.5 | 146.8 | 3.4 | 112.9 | 2.1 | 17.9 | 2.1 | 9.8 | 33.2 |
| Li, lithium | 0.0029 | 2.5^^ | 4.18 | 0.10 | 0.78 | 17.11 | 0.60 | 9.45 | 0.03 | 5.37 | 0.03 | 0.74 | 0.03 | 0.14 | 0.60 |
| Mg, magnesium | 0.0010 | 100.0 | 38.3 | 17.5 | 26.6 | 26.5 | 30.0 | 13.0 | 10.3 | 28.4 | 9.7 | 7.2 | 9.9 | 19.3 | 64.0 |
| Mn, manganese | 0.0004 | 0.50 | 0.010 | 0.301 | 6.231 | 0.434 | 8.454 | 0.360 | <0.0004 | 1.028 | 0.006 | 0.004 | 0.001 | 0.007 | 0.013 |
| Mo, molybdenum | 0.0083 | 0.02^ | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 |
| Na, sodium | 0.0047 | 200.0 | 543.6 | 35.6 | 122.1 | 3088.9 | 77.5 | 1664.2 | 25.3 | 1485.4 | 21.2 | 431.6 | 21.8 | 69.2 | 540.4 |
| Ni, nickel | 0.0074 | 0.05 | <0.0074 | <0.0074 | 0.106 | <0.0074 | 0.136 | <0.0074 | <0.0074 | 0.012 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 |
| Pb, lead | 0.0251 | 0.05 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | 0.032 |
| Sb, antimony | 0.0192 | 0.01 | <0.0192 | <0.0192 | 0.019 | <0.0192 | 0.026 | 0.030 | 0.022 | 0.049 | 0.020 | <0.0192 | <0.0192 | 0.022 | <0.0192 |
| Si, silica | 0.0263 | N/A | 17.0 | 18.2 | 19.0 | 20.9 | 22.5 | 36.5 | 27.9 | 8.1 | 7.3 | 21.4 | 7.4 | 29.2 | 0.04 |
| Sn, tin | 0.0353 | 0.025^^^ | 0.072 | 0.093 | 0.038 | <0.0353 | 0.048 | 0.094 | 0.045 | 0.126 | <0.0353 | 0.093 | <0.0353 | 0.060 | 0.090 |
| Zn, zinc | 0.0026 | 0.2 | <0.0026 | 0.004 | 47.902 | 0.007 | 61.847 | 0.004 | <0.0026 | 3.117 | 0.043 | <0.0026 | 0.033 | 0.011 | 0.022 |

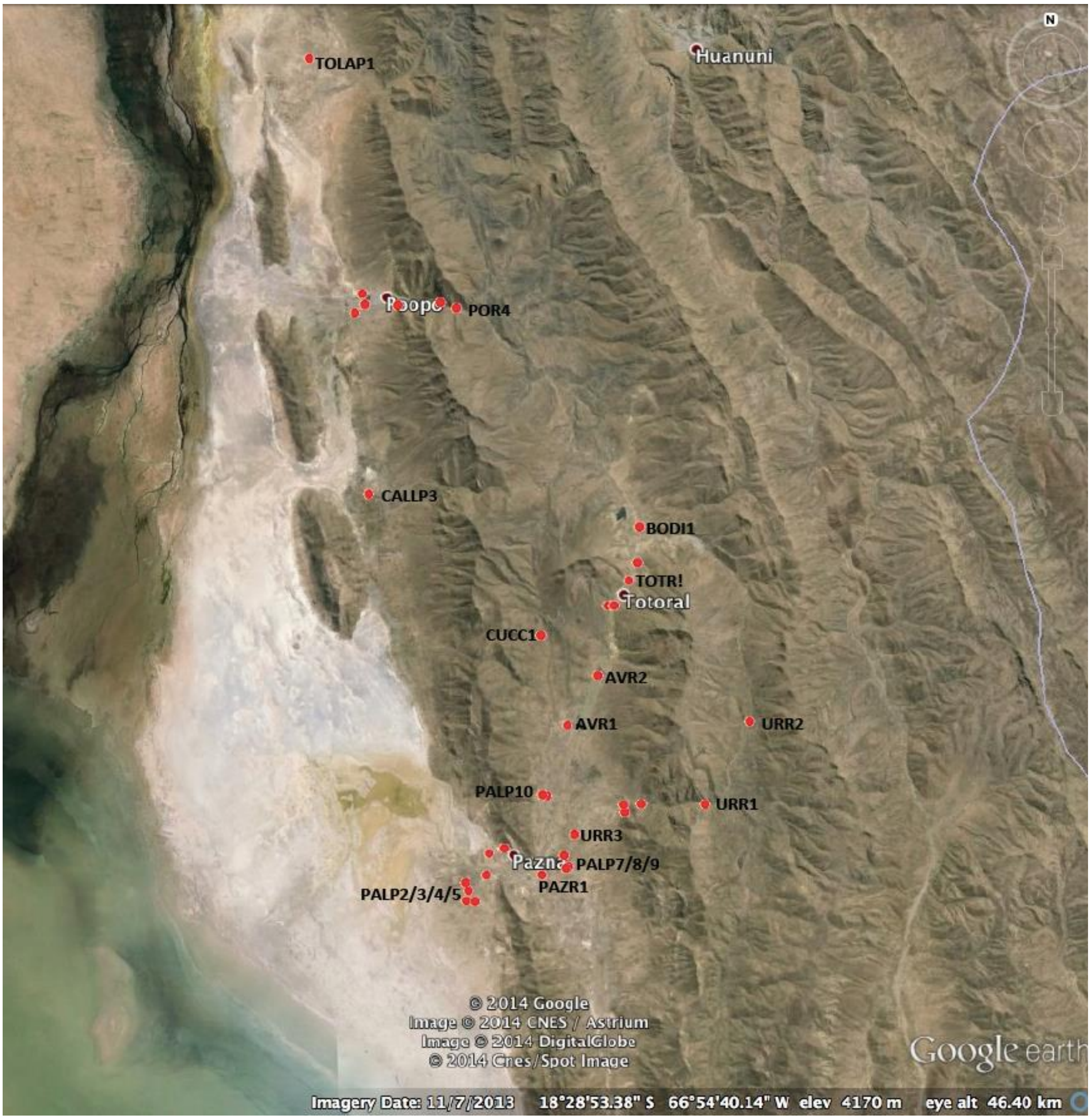
**Appendix A4:** July 2014 chemical concentrations (mg/L), physico-chemical data and Water Quality Rating (WQR, 1 = best, 10 = worst) for sample sites (Figure 1).

| **JULY 9 - 13th 2014** | | Site code: | | SORR1 | TID1 | TOLAP1 | TOTR1 | TOTR2 | TOTV2 | URC1 | URLT1 | URR1 | URR2 | URR3 | URV1 | VIP1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Type: | | River | Mine water | Well | River | River | Spring/ slope | Irrigation canal | Thermal | River | River | River | Spring/ slope | Well |
| Parameter (mg/L unless stated otherwise): | Detection limit (mg/L): | Bolivian A criteria: | WQR | 10 | 10 | 4 | 8 | 8 | 6 | 7 | 9 | 3 | 3 | 5 | 5 | 6 |
| pH | N/A | 6.0 - 8.5 | | 3.5 | 7.7 | 6.3 | 6.1 | 5.8 | 8.1 | 7.8 | 6.7 | 8.3 | 5.8 | 8.8 | 7.5 | 6.8 |
| Electrical conductivity (EC, dS/m) | N/A | <1.5* | | 2.02 | 9.89 | 0.34 | 3.32 | 3.22 | 0.46 | 2.40 | 6.30 | 0.32 | 0.44 | 1.40 | 1.39 | 1.20 |
| Dissolved oxygen (DO, % saturation) | N/A | >80% | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sodium adsorption ratio (SAR)** | N/A | | | 0.6 | 28.2 | 0.7 | 0.8 | 0.9 | 0.9 | 12.7 | 28.6 | 0.6 | 0.5 | 6.5 | 7.1 | 1.7 |
| Total dissolved solids (TDS) | N/A | 1000.0 | | 1008.0 | 4955.0 | 168.0 | 1670.0 | 1611.0 | 229.0 | 1199.0 | 3153.0 | 159.0 | 216.0 | 697.0 | 693.0 | 601.0 |
| Total alkalinity (mg/L) | N/A | | | --- | 71.6 | 86.8 | 11.2 | 5.8 | 48.4 | 183.6 | 439.0 | 98.0 | 85.0 | 127.6 | 331.0 | 141.4 |
| Cl, chloride | | 250.0 | | 35.8 | 2605.4 | 15.3 | 235.4 | 240.2 | 14.0 | 507.0 | 1628.7 | 11.3 | 14.9 | 314.0 | 207.1 | 76.8 |
| F, fluoride | | 0.6 - 1.7 | | 5.81 | 4.21 | 1.77 | 3.62 | 3.83 | 2.42 | 2.47 | 0.94 | 1.11 | 1.94 | 1.21 | 0.78 | --- |
| NO3, nitrate | | 20.0 | | --- | 3.70 | 7.80 | 19.40 | 20.70 | 3.30 | 14.50 | 27.40 | 7.60 | 5.60 | --- | 13.30 | --- |
| SO4, sulphate | | 300.0 | | 970.4 | 858.4 | 45.0 | 1649.4 | 1750.7 | 154.7 | 43.6 | 51.9 | 48.1 | 31.2 | 36.1 | 67.3 | 374.4 |
| Al, aluminium | 0.0312 | 0.2 | | 71.668 | 0.046 | <0.0312 | 0.762 | 1.370 | <0.0312 | 0.045 | <0.0312 | <0.0312 | 0.057 | 0.044 | <0.0312 | 0.058 |
| As, arsenic | 0.0248 | 0.05 | | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | <0.0248 | 0.080 |
| B, boron | 0.0266 | 1.0 | | 0.45 | 5.60 | 0.44 | 0.31 | 0.38 | 0.79 | 2.62 | 6.54 | 0.38 | 0.30 | 1.41 | 2.88 | 1.19 |
| Ba, barium | 0.0003 | 0.7^ | | 0.010 | 0.104 | 0.020 | 0.065 | 0.059 | 0.036 | 0.260 | HIGH | 0.022 | 0.020 | 0.101 | 0.050 | 0.080 |
| Ca, calcium | 0.0054 | 200.0 | | 103.9 | 277.9 | 32.3 | 700.5 | 752.6 | 43.6 | 45.7 | 80.5 | 27.8 | 23.8 | 42.1 | 32.2 | 120.6 |
| Cd, cadmium | 0.0011 | 0.005 | | 1.414 | 0.116 | 0.005 | 0.156 | 0.171 | 0.006 | <0.0011 | <0.0011 | 0.003 | 0.003 | <0.0011 | 0.002 | 0.006 |
| Co, cobalt | 0.0035 | 0.1 | | 0.401 | <0.0035 | <0.0035 | 0.011 | 0.017 | <0.0035 | <0.0035 | <0.0035 | 0.004 | <0.0035 | <0.0035 | <0.0035 | <0.0035 |
| Cr, chromium | 0.0052 | 0.05 | | 0.011 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 | <0.0052 |
| Cu, copper | 0.0044 | 0.05 | | 2.200 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 | <0.0044 |
| Fe, iron | 0.0019 | 0.3 | | 167.220 | 0.010 | 0.003 | 0.023 | 0.203 | 0.004 | 0.063 | 0.346 | 0.310 | <0.0019 | 0.010 | 0.007 | 1.886 |
| K, potassium | 0.0298 | N/A | | 7.9 | 106.6 | 3.2 | 13.1 | 15.1 | 3.1 | 41.6 | 118.2 | 2.3 | 6.1 | 20.5 | 10.9 | 18.5 |
| Li, lithium | 0.0029 | 2.5^^ | | 0.38 | 5.12 | 0.004 | 0.20 | 0.25 | <0.029 | 3.31 | <0.029 | <0.029 | <0.029 | 1.52 | 1.76 | 0.45 |
| Mg, magnesium | 0.0010 | 100.0 | | 54.6 | 24.3 | 10.9 | 12.6 | 15.3 | 14.2 | 10.8 | 12.4 | 11.7 | 10.7 | 10.8 | 19.4 | 35.3 |
| Mn, manganese | 0.0004 | 0.50 | | 22.711 | 1.012 | 0.004 | 1.126 | 1.384 | <0.0004 | 0.078 | 0.170 | 0.030 | <0.0004 | 0.009 | 0.024 | 0.776 |
| Mo, molybdenum | 0.0083 | 0.02^ | | <0.0083 | <0.0083 | <0.0083 | 0.009 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 | <0.0083 |
| Na, sodium | 0.0047 | 200.0 | | 32.4 | 1819.0 | 17.1 | 77.5 | 92.4 | 26.7 | 366.0 | 1037.9 | 13.9 | 11.9 | 183.3 | 206.3 | 83.9 |
| Ni, nickel | 0.0074 | 0.05 | | 0.530 | <0.0074 | <0.0074 | 0.019 | 0.023 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 | <0.0074 |
| Pb, lead | 0.0251 | 0.05 | | 0.034 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | 0.032 | <0.0251 | <0.0251 | <0.0251 | <0.0251 | <0.0251 |
| Sb, antimony | 0.0192 | 0.01 | | <0.0192 | <0.0192 | 0.021 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | <0.0192 | 0.030 | <0.0192 | 0.041 | <0.0192 |
| Si, silica | 0.0263 | N/A | | 43.7 | 7.6 | 16.3 | 3.9 | 4.2 | 14.1 | 12.9 | 24.7 | 8.9 | 10.2 | 10.0 | 8.8 | 18.1 |
| Sn, tin | 0.0353 | 0.025^^^ | | <0.0353 | 0.080 | 0.057 | 0.038 | 0.048 | 0.071 | 0.047 | 0.061 | 0.053 | 0.094 | <0.0353 | 0.093 | 0.065 |
| Zn, zinc | 0.0026 | 0.2 | | 37.475 | 3.127 | <0.0026 | 17.717 | 23.195 | 0.417 | <0.0026 | <0.0026 | 0.014 | <0.0026 | <0.0026 | <0.0026 | 0.009 |

**Appendix B**: Flow and well water levels in August and December 2013 and April and July 2014.

| **Flow measurements ($m^3/s$)** | | August 13-16th 2013 | December 16-20th 2013 | April 7-10th 2014 | July 9-13th 2014 |
|---|---|---|---|---|---|
| Site code: | Location (refer to Figure 1) | | | | |
| SORR1 (river) | Sora Sora | --- | --- | 0.6538 | 0.2769 |
| POR4 (river) | Poopó | --- | --- | 0.1019 | 0.0539 |
| MAD1 (AMD) | Poopó - Machacamaquita | --- | --- | --- | 0.0035 |
| POR3 (river) | Poopó | --- | --- | 0.1444 | 0.0889 |
| KER2 (river) | Kesukesuni | --- | --- | 0.0775 | 0.0654 |
| TOTR1 (river) | Antequera- Totoral | --- | --- | 0.1506 | 0.1893 |
| TOTR2 (river) | Antequera – Totoral | --- | --- | 0.1747 | 0.1483 |
| AVR1 (river) | Antequera - Avicaya | --- | --- | 0.0817 | 0.0704 |
| AVR3 (river) | Antequera - Avicaya | --- | --- | 0.2455 | 0.1097 |
| CUCC1 (tank) | Kuchi-Avicaya | --- | --- | --- | 0.0036 |
| PALR2 (river) | Pazña | --- | --- | 0.3233 | 0.1928 |
| PAZR1 (river) | Pazña | --- | --- | 0.3715 | 0.1740 |
| URR2 (river) | Urmiri | --- | --- | --- | 0.0064 |
| URR1 (river) | Urmiri | --- | --- | 0.0849 | 0.0384 |
| URC1 (channel) | Urmiri | --- | --- | 0.0534 | 0.0331 |
| URR3 (river) | Urmiri | --- | --- | 0.0505 | 0.0280 |
| **Well water levels (m below datum)** | | | | | |
| Site code: | Location (refer to Figure 1) | | | | |
| TOLAP1 (well) | Tolapampa | 7.05 | 7.10 | 4.72 | 4.09 |
| PUNP2 (well) | Puñaca | --- | --- | 4.68 | 4.74 |
| CALLP3 (well) | Callipampa | 7.30 | --- | 5.70 | 6.36 |
| PMO1 (well) | Morochi | --- | --- | --- | 2.30 |
| PQUE1 (well) | Quellia | --- | --- | 3.98 | 4.11 |
| TOTP5 | Antequera | dry | 2.17 | 1.40 | dry |
| PALP7 (well) | Pazña | 3.31 | 4.02 | 4.06 | 3.93 |
| PALP9 (well) | Pazña | 4.28 | 4.25 | --- | --- |
| PAZP3 (well) | Pazña | 1.63 | 1.88 | --- | 1.88 |
| PALP2 (well) | Pazña | 2.05 | 2.28 | --- | --- |
| PALP3 (well) | Pazña | 2.25 | 2.37 | 1.94 | 2.10 |
| PALP4 (well) | Pazña | 2.08 | 2.27 | 1.83 | 1.94 |
| PALP5 (well) | Pazña | 3.23 | 3.37 | --- | --- |

**Appendix C**: Google Earth image of study area (http://www.google.co.uk/intl/en_uk/earth/).



Google Earth image of Antequera River area, showing sample sites and indicating some possible main rainfall runoff inputs to river channels.