International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 10 No. 6s, 2024
https://theaspd.com/index.php

Land Use Planning Model for Geological and Social Coexistence. Case: Geochemistry of the Paucarcolla District, Puno, Peru

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Abstract
The development of society largely depends on soils, whose geochemistry provides essential information about the concentration and distribution of chemical elements that affect agriculture, the environment, and urban or rural areas. This study proposes a land-use planning model applied to the district of Paucarcolla, Puno, Peru, based on the geochemical characterization of agricultural alluvial soils. The methodology included systematic sampling of regoliths and soils within a 2x4 km grid, resulting in 24 samples and 3 repetitions, georeferenced and analyzed by ICP-OES (EPA 6010 and 3051-A), together with soil fertility parameters following the NOM-021-RECNAT-2000 standard. Results showed clayey and silty clay loam soils, with pH values ranging from 4.70 to 8.60, low levels of organic matter and nitrogen, and concentrations of heavy metals that exceeded international standards but remained within Peruvian regulations. Mapping identified cultivable soils, pastures, fallow lands, and urban expansion areas. This baseline supports sustainable territorial planning and management.
Keywords: *Territorial Planning; Geology; Geochemistry; Soils; Trace Elements.*

INTRODUCTION

The rapid urban expansion in rural communities of Puno, as in the rest of the towns surrounding the interurban roads and Lake Titicaca (Paucarcolla, Huata, Coata, and Capachica), raises concerns due to the lack of regulations for territorial planning that organize the use of urban and agricultural land, such as the invasion of farmland in Paucarcolla along the Puno-Juliaca highway. Although Environmental Land Use Planning (OTA) policies in Peru advanced significantly until 2015 in 16 regions, they were later relegated in favor of other national priorities.

According to Pinos-Arévalo [1] and Buzai [2], accelerated and disorderly urban growth, along with pressure on the territory, leads to the sacrifice of agricultural land by converting rural land into urban areas, thus impacting rural use and primary productive activity. Urban growth modifies landscapes and transforms land uses due to social and economic factors [3].

The Peruvian Andes play an important role by hosting a variety of ecosystems and diverse mineral deposits. However, they face the threat of soil contamination by heavy metals, which are toxic to organisms and difficult to degrade or eliminate through biological or chemical processes [4,5]. The issue of contaminated soils and subsoils has been neglected due to the lack of environmental legislation [6]. The presence and bioavailability of heavy metals in soils for plants depend on factors such as pH, organic matter (OM), and cation exchange capacity (CEC) [7].

Although nearby areas with heavy metal (HM) accumulation from mining activities have been studied [8,9], there is no active metallic mining in the district of Paucarcolla. However, remnants of old mining works were found in iron skarns containing HMs, which cause environmental impacts.

Studies on soils and waters demonstrate the applicability of geochemistry to determine contaminated zones, mainly in soils from abandoned mines, through distribution maps. Of particular concern are concentrations that exceeded guideline limits (LBG), the global average in soils, and the standards of the United States Environmental Protection Agency (USEPA) for As, Co, Cu, Mo, Ni, Pb, Sb, Hg, Cd, and Zn [10].

Tarvainen et al. [11] studied the geochemical baseline of soils in the cities of Taltal (Chile) and Tampere (Finland) for potentially toxic elements. They measured the concentrations of As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Sb, V, and Zn in soil samples sieved to <2 mm grain size, after extraction with aqua regia. The geochemical baseline served to show the level of contamination by As and other toxic metals, comparing them with global average values in soils.

Soils are formed by pedogenetic processes, through the interaction of five factors: climate, organisms, parent material, relief, and time [12]. Hu et al. [13] argue that the spatial distribution of heavy metals in agricultural activities significantly influences their accumulation in surface soils. In the district of Paucarcolla, there are cultivable soils for forage, quinoa, and potatoes, where fertilizers are used. The uncultivable barren soils are located on moderately dissected high hills with mineralized intrusive igneous rocks and around seasonal lagoons, lakes, and rivers. The lack of urban planning affects crop areas, caused by the expansion of the Puno-Juliaca transport route. Based on these premises, the objective of the study was to geochemically characterize the agricultural soils, quantify trace elements and heavy metals, and apply them as a baseline for environmental land-use planning in the district.

2. MATERIALS AND METHODS

2.1 Description of Study Area

The area is located in the district of Paucarcolla, north of the city of Puno, bounded by the coordinates 15°44'46" S and 70°03'31" W (Figure 1). It has a surface area of 203.33 km² and an average altitude of 3,845 meters above sea level. According to INEI [14], it has a population of 4,224 inhabitants. The annual temperature ranges between -4 and 18°C; rainfall occurs from September to April, with 13 mm of precipitation, but in January it rises to an average of 67 mm. The average wind speed is 9.1 km/h from north to south (senamhi update).

The eastern side of the district has 81.7 km² of buffer, recovery, and utilization zones belonging to the Titicaca National Reserve, and an irrigation area of 3.8 km² located between Pampa Yanico, Colila, and Isparani.

The vegetation includes native species adapted to the cold climate and high altitudes of the Andean plateau. The alluvial plains under cultivation contain potato (Solanum tuberosum), alfalfa (Medicago sativa), barley

(Hordeum vulgare), and quinoa (Chenopodium quinoa). Between the marshy plains and the lake grows totora (Schoenoplectus californicus). On igneous-origin hills, stands of ichu (Stipa ichu) and garbancillo (Astragalus garbancillo) are observed. On sedimentary hills with carbonate rocks, crespillo grasslands (Calamagrostis vicunarum) develop; sedimentary sandstone hills are covered by chilligua grasslands (Festuca dolichophylla). The wetlands contain crespillo grasslands, and in the valley bottoms grow shrubs of tola (Parastrephia lepidophylla) and ichu [15].

3.Geological Context

3.1 Lithostratigraphy

Quaternary Alluvial (Qh-al1). The Quaternary deposits extend towards the NE side of the district, where alluvial and palustrine deposits predominate, consisting of gravels, sands, and lenticular siltstones, derived from surrounding outcrops. Between the Totorani and Illpa rivers, remnants of the Azángaro Formation exist, whose composition includes clayey sand with iron oxide lenses, underlain by fine sand interbedded with coarse sand containing gravels with limestone clasts, brown sands, silts, and gray clays, down to a depth of 180 cm, limited by the water table. Quaternary Alluvial (Qh-al2) correspond to well-differentiated soil horizons, which contain sub-rounded polymictic pebbles and sporadic rock fragments, with the deeper horizons containing iron oxides. Palustrine deposits (Qh-pa) located on the edge of Lake Titicaca and temporary lagoons consist of sands, siltstones, peat with some carbonate horizons.

Finally, there are the wetland deposits (Qh-bo), which are made up of silts, black clays with organic matter levels, and an incipient presence of peat. All these deposits extend across the pampas of Llocajache, Palpa, Jiñata, Tican, Moro, Macho Contaduría, Velan, and Illpa. The Azángaro Formation (Qp-az) corresponds to a sedimentary fill associated with the Lake Titicaca basin, containing lacustrine, fluvial, alluvial, and colluvial sediments [16].

Volcanism of the Barroso Group (NQ-b). This occupies a large surface extension of the district, where flows of basaltic andesitic lavas and ignimbrites can be observed, expressed among the hills Ale, Jilanca, Pucara, Pilchane, Chuntacollo, Machallata, and More.

The Puno Group (P-pu) outcrops in the SW sector of the district (Bene Bene Hill) with feldspathic sandstones and polymictic conglomerates containing sub-rounded limestone clasts.

The Muñani Formation (P-m) is composed of fine to coarse-grained sandstones with intercalations of reddish-brown shales that outcrop at Coajata Hill. The Ayabacas Formation (Kis-ay), of Cretaceous age, is made up of sparitic to micritic laminar limestones intercalated with red shales and calcareous sandstones. This unit forms an iron skarn with a monzogranite at Machallata Hill. It is followed by the Huancané Formation (Ki-hn) as the basal unit, consisting of fine- to medium-grained quartz sandstones with cross and parallel stratification, whose rocks outcrop at Lechihuma Hill [16].

Dioritic intrusive (N-di). Belonging to the Cenozoic, these are differentiated by their dioritic composition, with outcrops dispersed throughout the district of Paucarcolla. They cross sedimentary rocks of the Ayabacas Formation, forming skarn (Ale Hill). Monzogranitic intrusive (N-mzgr). Located south of the district of Paucarcolla, it is in contact with andesitic lavas of the Barroso Group and the Ayabacas Formation, creating contact metamorphism halos. The mineralization in both skarn zones contains magnetite, hematite, limonite, goethite, specularite, pyrolusite, quartz, chalcedony, and disseminated phlogopite.

3.2 Geomorphology

The study area comprises high, dissected sedimentary hills of structural origin, composed of limestone and sandstone rocks, with slopes ranging from 4 to 50%, occupying 8.37% of the total district area (TDA). The southern sector contains high plutonic and volcanic hills of structural origin, moderately dissected with slopes between 8 and 50%, covering 28.78% of the TDA. The hill slopes and valley bottoms between the hills contain colluvial and alluvial sediments of Quaternary age, with a surface area of 1.05% of the TDA. The northeastern sector contains undulating high Andean plains with floodable alluvial and lacustrine deposits, with slopes ranging from 0 to 4% and covering 60.42% of the TDA [15].

The high Andean plains contain three terraces, differentiated by erosion and altitude, each with specific lithological characteristics (Figure 1). Terrace 1, located at 3824–3820 metres above sea level (m.a.s.l.) in the domains of the Totorani and Illpa rivers, presents remnants of the Azángaro Formation. Its composition includes gravels with limestone clasts, brown sands, silts, and gray clays. In the Illpa plain, the first soil layer is clayey and gray (60 cm thick), followed by a compact clayey-sandy brown layer (30 cm), with fragments of limestone and dissolved calcium carbonate. The third layer, sandy and brown (32 cm), contains limestone fragments and Fe oxides, in gradual contact with the previous layer [15].

Terrace 2, located between 3820 and 3818 m.a.s.l., comprises ancient alluvial deposits and palustrine deposits of the Azángaro Formation. It is characterized by a dark gray clay-silty soil (40 cm), followed by a grayish-brown clayey-sandy layer (60 cm) with sporadic carbonate fragments. The third layer, sandy and brown (100 cm), presents loosely compacted soil levels at depth, with fluctuations in the water table [15].

Terrace 3, located between 3818 and 3817 m.a.s.l., comprises ancient alluvial deposits with erosion processes and flood areas of Lake Titicaca and the Illpa River. In the populated center of Puquiani, a dark brown clayey to clay-silty soil (105 cm) was found, with sporadic occurrences of carbonate clasts. According to the USDA classification [17], this soil type is denominated as Mollisol; in the Illpa sector, it has been classified as Mollisol-Haplustoll of colluvial-alluvial and lacustrine origin [15].

3.3 Soil Sampling

The soils, being the result of chemical and physical weathering processes of the rock substrates, were sampled in the regolith at specific points by extracting 2–3 kg of altered material, which was then crushed to mesh 10, quartered to a weight of 250 g, and subsequently sent to the laboratory. For soils, the IUGS/IAGC methodology was applied to establish a geochemical baseline [18], under the guidance of the Forum of European Geological Surveys [19]. This methodology recommends multipurpose sampling in GTN grid cells, developed to map the Global Geochemical Baseline (GGB) by the Geological Survey of Finland (GTK) [20]. For the sampling of test pits and description of soil profiles, the established regulations [21] and the guidelines of the Ministry of the Environment [22], according to DS-002-2013-MINAM, were followed. Systematic sampling was carried out with an east–west alignment corresponding to alluvial terraces, obtaining 19 samples and 03 repetitions in test pits at depths of 2.0 m to describe the soil morphology and then identify the quality of agricultural soils at 60 cm. The organic matter horizon was removed in both types of test pits; afterward, the samples were extracted for quartering, bagging, and labeling. All sampling points were georeferenced using GPS, with UTM WGS84 coordinates (Table 1). In the test pits PGS-02, PGS-03, PGS-09, PGS-12, and PGS-15, two samples were extracted at depths of 30 cm: the upper horizon and the lower horizon.

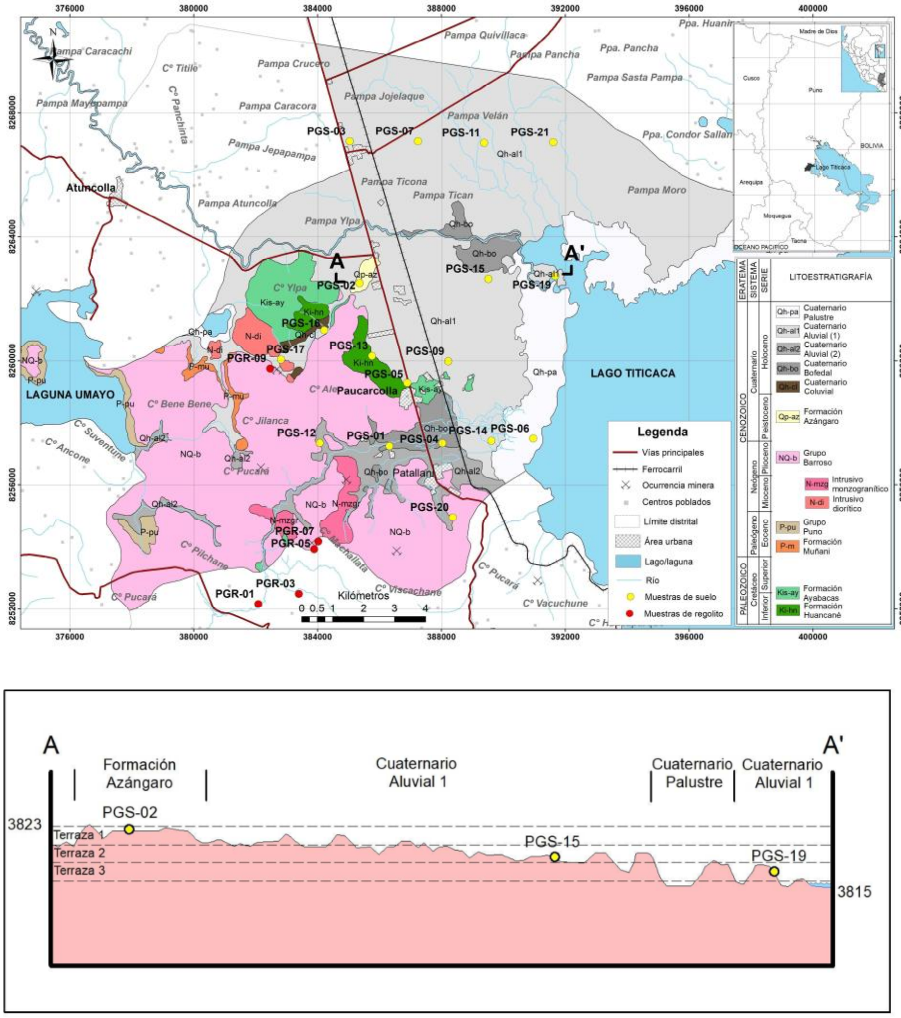

Figure 1. Geological units and geomorphological soil section A–A´. Source: Modified from Ingemmet, 2020.

Table 1. UTM coordinates of District of Paucarcolla, Puno.

Code	Location	Easting (m)	Northing
PGR-01	Maccano Chico	382092.00	8252152.00
PGR-03	Charina	383400.00	8252486.00
PGR-05	Winicunca Belen Totorani	383891.00	8253928.00
PGR-07	Winicunca Belen Totorani	384027.00	8254173.00
PGR-09	Winicunca Titile	382470.00	8259749.00
PGS–02i	Pampa Illpa	385355.00	8262505.00
PGS-02s	CE Illpa	385355.00	8262505.00
PGS–03i	Pampa Moro	384913.00	8267076.00
PGS-03s	Pampa Moro	384913.00	8267076.00
PGS–04	Pampa Pajcha	388033.00	8257340.00

PGS–05	Ampliación Paucarcolla	386895.688259294.38
PGS–06	Reserva Nac. del	390968.008257494.00
	Titicaca	387249.008267080.00
PGS–07	Pampa Moro	388223.908259983.62
PGS–09s	Pampa Llocajache	389380.008267027.00
PGS–11	Pampa Moro	384073.738257347.21
PGS–2	Pampa Lifunge	385759.308260156.92
PGS–13	Pampa Lichuma	389612.008257421.00
PGS–14	Pampa Pajcha	389520.008262637.00
PGS– 15_S	Pampa Palca	383306.008262445.68
PGS-16	Com. Alianza Chali	382822.018260041.02
PGS–17	Pampa Cupe	391676.008262734.00
PGS–19	Pampa Palca	388373.228254949.42
PGS–20	Benahuecco	391616.008267044.00
PGS-21s	Sta Barbara Moro	388223.008259983.62
PGS-09s	Pampa Llocajache	384073.738257347.21
PGS-12	Pampa Lifunge	389920.008262673.00
PGS-15s	Pampa Moro	

Source: Own elaboration

PGR=Paucarcolla Geoquímica Rocas, PGS=Paucarcolla Geoquímica Suelos

3.4 Sample Processing and Chemical Analyses

The samples extracted from the test pits were all fine fractions, dried at ambient temperature for 15 days, quartered and pulverized to mesh 10, and 500 g were sent to the Laboratorios Analíticos del Sur E.I.R. Ltda. (LAS) and Actlabs Skyline Arequipa. The geochemical analyses of trace element concentrations were determined using VH-ME-ICP2 and by ICP-OES, following USEPA method 6010D and EPA METHOD 3051-A USEPA, for microwave-assisted acid digestion of sediments, with an analytical range of -2.5 ppm (Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Mo, Ni, P, Pb, Sr, Zn). For fertility characterization and textural analysis, 1 kg of moist sample was sent to the National Institute of Agrarian Innovation (INIA) – Salcedo Puno, whose processing was carried out according to the Mexican Standard NOM-021-RECNAT-2000, in which the following physicochemical parameters were determined: pH, electrical conductivity (EC), organic matter (OM), total nitrogen (N), potassium (K), carbonates (CaCO3), equivalent phosphorus (P), exchangeable bases, cation exchange capacity (CEC), and texture analysis. For the statistical calculations, values below the detection limit were adjusted according to the method proposed by Aitchison [23], and the mean, median, minimum, maximum, geometric mean, percentiles, mean absolute deviation, 25th percentile, 75th percentile, and Threshold (LSLB) were calculated (Table 3).

3.5 Determination of the Geochemical Baseline

Baselines make it possible to define natural variations in terrestrial materials, guiding environmental policies [18]. The Geochemical Baseline (LBG), according to Salminen and Gregorauskiene [24], establishes environmental concentrations of elements, fundamental in environmental legislation for setting limits in contaminated soils and surface materials. These values, calculated using the upper limit method of the box plot [25], consider both geogenic and anthropogenic concentrations. In this work, the geometric mean plus two times the mean absolute deviation was used as the geochemical baseline for Paucarcolla. A box plot diagram [26] was also calculated, as well as the Tukey inner (upper) fence (TIF), whose calculation is TIF= Q3 + 1.5*RIQ **[27]**.

$$LSLB=LBG= P75 + 1.5x[P75 – P25]$$

Where: LSLB = Upper baseline limit, P75 is the 75th percentile of concentration X, and P25 is the 25th percentile of concentration X. Q3 = third quartile equivalent to P75, and IQR (interquartile range) is equal to P75 – P25. (Table 3).

4. RESULTS

The parent materials of the soils in Paucarcolla are Quaternary in origin, colluvial–alluvial and lacustrine, belonging to the Azángaro Formation, consisting of sub-rounded clastic fragments found at 1.5–2.0 m depth in the test pits PGS-01, PGS-12, PGS-13, and PGS-17. In the upper part, silts and clays are present, evidencing an alluvial period geochemically derived from a bedrock (regolith) originating from the volcanic rocks of the Barroso Group, sandstones of the Muñani Formation, and limestones of the Ayabacas Formation. The second stage of lagoonal transgression contributed fine sediments and organic matter, giving a dark coloration. According to USDA classification, this is denominated as Mollisol, corresponding to the description of test pit PGS-21.

4.1 Concentration of Heavy Metals in Regolith

The heavy metals considered in this study, such as As, Cr, Pb, and Zn, are included in the list of priority pollutants by USEPA 2014. Table 2 shows the high values of arsenic from colonial artisanal smelting (Maccano Chico), which are environmental liabilities from tailings discharged into the Totorani River, in the Paucarcolla sector. The regoliths show values between 24.73 and 56.38 mg/kg of As; however, in the colonial environmental liabilities, a value of 637.50 mg/kg of As was recorded. The sampling points are: PGR-01, PGR-3, PGR-5, and PGR-7 (Table 2).

Table 2. Regolith Statistics Values (mg/kg)

	As	Cr	Pb	Zn	Mn
Average	181.75	24.01	1695.75	731.64	1240.34
Median	56.38	14.33	1557.50	737.20	992.00
Mínimum	24.73	5.50	108.00	51.41	241.00
Maximum	637.50	52.21	3560.00	1546.00	2237.00
SD	245.24	17.55	1225.84	529.40	713.78

Source: Own elaboration

4.2 Heavy Metal Concentrations and Geochemical Spatial Distribution

Las The concentrations of trace elements and heavy metals are summarized in Table 3. According to the U.S. Environmental Protection Agency (USEPA) [28], As, Cr, Pb, Cu, Hg, Mn, Mo, and Zn are considered priority contaminants. In the study area, chemical concentrations were compared with the Finnish LBG Threshold values and the EU-SGV ranges through boxplot diagrams (Figure 2).

At Pampa Moro (PGS-03i, PGS-07, PGS-11, PGS-03s, PGS-21s), the highest concentrations were recorded for Zn (115.3–125 ppm), followed by As (16.5–52 ppm) and Cr (24.7–35 ppm), under neutral to alkaline pH conditions. In areas with moderately acidic soils, the concentrations observed were Zn (48.9–139 ppm), Pb (2–142 ppm), Cu (33.8–50.2 ppm), and As (3–23 ppm). Ingemmet [29] reported, at the Caracoto-Juliaca sampling site, concentrations of As (46.28 ppm), Cd (1.93 ppm), Cr (28.99 ppm), and Pb (92.61 ppm). Sample PGS-05, located in the Paucarcolla extension area, contained As (18 ppm), Cr (23 ppm), Hg (10 ppm), Cu (54.3 ppm), Pb (15 ppm), and Zn (106 ppm). This site corresponds to a depression where stormwater accumulates from the central part of Paucarcolla city, resulting in contamination due to anthropogenic activity. Arsenic concentrations were observed at PGS-03i, PGS-09, PGS-12, and PGS-15 (Table 2, Figure 2), with an average of 20.54 ppm and a threshold percentile of 94.0 ppm, corresponding to the Pampa Llocajache, Lifunge, Palca, and Moro areas (Figure 3).

Chromium contents in PGS-17 (61 ppm), PGS-13 (64 ppm), and PGS-20 (62 ppm) slightly exceeded the LBG value (57 ppm) (Table 3). Globally, the average chromium content in soils is estimated at 60 mg/kg. Copper concentrations were below the LBG but higher than the global mean (38.90 ppm) in PGS-04 (61.4 ppm) and PGS-12 (73.1 ppm), corresponding to the Pampa Pajcha and Lifunge sectors (Figure 3). Zinc concentrations were below the LBG but above the global average in PGS-03i (115.7 ppm), PGS-09s (132.79 ppm), PGS-11 (108 ppm), PGS-12 (117.1 ppm), PGS-13 (139 ppm), PGS-14 (120 ppm), and PGS15s (127.7 ppm). The global average range for Zn in soils is 30–100 mg/kg. Lead concentrations were below both the LBG and ECA-2017 standards; however, in four sites (PGS-01i, PGS-07, PGS-15s), Pb values exceeded the global average of 27 mg/kg (Figure 2).

Mercury concentrations exceeded both the LBG and global averages in PGS-03i (6 ppm), PGS-04 (5 ppm), and PGS-05 (10 ppm). The global mean Hg content in soils is 1.1 mg/kg, rarely exceeding 1 mg/kg, particularly in clay-rich soils. Urban soils are often more contaminated with Hg due to anthropogenic inputs. Manganese concentrations surpassed the global average (270–525 mg/kg) in 11 samples. The local mean in the district was 745.19 ppm, with maximum values reaching 1650 ppm. Globally, Mn concentrations in soils vary between 10 and 9000 mg/kg, with higher values typically found in clayey and calcareous soils [30].

Table 3. Geochemical Parameters, of Soil Samples

Element	Min	Perc25	MED-GEO	Perc75	Max	MAD	MED-GEO + 2MAD	TIF o LBG	ECA-2017 (mg/kg)	ProMund (mg/kg)	Thershold Finlandes	LSLB Jarva et al, 2010	Rang UE-SGV
Al-%	0.57	1.06	1.46	1.87	3.46	0.55	2.57	3.09					
As-ppm	1.59	16.50	20.54	47.50	79.00	19.04	58.61	94.00	50.00	6.83	5.0	15.00	10-200
Ba-ppm	41.20	189.00	226.60	336.00	395.00	76.68	381.97	556.50					100–600
Ca-%	0.20	0.64	1.33	2.89	5.10	1.24	3.81	6.27					
Cd-ppm	0.99	0.99	1.03	0.99	1.19	0.07	1.17	0.99	1.40	0.41	1.0	0.36	0.5-20
Co-ppm	0.99	3.00	7.49	17.25	26.00	6.47	20.44	38.63		59.50	100.0	72.00	30-1000
Cr-ppm	1.09	19.25	21.61	34.25	64.00	13.44	48.49	57.13		59.50	100.0	72.00	30-1000
Cu-ppm	1.29	31.70	33.40	51.05	73.10	12.06	57.53	80.08		38.90	100.0	47.00	40-1000
Fe-%	1.11	1.65	2.25	2.90	4.24	0.61	3.48	4.78					
Hg-ppm	0.99	0.99	1.44	2.25	10.00	1.48	4.41	4.14	6.60	0.07	0.5	0.11	0.5-80
Mg-%	0.05	0.14	0.35	0.78	1.20	0.28	1.07	1.69					
Mn-ppm	163.0	497.00	732.18	1260.75	1650.00	343.30	1418.77	2406.38		437.00			1500
Mo-ppm	0.09	0.99	1.27	2.25	8.00	1.21	3.70	4.14		1.10			2.5-60
Ni-ppm	1.00	6.00	11.06	28.50	45.00	11.03	33.13	62.25		29.00	50.0	34.00	30-300
P-%	0.01	0.05	0.07	0.10	0.92	0.08	0.24	0.19					
Pb-ppm	0.10	1.99	7.20	18.03	53.00	10.56	28.31	42.08	70.00	27.00	60.0	37.00	40.750
Sr-ppm	0.00	0.00	2.36	197.30	316.00	94.42	191.20	493.25					
Zn-ppm	16.00	69.70	81.42	117.83	139.70	26.20	133.81	190.01		70.00	200.0	163.0	60-2500

Source: Own elaboration

Legend: MG = geometric mean, MAD = mean absolute deviation, Vmin = minimum value; Vmax = maximum value; Perc25 = 25th percentile; Perc75 = 75th percentile; ProMund = World Average = World average soil values [31]; and Finnish Threshold for potentially harmful elements (Decree 214/2007), as well as the upper baseline limit (LSLB = ULBL) (Jarva et al., 2010) for urban soil samples (0–10 cm) from Tampere, Finland, and for agricultural soil samples (0–20 cm) and subsoil (50 cm depth).
MG + 2MAD = Threshold or upper limit for soils in Paucarcolla, which are above the world average for As, Hg, Mn, and Zn; below the Peruvian ECA-2017 standard for As, Cd, Hg, and Pb.
TIF = Tukey Inner (Upper) Fence, Geochemical Baseline (LBG) = P75 + 1.5 × (P75 – P25). RANGE-UE-SGV = Range European Soil Guideline Value [27].
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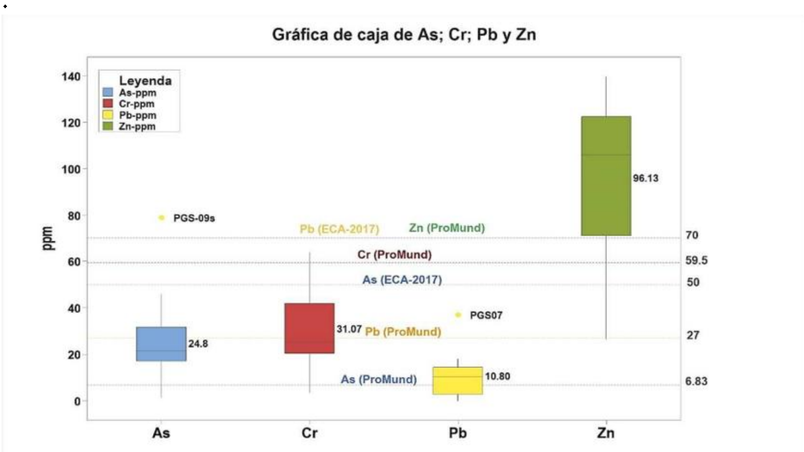

Figure 2. Box Plot diagram of As, Cr, Pb and Zn Source: Research Team

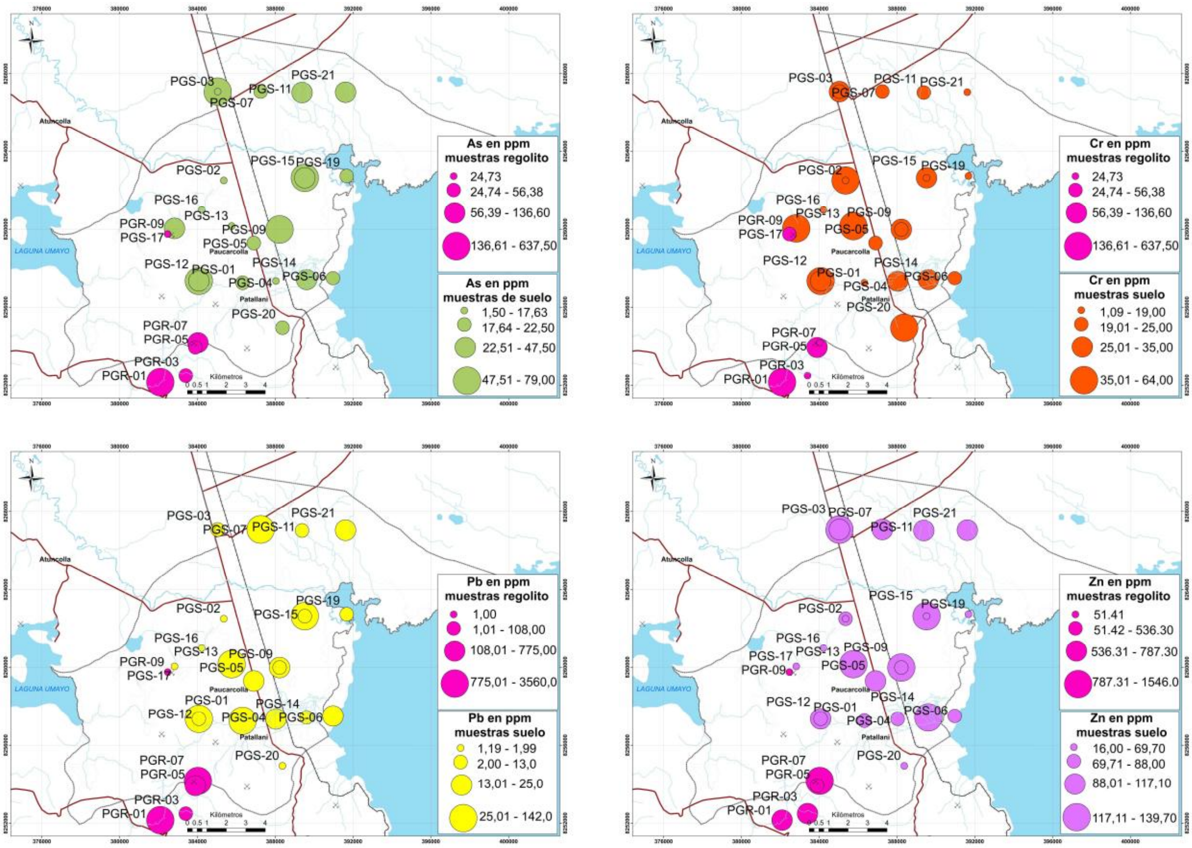

Figure 3. Geochemical concentration map of As, Cr, Pb and Zn Source: Research Team

4.3 Physicochemical, textural, and Fertility Characterization of Soils

The physicochemical characteristics of the soil influence the processes that affect the distribution and abundance of flora and fauna. The textural analysis revealed a composition of 32.2% sand, 41.7% clay, and 26.1% silt, classifying the soil as clay loam (Table 4). The chemical analyses showed an average pH of 7.2, indicating a neutral soil. The fertility table shows organic matter (OM) levels ranging from 0.09% to 4.60%. The sampling points PGS-06s and PGS-13 present high levels (4.6% and 3.2%), within the medium to high classification [32], which leads to the accumulation of organic matter in the upper horizon, giving it a dark color (mollisol).

The nitrogen content is low (<0.2%), while phosphorus shows a high value (>11 mg/kg). The availability of potassium is 548 ppm, considered medium to high. In addition, calcium content ranges from medium to high, reaching 5 to 14.8% (Table 4).

Table 4. Soil fertility and Textural Analysis

I.D	Fertility analysis							Textural Analysis			
	pH	EC (mS/m)	OM (%)	N_2 (%)	P (mg/Kg)	K Disp(ppm)	Carb equiv(%)	Sand (%)	Clay (%)	Silt (%)	Textural class
Average	7.2	40.1	1.6	0.1	40.0	548.6	5.0	32.2	26.1	41.7	
Median	7.3	5.6	1.7	0.1	22.5	360.0	3.7	30.0	26.9	41.8	Medium
Mínimum	4.7	2.3	0.1	0.0	0.7	64.0	0.4	15.3	2.9	21.8	Silty clay
Maximum	8.6	287.0	4.6	0.2	274.8	1730.4	14.8	60.0	50.9	75.1	Clay loam
SD		79.9	1.2	0.1	62.6	421.1	4.3	13.3	13.7	11.4	

Source: Own elaboration

4.4 Aspects of Land Use Planning in the District of Paucarcolla

The Quaternary deposits, which represent 63% of the district's territory, cover 128.46 km². Soils suitable for pastures of low agrological quality cover 52.56 km², equivalent to 25.85% of the territory. These soils, affected by floods of the Illpa River during extraordinary rains, present average contents of As, Cr, Cu, Hg, Mn, Mo, Pb, and Zn of 31.60 ppm; 19.82 ppm; 40.43 ppm; 1.67 ppm; 1021.50 ppm; 1.40 ppm;

15.68 ppm; and 89.02 ppm, respectively (PGS–06, PGS–15s, PGS–04, PGS–14, PGS–19, PGS–11, PGS-21s).

Soils suitable for pastures of low agrological quality, affected by soil and salts, cover 46.64 km², representing 22.94% of the district's territory. These soils are prone to transient crops and are affected by exceptional rises in lake levels and the disorganized growth of small population centers, linked to the Puno–Juliaca dual carriageway. The average contents of As, Cr, Cu, Hg, Mn, Mo, Pb, and Zn are 21.22 ppm; 26.06 ppm; 32.87 ppm; 1.60 ppm; 814 ppm; 2.15 ppm; 9.73 ppm; and 90.84 ppm, respectively (PGS-02i, PGS-03i, PGS–07, PGS-02s, PGS-03).

Lands suitable for pastures of low agrological quality, affected by soil and erosion, cover approximately 45.19 km², representing 22.23% of the territory. These soils are found on hillsides, where dense ichu grasslands predominate, and are poorly developed due to the type of lithological substrate. The average contents of As, Cr, Cu, Hg, Mn, Mo, Pb, and Zn are 13.83 ppm; 49.67 ppm; 48.63 ppm; 3.99 ppm; 1099.67 ppm; 4.0 ppm; 5.66 ppm; and 105.23 ppm, respectively (PGS-05, PGS–13, PGS–20).

Soils suitable for clean crops of low agrological quality, affected by soil and climate, cover 7.32 km², representing 3.60% of the district's territory. Currently, these soils are used for transient crops and are found in grasslands, peat bogs, wetlands, and naturally eroded bare lands. The average concentrations of As, Cr, Cu, Hg, Mn, Mo, Pb, and Zn are 50.88 ppm; 35.42 ppm; 48.55 ppm; 3 ppm; 779.67 ppm; 1.23 ppm; 23.57 ppm; and 90.45 ppm, respectively (PGS–09s, PGS-01i, PGS-09s, PGS-12, PGS–17).

Lands suitable for crops and pastures of low agrological quality, limited by soil, drainage, and climate, occupy approximately 2.35 km², representing 1.16% of the district's territory. They are mainly found in grasslands and are restricted to floodplain valley bottoms, near iron mining areas. The concentrations of As, Cr, Cu, Mn, Mo, Pb, and Zn are 1.59 ppm, 1.09 ppm, 1.29 ppm, 163 ppm, 1.39 ppm, 1.9 ppm, and 16 ppm (PGS16) (Figure 4).

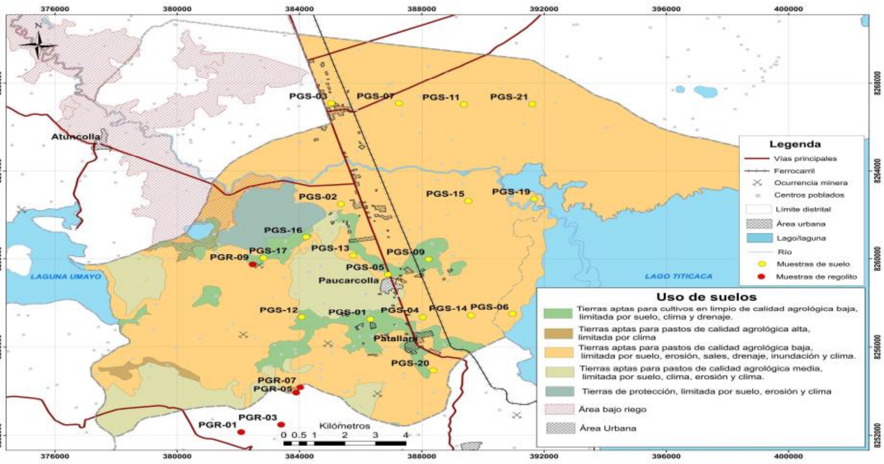

Figure 4. Land use in the District of Paucarcolla Source: Modified from ZEE-OT, GR Puno

4.5 Geochemical Baseline of Paucarcolla

The descriptive statistics of the samples from Paucarcolla are summarized in Tables 2 and 3. Table 3 presents

LBG values calculated for the same lithogeochemistry and sampling depths; the agricultural soils were Quaternary (Molisol-Qa) of medium texture. In the study area, the chemical concentrations were compared with the Finnish LBG Threshold values and the European Union range (UE-SGV) using box plot diagrams

(Fig. 2).

5. DISCUSSION

Los The global average soil values [31], Finnish threshold values, and agricultural soils of the European Union are presented as reference values in Table 3. According to the results, the upper limit of basal variation calculated for the Quaternary lithologies (Qa) of Paucarcolla for As, Cr, Pb, and Zn. As is above the value of the Peruvian standard ECA-2017, world average, Finnish threshold, but still below the European Union standards. For chromium and lead it is below the reference values, Zn is above the world average, but below the Finnish and European Union thresholds.

The average geochemical background of arsenic should not exceed 15 mg/kg, although in the study area it averages 20.54 mg/kg, within the Peruvian limit of 50 mg/kg (ECA-2017), although there are higher values at points PGS-12 and PGS-15s (Figure 2), like those obtained by INIA, reaching 74.3 mg/kg (Table 3 and Figure 2). This high content could be related to the polymetallic mineralization of Cerro Antoñiani and the monzogranite intrusives. Without adequate monitoring, arsenic dissolved in minerals and rocks can accumulate and magnify in groundwater through irrigation [33].

The average chromium content in soils worldwide ranges between 20 and 80 mg/kg, being lower in sandy soils and higher in clay loam and organic soils [30]. In the study area, the average Cr content is 21.61 mg/kg, but well below the EU-SGV range of 30–1000 mg/kg for Cr (III) compared [27], (Table 3), below the world average. However, samples analyzed by INIA showed 26 mg/kg, exceeding the standard of 0.4 mg/kg for Cr (VI) (ECA-2017). The average global zinc content in soils varies from 10 to 100 mg/kg, and high concentrations (>1000 mg/kg) have been detected near smelters, mining areas, and galvanized structures. Its presence is closely related to soil texture and can be high in calcareous and organic soils [32].

In the study area, zinc concentrations range between 16 and 139 mg/kg, exceeding the world average of 70 mg/kg, but within the EU-SGV range of 60–250 mg/kg (Table 3 and Figure 2). The deficiency is related to the physical development of the population; therefore, it is necessary to raise awareness among authorities and environmental planners to determine habitable places and suitable cultivation areas that unfortunately are being occupied by housing constructions along the main Puno-Juliaca Road.

The average global lead content in soils is 27 mg/kg. During weathering, lead sulfides oxidize slowly and are retained in the soil by clay minerals, hydroxides, and soluble organic matter, with a retention capacity that increases with pH. The Pb2+ ion shares geochemical characteristics with divalent elements of the alkaline earth group, such as K, Ba, Ca, and Sr, allowing it to substitute them in minerals and adsorption sites.

Lead in soils represents a public health risk, especially for children. A level of 600 ppm of lead in soil is considered "safe," which would not exceed 5 μg/d of blood exposure in children under 12 years. According to Supreme Decree No. 011-2017-MINAM [34], the permissible limit for agricultural soils is 70 mg/kg. In the studied area, lead levels reach up to 53 mg/kg, remaining within acceptable ranges and complying with European standards (40–750 mg/kg).

6. CONCLUSION

- This study sought to geochemically characterize the agricultural soils in the district of Paucarcolla, Puno, and to establish a baseline of trace elements and heavy metals for territorial planning. Despite the absence of active metallic mining, elevated concentrations of As, Cr, Pb, Cu, Mn, Mo, and Zn were found above world averages and international standards, although within Peruvian regulations. These come from local geogenic sources such as the mineral deposits of the Antoñiani, Cupe, and Maccano Chico hills. The mapping identified areas of cultivable soils, pastures, wastelands, and urban expansion over agricultural land, showing the need to implement territorial planning policies in view of the disorderly urban growth that sacrifices lands with agricultural potential. The geochemical baseline obtained is fundamental to plan the sustainable use of the territory in Paucarcolla located in the Andean region of Puno, Peru.
- The concentrations of heavy metals As, Cr, Pb, Cu, Mn, Mo, and Zn in the agricultural soils studied, although they comply with Peruvian regulations, exceed the stricter international standards and world averages. Therefore, it is recommended to adopt a preventive and precautionary approach, gradually approaching the international limits to protect public health and the environment in the long term. The Peruvian authorities should consider updating environmental regulations based on short physical stature, mental development, and public health. At the same time, geochemically suitable lands for agriculture must be identified and effective territorial planning policies established to control the disorderly urban expansion over lands with agricultural potential such as that identified between the railway line and the Puno–Juliaca highway. This geochemical baseline will allow planning and sustainable use of the territory in the Andean region.

Acknowledgement

The research was funded by the Special Fund for University Development (FEDU) of the Vice-Rectorate for Research at the National University of the Altiplano Puno, under funding contract No. 0109-2023-VRIUNA-Puno.

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