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Geomorphological Overview of the Lowell Mining Concessions, Ecuador

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Abstract
This study focuses on determining the geomorphological characteristics of the area within and around the Lowell mining concessions located in the Morona Santiago province, Amazon region of Ecuador, to determine potential use of land applications and territorial planning for local communities in the future.
We outlined the geomorphology units proposed by the SIGTIERRAS project for the Limon Indanza and San Juan Bosco cantons. In total, 31 geoforms were briefly described in order by major to minor surface in the study area on each of the five geomorphological groups based on genesis: slope, tectonic-erosive, fluvial, structural, and polygenic. Then, slope and basin analysis were carried out mainly from digital elevation models (DEM) using QGIS free software. It was identified the Lowell mining concessions lay within two micro basins at official level 5 by Pfafstetter coding system for hydrographic units in Ecuador: basin 49981 for the Santiago River and 49983 for Zamora River, so they were characterized. As a result, multiple morphometric parameters on linear (e.g., stream order), aerial (e.g., circulatory ratio), and relief aspects were obtained for each one. Among other findings, both micro basins are order 4th according with Strahler, elongated form and apparently less susceptible to flooding suggested by values of circulatory ratio (0.36 and 0.52). Moreover, hypsometric curves of the Santiago River (49981) and Zamora River (49983) indicate the two rivers are in a mature to old stage.
In addition, we tested multispectral satellite image analysis, processing two free ASTER L1T images. Several RGB band combinations for clay and iron oxide minerals mapping are presented. However, no significant zone was detected at the study area due to vegetation. Therefore, we propose to use more advanced techniques (e.g., airborne magnetics). Finally, the new insights presented in this study could help to increase the knowledge of the geomorphological characteristics of the zone and hopefully delineate new studies on the region.

Keywords: *geomorphological, mining concessions, ecuador.*

INTRODUCTION

The LOWELL mining company, owned by the Canadian Solaris Resources Inc. company, holds 8 concessions (Caya 21, Caya 22, Clemente, Curigem 9, Maiki 01, Maiki 02, Maiki 03, Maiki 04) for the Warintza Project located at the southern of Ecuador in the Morona Santiago province, specifically at the Limon Indanza and San Juan Bosco cantons (Figure 1).

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Geologically, the study area is part of the sub-Andean tectonic zone that is composed of Triassic to Cretaceous sedimentary and igneous rocks (INIGEMM, 2017). Limited to the west with the Real Cordillera that is formed by Paleozoic to Cretaceous metamorphic rocks (Litherland et al., 1994). The Warintza project is characterized by a series of plutonic and porphyritic intrusions of intermediate composition (quartz-monzonite to granodiorite and diorite) emplaced after the Jurassic Zamora batholith and the volcanic and sedimentary rocks of the Misahualli unit and Chapiza formation with a mineral resource estimation on indicated category of 579 Mt at 0.3% CuEq cut-off grade (Solaris Resources, 2022).

In 2011, Ecuador achieved a loan from the Inter-American Development Bank (IDB) to generate information for land-use and urban planning on all the country. This project, managed by the Ministry of Agriculture, Livestock Aquaculture and Fisheries (MAGAP), was called SIGTIERRAS and, among other products, generated orthophotography, digital elevation models (DEMs), geomorphology, etc. on 58 cantons of Ecuador at a semi-detailed 1:25.000 scale. Thus, the geomorphological maps and reports of the Limon Indanza and San Juan Bosco cantons published by that project (SIGTIERRAS, 2015) were employed for this summary.

A geomorphological characterization of a specific region allows to stablish the natural potential and problems of the terrain, based on their physical properties, in order to determine the strategies for an appropriate land use planning (Gaspari et al., 2013). Therefore, this study aims to provide an overview of the geomorphological features of the zones within and around the Lowell mining concessions at the Morona Santiago province in Ecuador to understand the potential use of land for the development of local communities on that area such as Warintza y Yawi by means of analyzing digital data (e.g., DEMs) that may help on urban planning in the future.

MATERIAL AND METHODS

Data used in the present study was provided by the SIGTIERRAS project, and the methodology employed by them was as follows: literature review, data collection, photointerpretation, field verification and validation, final map and report elaboration. The identified geoforms were classified by genetic groups and subgroups.

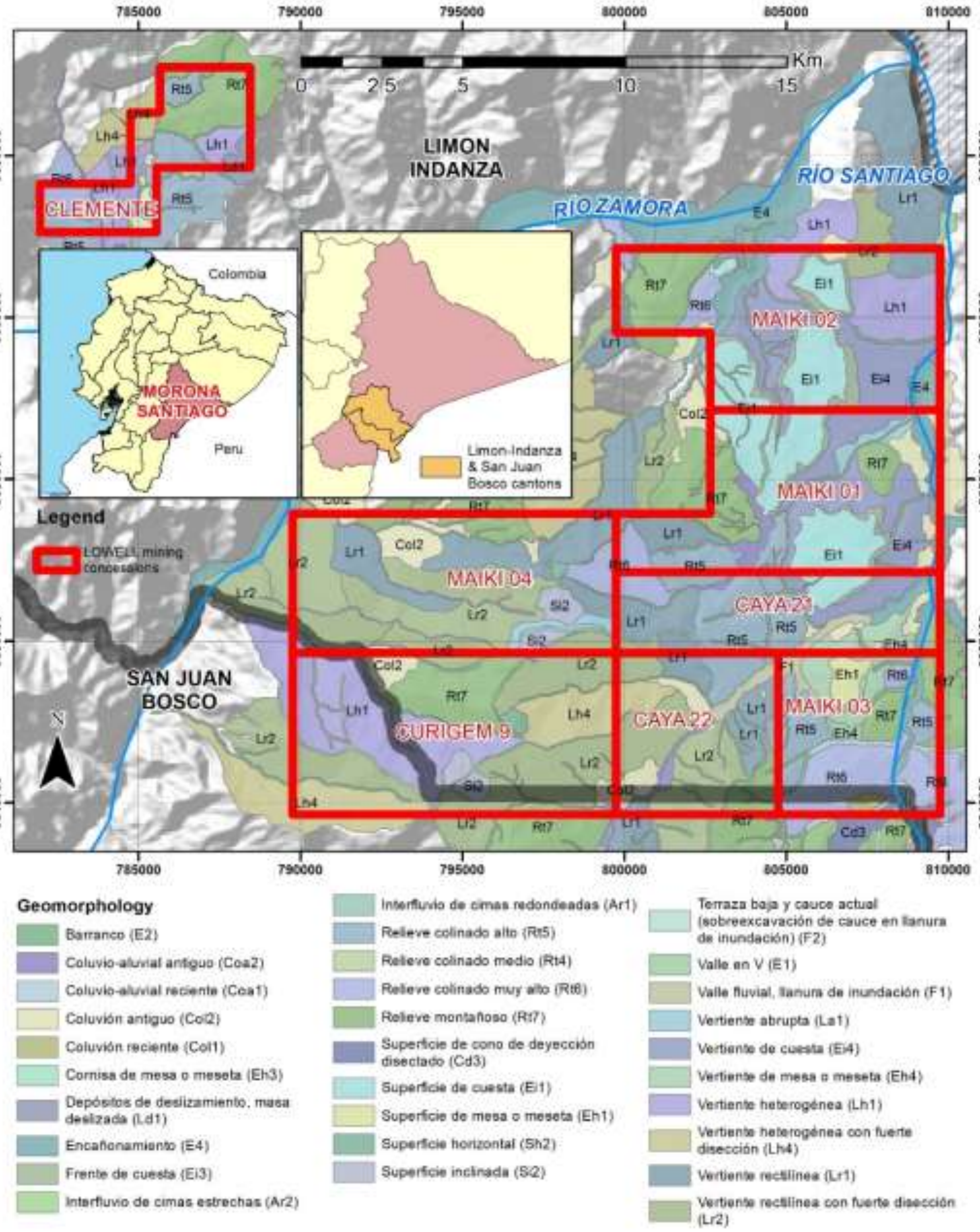
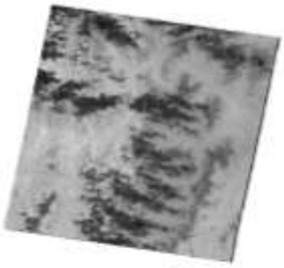
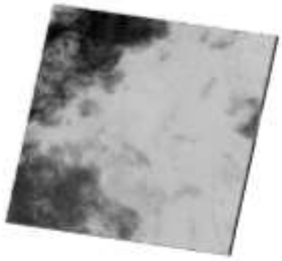


Figure 1 Simple geomorphological and location maps of the study area. Modified from SIGTIERRAS (2015).

Digital elevation models (DEM) of 5x5 meter resolution were utilized to build a slope map in raster format using QGIS free software. The classification of ranges and limits was set in accordance with the proposal of Van Zuidam (1986) based on the conditions of land. Additionally, basic morphometric parameters of subbasins were calculated from geographic information systems (GIS). The analysis of subbasins was performed employing the official delimitation of hydrographic units in Ecuador, level 5 by Pfafstetter coding system (SENAGUA, 2009). Most of the quantitative physical and geomorphologic characteristics associated with watersheds were calculated using the common equations for a basic analysis (Horton, 1945; Schumm, 1956; Strahler, 1964; etc.) described by Ikbal et al. (2017).

Table 1 ASTER satellite imagery specifications.

Sensor	ASTER		ASTER	
Satellite	TERRA		TERRA	
acquisition date	March 3rd 2023		March 3rd 2023	
Source	Earth Explorer		Earth Explorer	
ID	AST_L1T_00303272008154411_20150523124320_38821.hdf		AST_L1T_00311182003153907_20150502020111_111930.hdf	
Bands	Spectral range (µm)	Spatial resolution (m)	Spectral range (µm)	Spatial resolution (m)
Band 1	0,56 – 0,66	15	0,56 – 0,66	15
Band 2	0,66 – 0,81	15	0,66 – 0,81	15
Band 3	0,81 – 1,65	15	0,81 – 1,65	15
Band 4	1,65 – 2,165	30	1,65 – 2,165	30
Band 5	2,165–2,205	30	2,165–2,205	30
Band 6	2,205- 2,26	30	2,205- 2,26	30
Band 7	2,26 – 2,33	30	2,26 – 2,33	30
Band 8	2,33 – 2,395	30	2,33 – 2,395	30
Band 9	2,395 – 8,3	30	2,395 – 8,3	30
Band 10	8,3 – 8,65	90	8,3 – 8,65	90
Band 11	8,65 – 9,1	90	8,65 – 9,1	90
Band 12	9,1 – 10,6	90	9,1 – 10,6	90
Band 13	10,6-11,3	90	10,6-11,3	90
Band 14	11,3	90	11,3	90

Several techniques were performed for satellite image analysis such as atmospheric corrections, band rationing and combinations, NDVI spectral indices, among other; using QGIS and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite data downloaded from the USGS earth explorer website. Specifically, two free ASTER L1T (raw data) images were acquired on March 3rd of 2023, which cover around 80% of the Lowell mining concessions set with fourteen bands (Table 1). Initially, layer stacking and atmospheric correction was carried out to the images, then diverse band combinations were applied to every rectified image.

GEOMORPHOLOGY OUTLINE

According to SIGTIERRAS (2015), the Lowell mining concessions cover 30 geoforms listed by major to minor surface in the study area (Table 2) described below in their respective (one of the five) geomorphological groups: slope, tectonic-erosive, fluvial, structural, and polygenic. The Relieve montañoso (Rt7) is the geoform with more extension (77.96 km2) intercepting the Lowell mining concessions (Figure 2A). It shows differences in elevations higher than 300 meters and slopes ranging from 25%-100%. This geoform is related to the Cordillera del Cutucú and the eastern flank of the Cordillera Real. It includes the Santiago, Chapiza, Hollin and Napo geological formations (INIGEMM, 2017).

Within the same group, Tectonic-erosive, it can be found three additional geoforms. The Relieve colinado alto (Rt5) has a level offset between 100 and 200 meters and moderate to very steep slopes (12%-70%). The top of this topographical relief is preferably rounded or sharp, and rarely planar. The Relieve colinado muy alto (Rt6) is associated with four morphological contexts: sharp reliefs on metamorphic rocks (Cordillera Real), reliefs on calcareous rocks and sandstone (Cordillera del Cutucú), hilly reliefs on granitic rocks and structural shapes on sandstone (Cordillera del Condor), and marginal depressions with low slopes. Lastly, the Relieve colinado medio (Rt4) is less frequent and has variation in elevations between 50 and 100 meters with moderated to long (50 to 250 meters) distance from the top to the foot.

The Vertiente rectilínea con fuerte disección (Lr2) covers 70.19 km2 and is part of the Slope predominant geomorphological group in the study area. This geoform shows a clear straight longitudinal profile and intense dissection, keeping uniformity among them (Figure 2B). It has moderate to very steep slopes (25%-70%) and difference in elevations between 100 and 300 meters. Other seven geoforms can be identified at the slope group. The Vertiente rectilínea (Lr1), similar to the last one (Lr2), has moderate to very steep slopes (25%-70%), but with 50 and more than 300 meters at level difference and long to very long (250 to 500 meters) length oscillation mainly in the Cordillera del Cutucú.

Table 2 List of geoforms intercepting Lowell mining concessions according with SIGTIERRAS (2015).

Group	**Geoforms**	**Count**	**Total area (km^2)**
Tectonic-erosive	Relieve montañoso (Rt7)	11	77.69
Slope	Vertiente rectilínea con fuerte disección (Lr2)	12	70.19
Fluvial	Encañonamiento (E4)	3	40.48
Slope	Vertiente rectilínea (Lr1)	11	38.55
Tectonic-erosive	Relieve colinado alto (Rt5)	10	30.25
Slope	Vertiente heterogénea (Lh1)	6	29.89
Tectonic-erosive	Relieve colinado muy alto (Rt6)	7	27.16
Slope	Vertiente heterogénea con fuerte disección (Lh4)	5	26.52
Structural	Superficie de cuesta (Ei1)	5	21.09
Structural	Vertiente de cuesta (Ei4)	3	20.95
Slope	Coluvión antiguo (Col2)	25	20.10
Fluvial	Barranco (E2)	51	14.56
Structural	Vertiente de mesa o meseta (Eh4)	2	5.62
Fluvial	Valle en V (E1)	5	4.97
Structural	Frente de cuesta (Ei3)	5	4.54
Polygenic	Coluvio-aluvial antiguo (Coa2)	5	4.01
Polygenic	Superficie inclinada (Si2)	4	3.32
Polygenic	Interfluvio de cimas estrechas (Ar2)	2	3.02

Polygenic	Interfluvio de cimas redondeadas (Ar1)	8	2.77
Fluvial	Valle fluvial, llanura de inundación (F1)	1	2.70
Slope	Vertiente abrupta (La1)	4	2.50
Fluvial	Superficie de cono de deyección disectado (Cd3)	2	2.09
Structural	Superficie de mesa o meseta (Eh1)	1	1.53
Polygenic	Coluvio-aluvial reciente (Coa1)	3	1.38
Polygenic	Superficie horizontal (Sh2)	3	1.19
Slope	Depósitos de deslizamiento, masa deslizada (Ld1)	1	1.06
Slope	Coluvión reciente (Col1)	1	0.54
Structural	Cornisa de mesa o meseta (Eh3)	1	0.21
Tectonic-erosive	Relieve colinado medio (Rt4)	1	0.19
Fluvial	Terraza baja y cauce actual (sobreexcavación de cauce en llanura de inundación) (F2)	1	0.16

Likewise, the Vertiente heterogénea (Lh1) is majorly distributed at the Cordillera del Cutucú and at marginal depressions (e.g., Limón-Gualaquiza). The longitudinal profile is mixed or irregular, and the elevations are diverse. The Vertiente heterogénea con fuerte disección (Lh4) is mainly characterized by very steep slopes (40%-70%). The Vertiente abrupta (La1) shows extremely steep slopes with more than 70% at the Cordillera del Cutucú and partially the easter flank of the Cordillera Real. The Coluvión antiguo (Col2) is variated in morphology as it presents straight, concave, convex, mixed, and irregular profile, and slope varies from gentle to steep (5%-70%). On the other hand, the Coluvión reciente (Col1) is located at the low at medium hillside because the moderate to steep (12%-70%) slope helps the fine sediment and heterogeneous rock fragments accumulation. To differentiate this geoform (Col1) from the early one described (Col2), compaction may be used since the older sediments have a higher cementation grade than the recent ones. The Depósitos de deslizamiento, masa deslizada (Ld1) are rock mass and soil produced by gravity instability situated at the foot of the landslides. This geoform is hardly observed at usual marginal depressions with moderate to steep slopes (12%-70%).

The Encañonamiento (E4) is the third major geoform in extension at the study area and corresponds to the Fluvial geomorphological group. This geoform occurs in the Amazon alluvial zone. Specifically, along major sections of the Yungantza, Namangoza, Santiago and Zamora rivers. It is originated by fluvial erosion with difference in elevations between 50 and higher of 300 meters, and typically lengths major of 500 meters with extremely steep slopes (> 70%). It is distinguishing the V shaped morphology in the valleys (Figure 2C). Five extra geoforms (E2, E1, F1, F2, Cd3) are also part of the fluvial group.

The Barranco (E2) is the more repetitive geoform as it occurs 51 times in the study area. However, it is limited in extension mainly to the upper course of the rivers. Generally, it presents very steep slopes (40%-70%) and even higher sometimes, thus soil occurrence within this geoform is rare (Figure 2D). The Valle en V (E1) is defined by a V shaped transversal profile, normally with hectometric scale in width and kilometric order in length. The Valle fluvial, llanura de inundación (F1) is associated with the Indanza, Yungantza and Warintza rivers. It contains alluvial deposits transported by channels with diverse grain-size distribution and facies variation in vertical and lateral scales. It has mostly gentle slope (2%-12%) that are totally or partial flooded in rainy seasons. The Terraza baja y cauce actual (sobreexcavación de cauce en llanura de inundación) (F2) appears at the confluence of the Zamora and Santiago rivers. This geoform is identified by forming isolated gravel islands, and commonly the drainage is coarse with dendritic forms. The Superficie de cono de deyección disectado (Cd3) is originated because of the superficial runoff erosion, and it is composed of silt, clays, sand, and gravel in variated proportion.

The Superficie de cuesta (Ei1) and the Vertiente de cuesta (Ei4) are part of the Structural geomorphological group with four more geoforms at the study area. The first one (Ei1) follows a structural belt in the context of the Cordillera del Condor with hilly reliefs over granites and sandstones. The surfaces are gently tilted at the same dip direction of the sedimentary layers. The second geoform (Ei4) connects the early one (Ei1) with another geoform (Ei3). It presents very steep slopes (40%-70%) with difference in elevations between 25 and higher of 300 meters. The Vertiente de mesa o meseta (Eh4) is like the last one, but it is located at the base of ledges (Eh3) in the Cordillera del Cutucú (associated with the Hollin formation) and the Cordillera del Condor (related to the Santiago formation).

The Frente de cuesta (Ei3) is the frontal, abrupt limit between the geoforms described before (Ei1 and Ei4). The length is moderated (50 to 250 meters) with extremely steep slopes (> 70%). The Cornisa de mesa o meseta (Eh3) is developed in the Cordillera del Cutucú and the Cordillera del Condor. It also has very steep slopes with elevation difference between 100 and 200 meters in the north and between 25 and 100 meters in the south. The Superficie de mesa o meseta (Eh1) is exclusive in the context of the Cordillera del Cutucú, specifically at the southeast of the Warintza sector. It shows gentle slopes (5%-12%) over limestones from the Santiago formation.

Figure 2 Main geoforms at the study area. A. Relieve montañoso (Rt7). B. Vertiente rectilínea con fuerte disección (Lr2). C. Encañonamiento (E4). D. Barranco (E2). Modified from SIGTIERRAS (2015).

Finally, the Coluvio-aluvial antiguo (Coa2) with five further geoforms comprises the Polygenic group that is the least representative geomorphology within the study area. This geoform has moderate to steep slopes (12%-70%) and presents vegetation coverage. Contrary, the Coluvio-aluvial reciente (Coa1) contains silt, clay, sand and gravel from the slope and fluvial dynamic, filling the bottom of small drainages. The Superficie inclinada

(Si2) differentiates from the Superficie horizontal (Sh2) due to the slopes higher of 5% while the second one (Sh2) has very gentle slopes (2%-5%). The Interfluvio de cimas estrechas (Ar2) shows steep to very steep slopes (25%-100%) and is distinct from the Interfluvio de cimas redondeadas (Ar1) by lithology. In general, the first geoform (Ar2) is related to concave slopes, meanwhile the second one (Ar1) is associated with convex slopes.

GEOGRAPHIC INFORMATION SYSTEM (GIS) ANALYSIS

The slope analysis map of the study area (Figure 3) shows a predominant steep slope classification with 30%-70%. It covers 214.07 km2 and represents about 55% of the surface intercepting the Lowell mining concessions (Table 3). Then, the very steep and moderate steep categories correspond to the 21% (83.20 km2) and 17% (65.25 km2) respectively. On the other hand, the sloping, gently sloping, and flat or almost flat slope ranges sums up about 6% of total area of the map. Finally, only 2.51 km2 that equivales to 1% occurs with extremely steep slopes (>140%). It coincides with the description of the geoforms identified by SIGTIERRAS (2015).

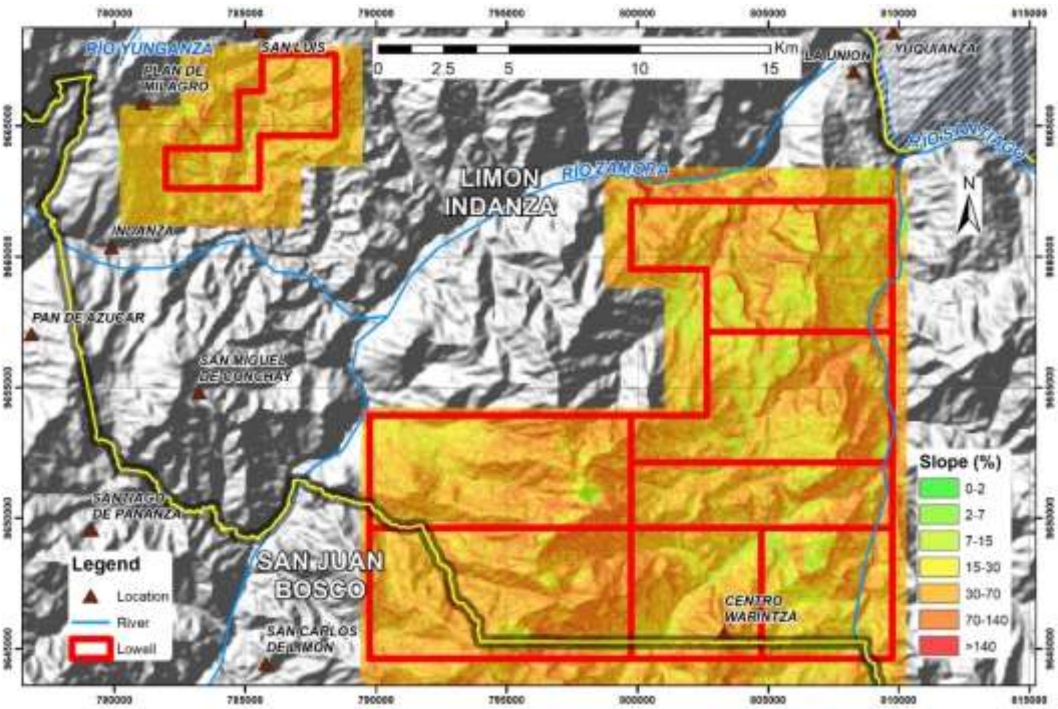


Figure 3 Slope map of the study area.

Furthermore, the morphometric parameters of the two micro basins, 49981 and 49983, at level 5 by Pfafstetter coding system at the study area were evaluated and calculated using GIS, obtaining the following results (Table 4). Both basins belong to the Rio Santiago hydrographic system of Ecuador that drains to the Atlantic Ocean. Some elementary basin parameters as the area indicates these basins may be classified as medium between 250 and 2500 km2 (49983) and large > 2500 km2 (49981) watersheds (Figure 4), therefore land and channel phases are respectively dominant in storage. Another watershed physical and geomorphologic characteristic as the perimeter shows obvious difference which is normal since the basin 49981 is larger than the basin 49983.

Table 3 Slope classification according to Van Zuidam (1986) and spatial analysis at the study area.

Slope (%)	Classification	Area (km^2)
0-2	Flat or almost flat	0.81
2-7	Gently sloping	5.39
7-15	Sloping	19.26
15-30	Moderate steep	65.25
30-70	Steep	214.07
70-140	Very steep	83.20
>140	Extremely steep	2.51

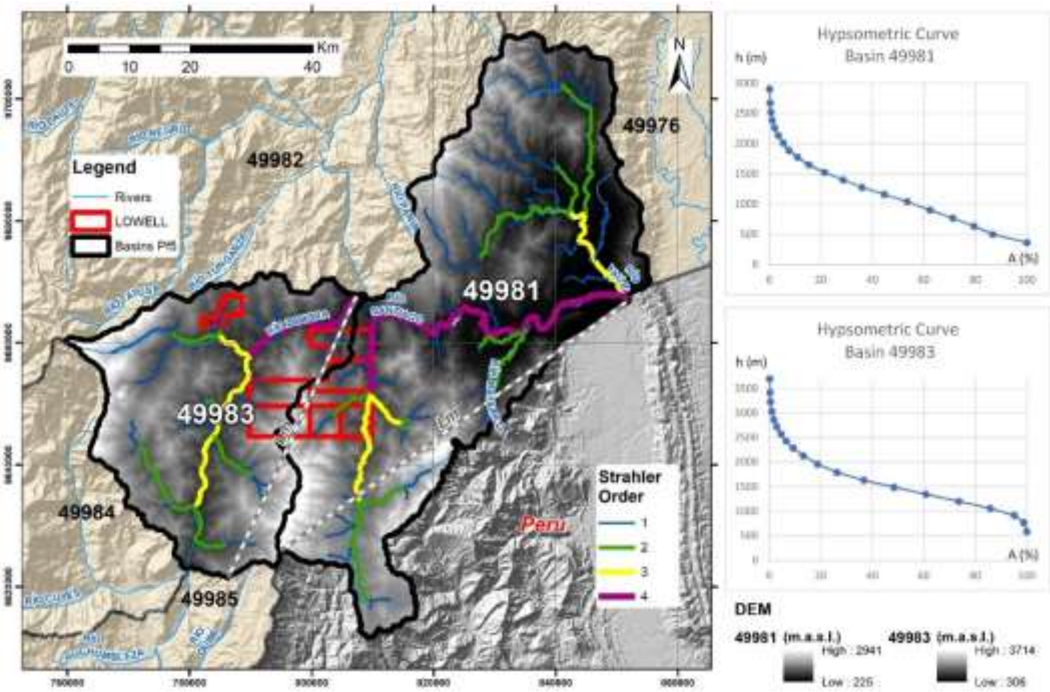


Figure 4 Strahler stream order and hypsometric curves of the study area.

The Basin Length was obtained by three approaches. First, the measured Length (Lm) was determined using the greatest distance between the outlet and any point on the perimeter as it is shown in the map (Figure 4). Then, the Length (Lb) was calculated from the relation between mainstream length and drainage-basin area using the formula Lb = 1.312 A0.568 (Zavoianu, 1985). Afterwards, the Length of the main stream was achieved employing GIS from second order to fourth order because the two basins are similar stream order 4th according with the Strahler ordering scheme. Analyzing these values, it can be observed that the last two lengths are more consistent between them since they were calculated considering the morphometric variables of the principal streams.

This morphometric analysis also determined some linear aspects such as the stream order of the two micro basins. It shows the Lowell mining concessions intercept first to fourth order streams (Figure 4), being the fourth order the main rivers in the study area. Specifically, the 4th order stream of the basins 49981 and 49983 are the Santiago and Zamora rivers respectively. Table 4 summarizes the number and length of each stream order for both basins. As a result, it was revealed the Sum of Stream Lengths of the basin 49981 (487.38 km) is more than twice the basin 49983 (209.42 km). Although this fact, the Drainage density is almost similar in the two basins. Low drainage densities are observed (0.04 for basin 49981 and 0.05 for 49983), so it indicates the basin is highly permeable subsoil and present vegetation cover (Nag, 1998). Likewise, the Constant of Channel Maintenance (C) values are similar as it is inverse of drainage density (Schumm

1956) and depends on the lithology, permeability and infiltration capacity of soil, in addition to climatic conditions and vegetation.

Moreover, some aerial aspects were calculated to characterize the basin shape because it may influence the runoff reaching the outlet. The Form Factor (Rf) calculated by dividing basin area by square of the basin length is almost equal in both basins (0.54 and 0.55), which indicates elongated shape for the basins with low to medium peak flows of longer duration. The Circulatory ratio (Rc) is a helpful assessment to understand flood hazard (Bogale, 2021). The values of 0.36 for basin 49981 and 0.52 for 49983 indicate the second one (49983) is relatively more circular than the first one (49981) as it is closer to 1. In both cases, it suggests the basins are elongated and less susceptible to flooding. The Elongation Ratio (Re) is similar in both basins (0.83 and 0.84); thus, it indicates oval (0.8-0.9) classification of a region of low relief.

However, Relief aspects as the relative Basin relief (H) defined as the difference in elevation between the highest and the lowest points of the basins, obtained from DEM, shows high relief for both basins. The 2716 m for basin 49981 and 3714 m for 49983 may indicate the gravity of water flow, low infiltration, and high runoff conditions (Magesh, Jitheshlal, & Chandrasekar, 2013). The Relief ratio computed between the basin relief and the length of the basin could be an indicator of intensity of erosion processes and sediment delivery rate of the basin (Strahler, 1964). The values are similar in both basins (0.02 and 0.04), suggesting the presence of less resistant rocks at the area (Dahiphale et al., 2014).

Completely, the Basin Slope was calculated considering the mean of the slope analysis for both basins. The resultant values 18.58% for basin 49981 and 40.73% for 49983 indicates the second one (49983) is in general steeper than the first one (49981). Further, the Channel Slope or Slope mean stream shows a gently sloping classification for the two mainstreams at the study area. Specifically, 2.41% for the Santiago River (49981) and 5.21% at the Zamora River (49983). Finally, the hypsometric curves of the two rivers (Figure 4) present concave form. It could be interpreted as rivers in a mature to old stage and associated with a dissected, eroded landscape; being the erosion at the Zamora River (49983) apparently lower than at the Santiago River (49981) due to that most of the basin area lies at comparatively low relief.

Table 4 Morphometric indices of basins at the study area. *Lm distance shown in Figure 4. **main stream from order 2nd to 4th.

Morphometric Parameters	**Basin 49981**	**Basin 49983**
Area (km^2)	2618.06	1413.21
Perimeter (km)	301.28	185.41
Length (km) Lm*	69.82	50.70
Length (km) Lb	114.64	80.77
Length main stream (km)**	112.65	65.44
Basin order (Strahler)	4th	4th
Number of 1st Order Streams	75	25
Number of 2nd Order Streams	27	9
Number of 3rd Order Streams	16	9
Number of 4th Order Streams	21	5
Length of 1st Order Streams (km)	240.15	95.55
Length of 2nd Order Streams (km)	125.95	53.75
Length of 3rd Order Streams (km)	49.43	36.75
Length of 4th Order Streams (km)	71.86	23.37
Sum of Stream Lengths (km)	487.38	209.42
Aerial aspects		

Drainage Density (km/km^2)	0.04	0.05
Constant channel maintenance (C)	23.24	21.60
Form Factor (Rf)	0.54	0.55
Circulatory ratio (Rc)	0.36	0.52
Elongation Ratio (Re)	0.83	0.84
Relief aspects		
Initial elevation (m.a.s.l.)	2941	3714
Final elevation (m.a.s.l.)	225	306
Basin relief (m) H	2716	3408
Relief ratio	0.02	0.04
Mean basin slope (%)	18.58	40.73
Slope mean stream (%)	2.41	5.21

SATELLITE IMAGE ANALYSIS

This work also evaluated zones with occurrence of minerals like clays, oxides, and hydrothermal alteration mineral assembles by means of multispectral satellite image analysis and processing. The ASTER sensor is capable to record multispectral data within three subsystems: Visible and Near-Infrared (VNIR) with 3 bands of reflected range 0.5-0.9 µm and 15 m of spatial resolution, Shortwave Infrared (SWIR) with 6 bands between 1.6 and 2.5 µm and 30 m of spatial resolution, and Thermal Infrared (TIR) with 5 bands of 8.125 - 11.65 µm range and 90 m of spatial resolution. The multispectral system allows to detect different materials like rocks with variable content of silica, silicate, and carbonates, etc.; main rock forming minerals at the crust whose spectral characteristics are related to fundamental vibrations of Si-O and C-O chemical bonds and mineral structure (Castro Godoy, 2007).

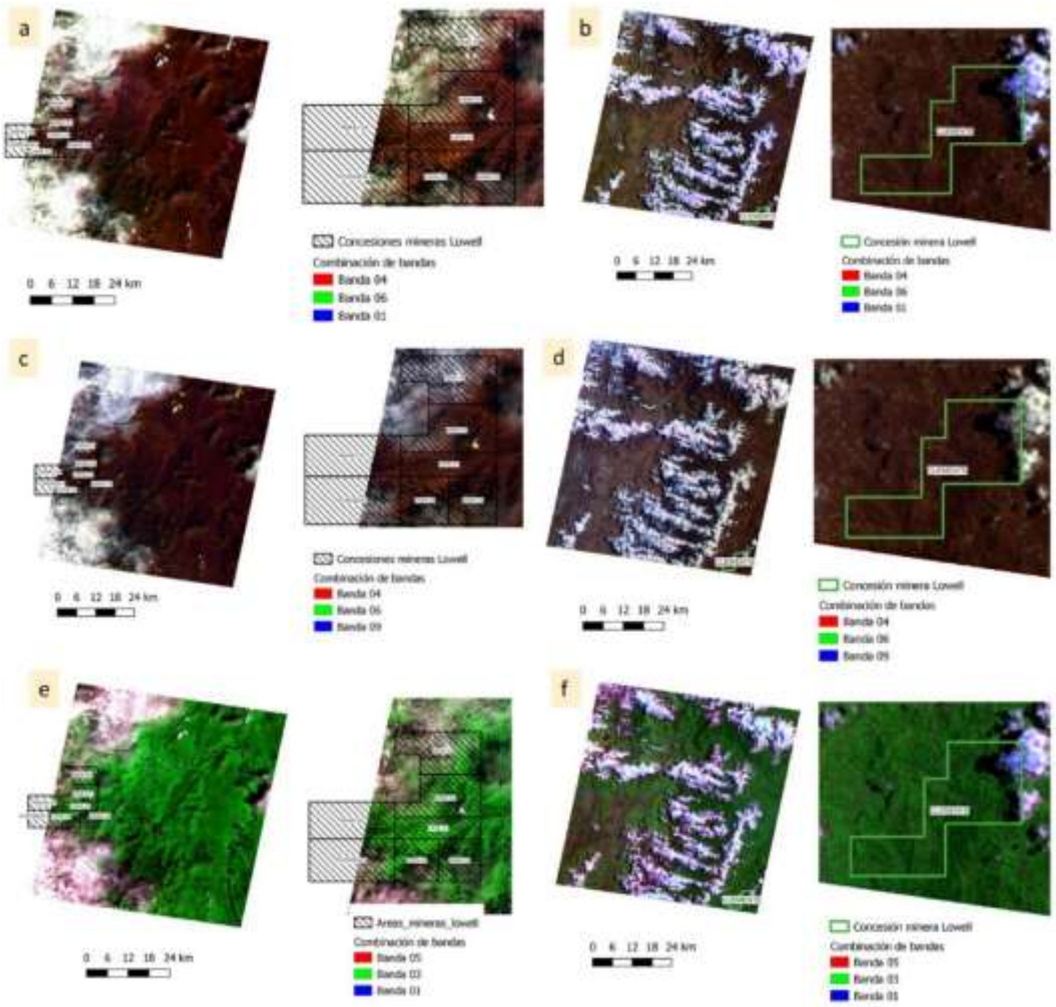


Figure 5 ASTER band ratio results for clay mineral mapping. (a-b) 461, (c-d) 469, (e-f) 531 RGB combinations.

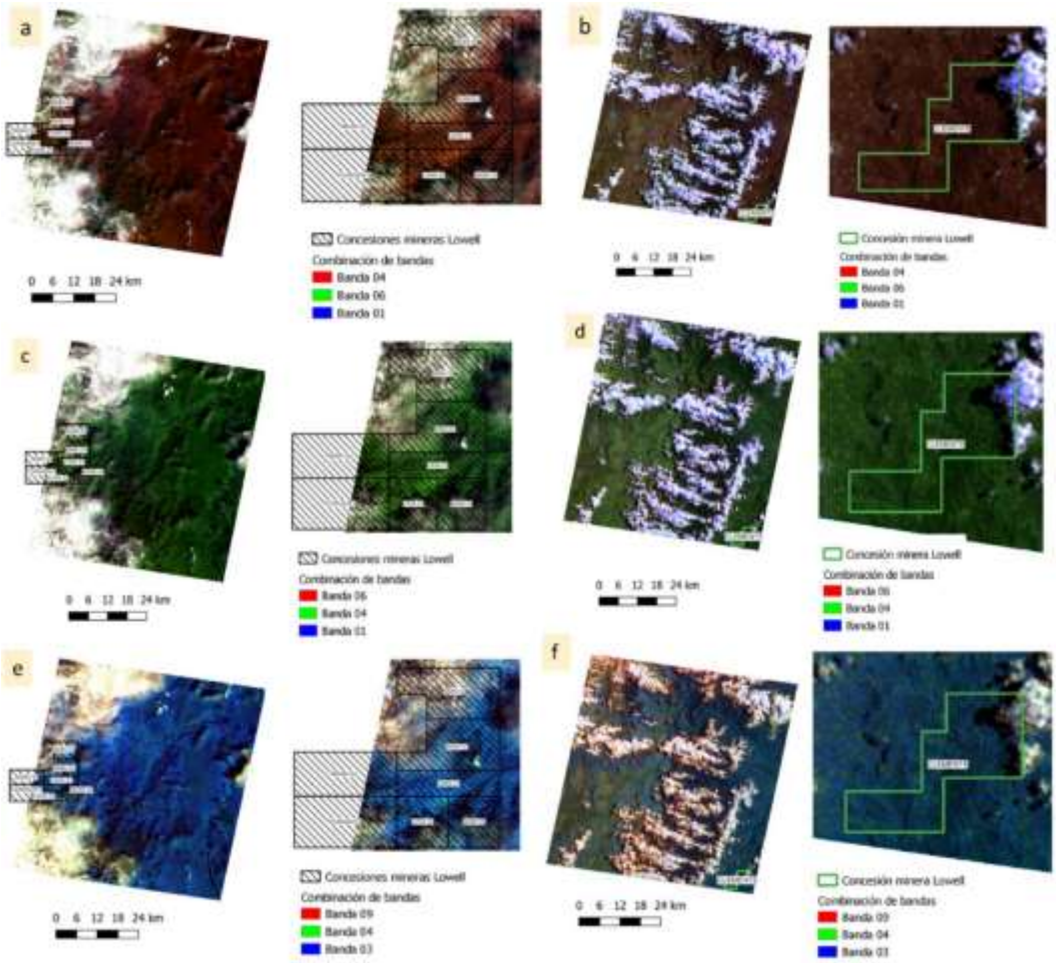


Figure 6 ASTER band ratio results for iron oxide index. (a-b) 461, (c-d) 641, (e-f) 943 RGB combinations.

The RGB band combinations employed for clay mineral mapping were 461, 469, and 531, while the band combinations for identification of iron oxide index were 461, 641, and 943. As a result, any significant zone was detected within the study area since non enhanced areas (brighter tone) were observed (Figure 5 and Figure 6). Clay minerals detected by remote sensing application might be derived from hydrothermal alteration or common soil forming weathering processes of minerals like plagioclase or feldspar. ASTER satellites could help to recognize multiple alteration minerals. For instance, kaolinite, allunite, halloysite, sericite (muscovite), illite and smectite can be easily identified within VNIR according with Macheyeki et al., (2020). Nevertheless, any area is detected for clay minerals within or surrounding the Lowell mining concessions as Figure 5 show nonwhite color zones more than clouds. It might be because remote sensing data are still very limited since no single sensor combines the optimal spectral, spatial, and temporal resolution.

Furthermore, Panda & Banerjee (2021) indicates ASTER data have more influence than Landsat data to enhance the iron oxide region because iron minerals spectra (especially limonite) have low reflectance in blue band and high reflectance in red band. However, any area is detected within or surrounding the Lowell mining concessions as it can be examined in Figure 6. This result could also be due to the exuberant vegetation coverage at the zone since the study area is located at the western border of the Amazon region of Ecuador.

Finally, Figure 7 show clearly that all the Lowell mining concessions (Clemente, Maiki 01, Maiki 02, Caya 21, Caya 22, Maiki 03, Maiki 04, Curigem 9) predominantly present abundant vegetation response calculated by the Normalized Difference Vegetation Index (NDVI) between 0.61 and 1 and moderated vegetation between 0.33 and 0.66 range values respectively. Therefore, this should be the reason why the study area is not suitable for remote sensing exploration for clays or iron oxide minerals as the ASTER sensors cannot penetrate dense vegetation like the occurred in the area of this research, so more advanced techniques like geophysics (e.g., airborne magnetic) are suggested.

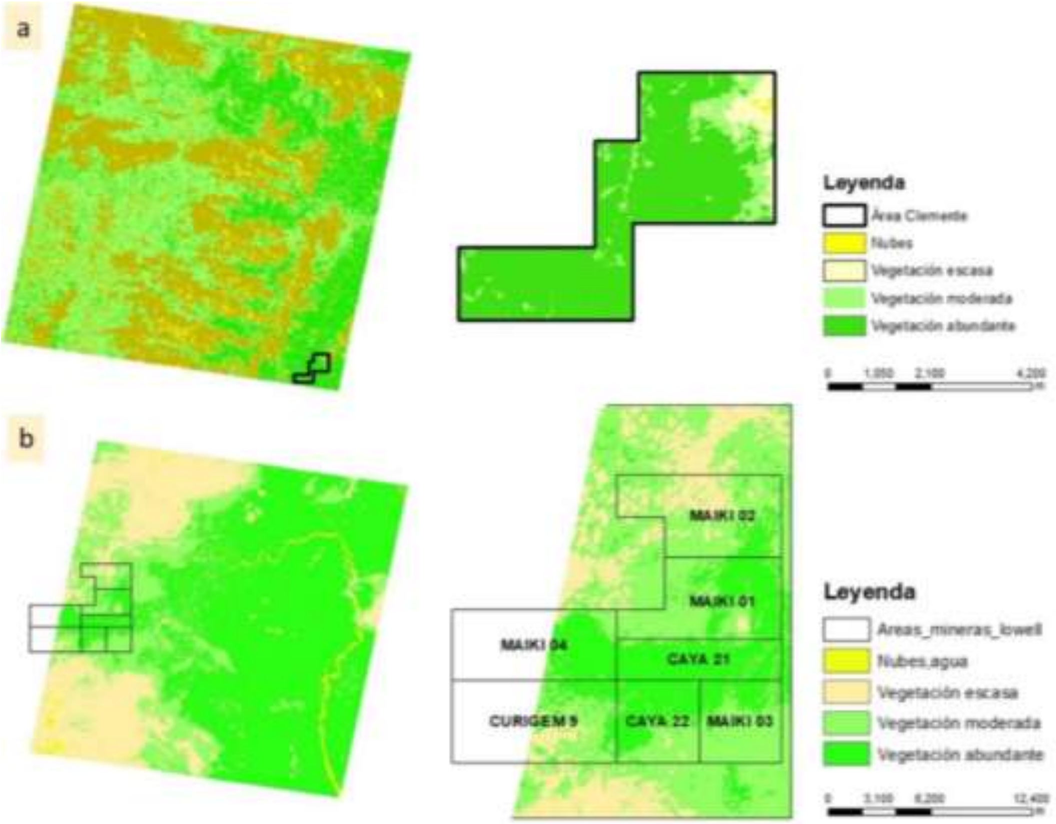


Figure 7 NDVI Spectral Indices calculation at the study area.

CONCLUSIONS

This study has reviewed the geomorphology data provided by SIGTIERRAS project, summarizing at least 30 geoforms corresponding to five genetic geomorphological groups at the Lowell mining concessions. The Relieve montañoso (Rt7) was identified as the geoform with more extension (77.96 km2) at the study area, characterized by in general steep slopes (25%-100%). Likewise, Barranco (E2) was detected as the more frequent geoform since it occurs 51 times in the study area. However, it is limited in area or extension mainly to the upper course of rivers.

The slope analysis confirms a predominant steep slope classification (30%-70%) in the study area as it covers 214.07 km2, representing about 55% of the surface intercepting the Lowell mining concessions. Several morphometric parameters are presented as well for two micro basins at level 5 by Pfafstetter coding system at the study area, 49981 for the Santiago River and 49983 for Zamora River. This analysis determined the Lowell mining concessions intercept first to fourth (maximum) order streams according with the Strahler ordering scheme. Some linear and aerial aspects (e.g., Circulatory ratio) suggest both micro basins are elongated and apparently less susceptible to flooding. Hypsometric curves indicate the Santiago and Zamora are mature to old stage rivers, seeming the first one (Santiago) more eroded than the second one.

Furthermore, the satellite image analysis tested various RGB band combinations for two free ASTER L1T images. Nevertheless, any significant zone for clay or iron oxide minerals was detected at the study area. It is because the Lowell mining concessions are in a zone with predominantly abundant (0.61 and 1) and moderate (0.33 and 0.66 range values) vegetation, probed and calculated by NDVI Spectral Indices. Therefore, it is recommended to try more advanced techniques like geophysics (e.g., airborne magnetic) in order to determine some geological structures in the subsurface that apparently have control in the geoforms observed at surface. Finally, more detailed studies and fieldwork are also suggested to support or improve the information provided in this research.

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