

Hydrogeological and geomorphological characterization of the basin and dam of La Nitrera Natural Park, Concordia (Antioquia)

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Abstract: La Nitrera Natural Park, established as a nature reserve classified as low-lying montane rainforest with a highly rugged topography, is located in southwestern Antioquia, in the rural area of the municipality of Concordia. This park has a reservoir that is the sole source of water for the municipality's urban area. From December to March, the park experiences water shortages and the collapse of its retaining walls due to the dry season. From May to August, the rainy season brings problems with gravitational movements in the riverbed. Due to the cyclical recurrence of this problem, which leads to water service restrictions, a geomorphological study of the watershed and reservoir was undertaken to evaluate the impact of existing structures and their dynamics. The evaluation identified units such as ridges with steep slopes and flat summits. Along with the evaluation of these units, a soil characterization was conducted to compare the relationship between the residual soil and the steep slopes.

Key words: surface units; geomorphology; hydrogeology; soil

1 Introduction

The mutual interaction of the three domains — atmosphere, lithosphere, and hydrosphere — generates constant changes or geological processes, responsible for the origin and evolution of the landscape (Phillips, 2016). Geological processes are related to the interaction between the physical environment and human beings. In relation to this interaction, geology, from its dynamic perspective, studies processes that are not inherently dangerous, or are only dangerous to the extent that humans do not expose themselves to them or induce them through their activities, such as erosion, landslides, flows, and avalanches (Rincón & Vegas, 2000).

In the earth sciences, the dependence of geomorphology on the interaction of geology, climate, and water movement across the land has been recognized. The physical characteristics of a watershed form a set that profoundly influences the hydrological behavior of that area, both in terms of disturbances and the responses of the watershed considered as a system. Thus, the systematic study of the physical parameters of watersheds is of great use in hydrological studies (University of the Andes, Venezuela, 2013).

Through hydrogeological characterization, units of importance are defined within the basin area, considering geology, hydrography, and using GIS methods. Based on the hydrogeological characterization, the basin's performance is studied and analyzed, leading to the estimation and characterization of the basin's morphometric parameters (Piñeiro, 2015).

Both geomorphology and hydrogeology can be used as tools for interpreting the prospecting, capture, and protection of water resources (Flores et al., 2015). Likewise, it is necessary to study and analyze geomorphological processes and the

arrangement of surface geological structures that affect the quality of life and resource availability for the population settled in any region (Gonzalez & Soto, 2010). This research seeks to understand in detail the relationships between the hydrosphere, lithosphere (rocks, deposits, and structures), and the products and impacts of weathering, erosion, and soil behavior that have occurred since then, in order to develop management plans for the La Nitrrera reservoir. This understanding will enable the creation of prevention plans for the protection of this vital water body for the municipality's population.

2 Study area

The Southwest subregion of Antioquia, comprised of 23 municipalities, including Concordia, represents 10.4% of the department's total area, making it the third smallest subregion despite having the most municipalities (Medellín Chamber of Commerce for Antioquia, 2015). Concordia (see Figure 1) is located between 1118800–1138000 E and 1161000–117300 N (Magna Oeste Colombia) (Government of Antioquia, 2015). The municipality covers an area of 234 km² and has an average elevation of 2,000 meters above sea level (Mayor's Office of Concordia, 2015). The study area is located on the eastern slope of the western mountain range and is characterized by a broken relief with slopes of up to 30° inclination with great length, with high slope drainages and low average flows (Cárdenas & Restrepo, 2006).

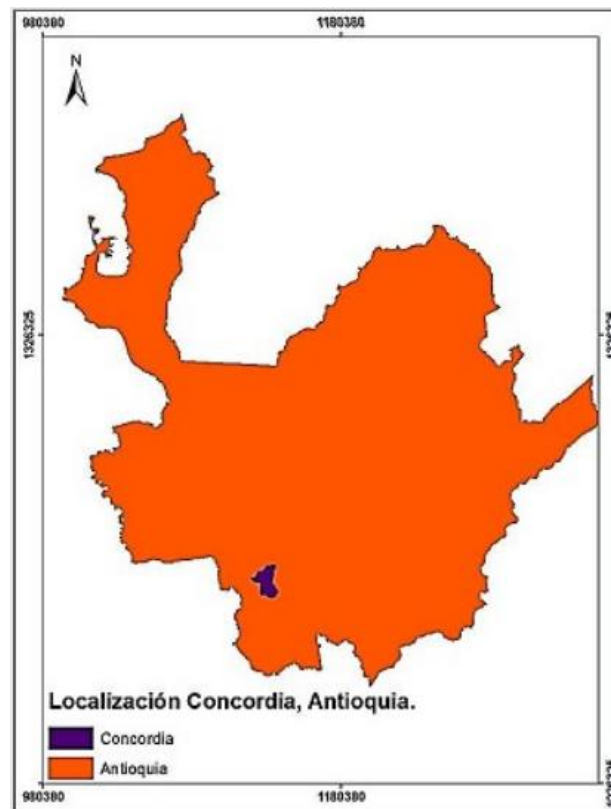


Figure 1. Location of Concordia.

Created by the author based on information from the Government of Antioquia.

To guarantee the water supply in the main town of Concordia, the gravity-fed conveyance of water from the Santa Mónica stream was adapted and has the following parameters:

- A system with a regulating dam, built on the former bed of the Santa Mónica ravine.
- A concrete spillway at one end of the dam.
- An intake tower located upstream of the embankment.

- A drainage pipe that passes through the dam.
- A regulating reservoir with an initial capacity of 76,850 m³.

Figure 2 shows the dam's design plan and the aforementioned parameters.

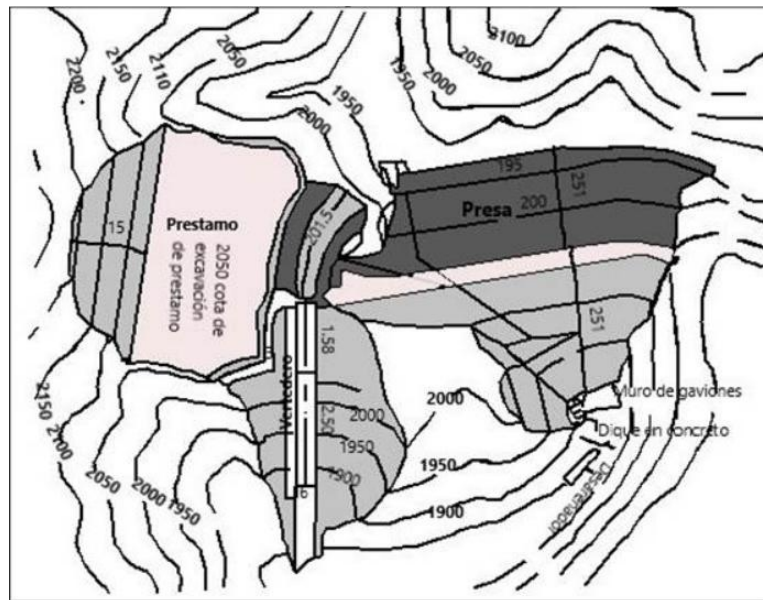


Figure 2. General plan of the dam. Source: Acuantioquia (1996).

Figure 3 presents a medium-scale description of the geology present in the municipality of Concordia, Antioquia, showing the formations, faults, and contacts in the area. Some of these, such as the Mistrató Fault, have a direct impact on the Natural Park. The municipality of Concordia is crossed from north to south by one of the branches of this system, the Mistrató Fault, which exhibits displacement. It has a length of 63.3 km and an area of influence, from east to west, of 52.4 km. According to recent studies, the Mistrató Fault has a seismic probability between 0.5% and 2.5%, and analyses using focal mechanisms classify it as a normal fault with a strike-slip component and a focal depth between 30 and 86 km. Based on the analysis of aerial photographs, the hydrographic network, and fieldwork, several geological lines were determined, with the main directions being N10°E, N10°W, N36°W, N36°E, and N-S (Government of Antioquia, 2015). For a more precise contextualization of the study area, Figure 4 shows the delimitation of the reservoir within the Natural Park and the location of the tributary streams on the corresponding contour lines to determine the framework of the currents and their mouths.

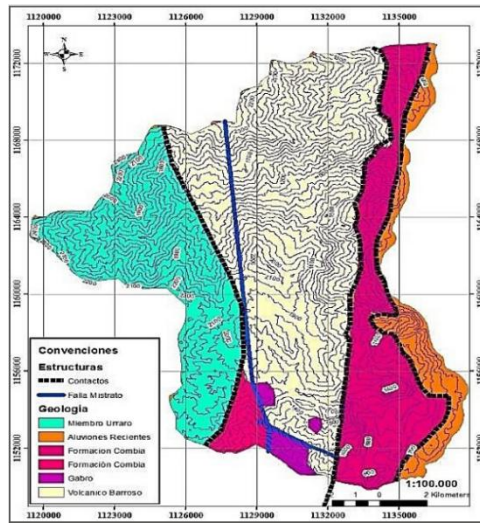


Figure 3. Geology map of Concordia. Author's own work.

3 Methodology

The methodology chosen for this research is a combination of different techniques that allowed us to gather sufficient information about La Nitrera Natural Park without altering its natural state. Due to a lack of documentation on the area and the difficulty in finding vegetation-free zones, and given the ecological nature of La Nitrera Natural Park, we used land cover imagery and fieldwork involving photographs, samples, and plot sampling in vegetation-free areas of the park for evaluation.

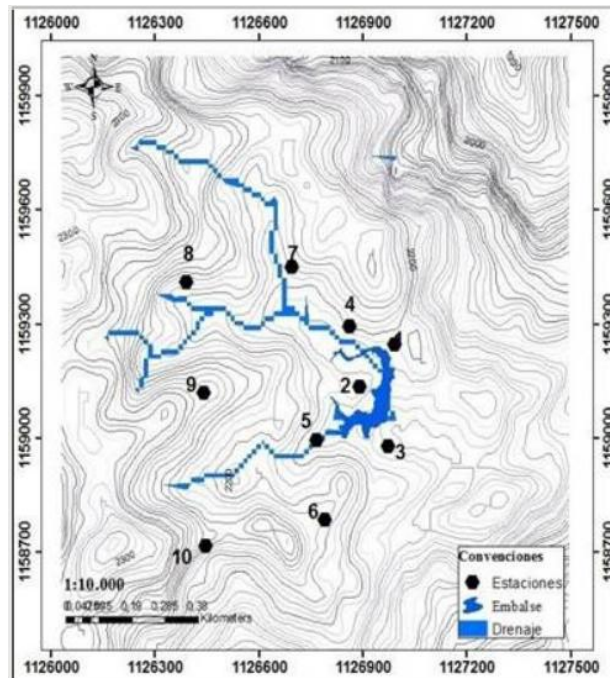


Figure 4. Study area. Own elaboration.

3.1. Structural and geological review

A literature review was conducted, consulting publications, books, articles, data, and reports from the mayor's office and Corantioquia. Information was sought in databases to conceptualize and define the problem using academic data. To consolidate the information geographically, maps and the ALOS DEM with a spatial resolution of 12.5 m were consulted to spatially locate the structures of interest.

The basic steps for developing this item were the collection of related secondary information, the definition of the region's geological and structural framework, the delimitation and characterization of the units, and subsequently the creation of a base map from the basic cartography and the digital elevation model. For geomorphology, first- and second-order relief units were identified through the analysis of digital elevation models (Patiño et al., 2011), following the guidelines proposed in the *Proposal for the Standardization of Geomorphological Cartography in Colombia* (Carvajal, 2012).

To have a clearer view of the aforementioned process, a complementary diagram is shown in Figure 5.

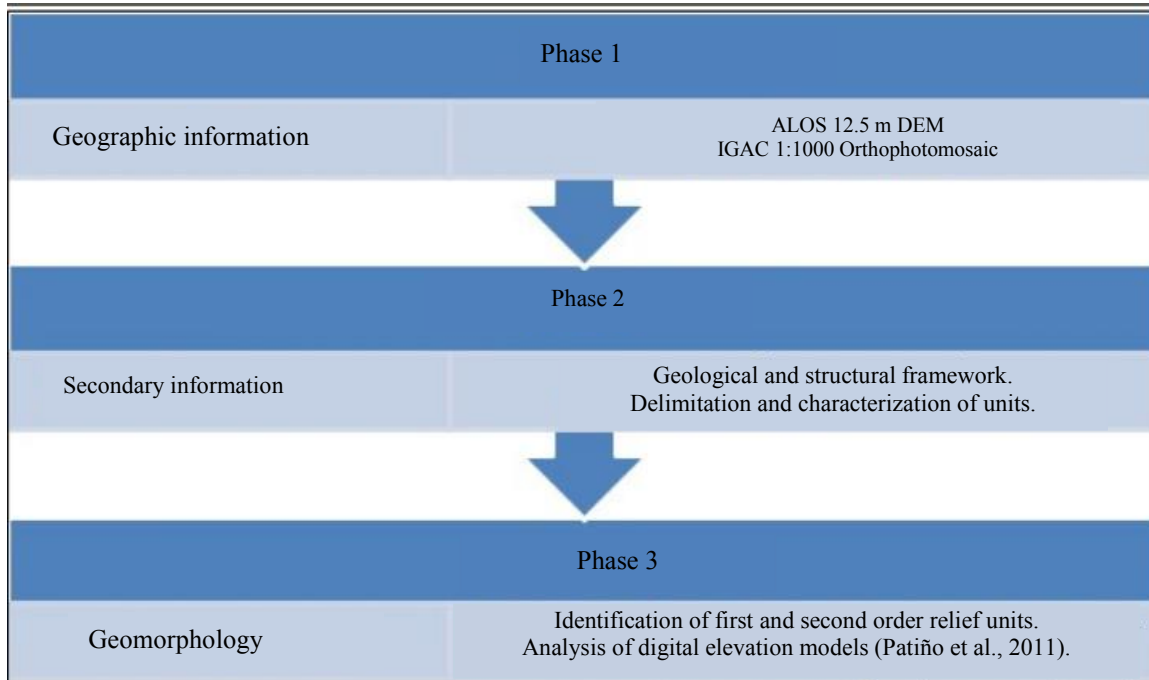


Figure 5. Structural and geological review phases.

Author's own elaboration.

3.2. Geomorphological and morphometric parameters of the basin

To characterize the watershed, several geomorphological indices were determined. These included the area, length, and perimeter of the watershed, average slope, hypsometric curve, altimetric frequency histogram, average height and elevation, drainage density, profile and average slope of the main channel, as well as indices of watershed shape and time of concentration (Villaruel, 2013). Due to a lack of available information, a comparison and correlation of field data was performed using GIS. A brief description of the main parameters for this study follows.

1. Length and width:

The length, L , of the basin can be defined as the horizontal distance of the main river between a downstream point and an upstream point (Hernani & Ramírez, 2002).

The width is defined as the ratio between the area (A) and the length of the basin (L) and is designated as W . Thus:

$$W = \frac{A}{L} \quad (1)$$

2. Basin area:

It is defined as the horizontal projection of the entire drainage area of a runoff system directed directly or indirectly to the same natural channel (Rojo, 2014).

Area is a very important geomorphological parameter, and its importance lies in the following reasons (Sanguinetti et

al., 2015):

- It is a value that will be used for many calculations in various hydrological models.
- For the same hydrological region or similar regions, it can be said that a larger area corresponds to a higher average flow.
- Under the same hydrological conditions, basins with larger areas produce hydrographs with smoother and flatter variations over time. However, in large basins, hydrographs with peak flows can occur when precipitation has been intense in the vicinity of, upstream of, the gauging station.
- Under the same hydrological conditions, basin area is inversely related to the ratio between extreme flows: minimum/maximum.

3. Compactness coefficient or Gravelius index:

It is defined as the ratio between the perimeter P and the perimeter of a circle containing the same area A as the watershed:

$$K = 0.282 \frac{P}{\sqrt{A}} \quad (2)$$

Where K is the radius of the circle equivalent in area to the basin. Based on how it was defined:

$K \geq 1$. Obviously, for the case $K=1$, there is a circular basin (University of the Andes Venezuela, 2013).

4. Horton's form factors:

Observations from a large number of real basins around the world allow us to establish the following relationship between the basin area A and the area of a square of length L, where L is the length of the main channel:

$$\frac{A}{L^2} = \frac{A^{-0.136}}{2} \quad (3)$$

Solving for the value of L, we get:

$$L = 1.41 \times A^{0.568} \quad (4)$$

3.3. Physical and chemical properties of the soil

The soil has been characterized in three specific aspects: physical, chemical, and biological properties, as the most representative within an environmental study (McCauley et al., 2005). In order to carry out the soil survey and identification, the general methodology proposed by the USDA was used, which is divided into four main topics (McCauley et al., 2005):

1. Describe the soil characteristics of the area near the watersheds and reference points of the Park.
2. Classify the soil zones according to the Deere and Patton standard classification system.
3. Plot the soil boundaries on the map.
4. Make predictions about soil behavior.

This section began with laboratory analysis of the various physical and chemical properties. Because the study area is located in a highly weathered tropical region, the methodology of Deere & Patton (1971) was used, which defines three zones, each with its own horizons. Figure 4 shows the referenced points, which are the stations selected for sampling within the park. Due to the challenging terrain, simple random sampling was used at this point.

The properties measured on the soil samples were: pH, percentage of organic matter (colorimetry), particle size distribution, liquid and plastic limits, and compressive strength in unconfined samples. These were chosen due to their specific relevance to soil quality with respect to maximum water saturation and its stability for reservoir management. The evaluation of these properties considered the regulatory framework for Colombia proposed by INVIAS and ICONTEC

(ICONTEC, 2006). The NTC 1504 standard (ICONTEC, 2006) was used as the primary framework, but for certain classifications, ASTM D2487 was consulted, as it is considered equivalent for soil classification.

3.4 Toposequence

The La Nitrrera Natural Park has an ecological character that prevents large-scale excavations or earthmoving, in addition to dense vegetation covering much of the area. Given this situation, several techniques were integrated to assess the zone. Using drone imagery and Google Earth, surface contacts were demarcated. Furthermore, an orthophoto mosaic from the IGAC (Agustín Codazzi Geographic Institute) was compiled, which, being from 2012, provided a basis for determining if any significant changes had occurred. For sample collection, a simple random selection was made at the points shown in Figure 7. Plots were taken from areas previously modified by local residents, areas that exposed the soil with sparse vegetation, demarcating 1 m on each side.

Table 1. Standards applied in laboratory tests

Test	Norm	Description	Reference
Plastic Limit	INVIAS 126	Minimum water content	(I.N.V.E–126, 2007)
Liquid limit	INVIAS 125	Water content expressed as a percentage	(I.N.V.E–125, 2013)
Particle Size Analysis (Gradation)	INVIAS 123	Quantitative determination of grain size	(I.N.V.E–123, 2013)
Colorimetry	INVIAS 121	Method for determining organic content	(I.N.V.E–121, 2007)
Humidity	INVIAS 122	Water content assessment	(I.N.V.E–122, 2007)
Unconfined compression	INVIAS 152-13	Force on cohesive soil	(I.N.V.E–152, 2008)
pH determination	NTC 5264	Determination of active acidity	(ICONTEC, 2008)
Soil classification system	NTC 1504	Mineral and organic classification of soil	(ICONTEC, 2006)

Original work.

Table 2. Description of soil horizons

Zone	Horizon	Description
Zone I	1A	Surface soil, roots and organic matter. Leaching and eluviation zone
Residual soil (regolith)	1B	Enriched in clays and accumulations of Fe, Al, and Si. Absence of inherited structures
	1C	Silt to sand-sized material, less than 10% rock cores
Zone II Weathered Rock	2A	Transition from residual soil (saprolite) to partially weathered rock
	2B	Soft to hard rock
Zone III	3	Fresh rock

Original work.

Since the study area is located in a highly weathered tropical region, the methodology of Deere & Patton (1971)—which defines three zones that in turn comprise horizons—was employed (Table 2).

4 Results

The results of the identification of geological structures, the geomorphological and morphometric characteristics of the area are presented below. Finally, the results of the selected characteristics for the evaluation of the soil properties within the reservoir basin are presented.

4.1. Regional geology

No fault features were evident over the reservoir and the park's trails; therefore, aerial photographs and an orthomosaic were used, yielding lineaments that reflect stratification planes and faint traces of the Mistrató fault. Some sedimentary sequences were identified as being of interest because they represent some of the few steep areas, and

consequently, dip measurements were taken of the stratification, with strikes ranging from N20W to N45W and dips between 75W–80W and 60E–70E. For the formations affected by the fault trace, the orientation is towards S-E (ANH & Universidad EAFIT, 2007).

4.2. Geomorphology and hydrology

The identification of geomorphological units was based on knowledge of structures found in the geological identification; geomorphological and hydrological indices were determined that show their dimensions and relate the geological characteristics (Marini & Piccolo, 2005).

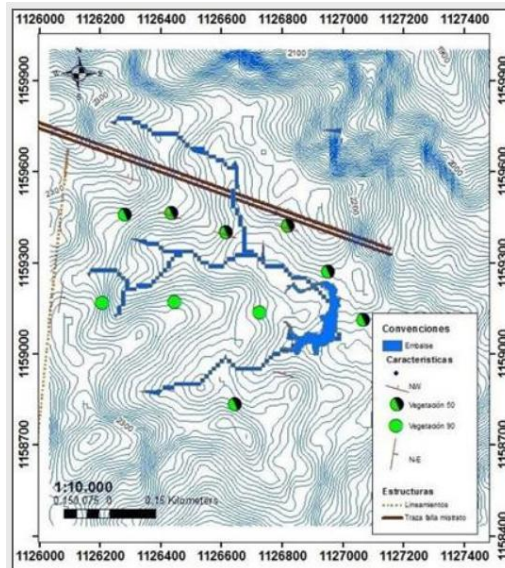


Figure 6. Hydrogeomorphological map.

Created by the authors using vector files from the municipalities of the southwest (Corantioquia, 2012).

Figure 6 presents the hydrogeomorphological map showing the location of the lineaments, the trace of the Mistrató Fault with its direction, permanent and intermittent drainages, as well as a brief description of the channel direction and vegetation distribution. It is worth noting that areas with full vegetation are shown in green, areas with more than 90% vegetation cover are shown in black, and areas with 60-50% vegetation cover are shown in half black. The most prominent lineaments in the park and the trace of the Mistrató Fault are also demarcated.

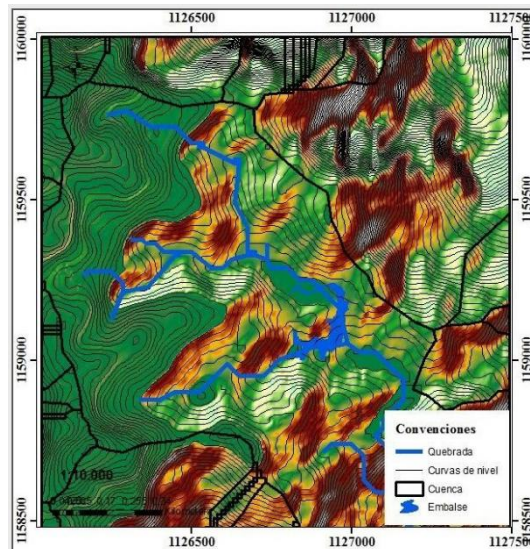


Figure 7. Watershed delineation.

Created by the authors using vector files from the municipalities of the southwest (Corantioquia, 2012).

Based on the geological and geomorphological survey, a map of the basin was created, demarcating the perimeter of the main watershed and showing the drainage patterns over shaded areas to identify the steepest slopes. Figure 7 shows the location of the basin's lineaments, permanent and intermittent drainages, as well as the contour lines and the steepest areas.

4.2.1 Hydrogeological, structural and geomorphological characteristics

The characterization of the park's geomorphological units led to a regional analysis to establish guidelines, given the park's small size on a cartographic scale. The Las Ánimas Geomorphological Unit, described by Herrera & Toro (2000), comprises the central-western area of the municipality of Concordia, including the watershed that feeds into the La Nitrera reservoir. While the Las Ánimas unit features extensive slopes with long ridges that vary from sharp to flat, the La Nitrera reservoir watershed exhibits moderate slopes with short ridges in the Santa Mónica stream basin. In contrast, the La Nitrera stream basin has steeper and straighter slopes due to the presence of the Mistrató fault trace, which forces an abrupt change in direction from west-east to southeast. Three types of geomorphological units are found within the Natural Park (Figure 8). It should be emphasized that the slope of each ravine in the reservoir is of a different type, therefore the type of ridge also changes (Másmela, 2010). Figure 9 shows the ridges mentioned above.

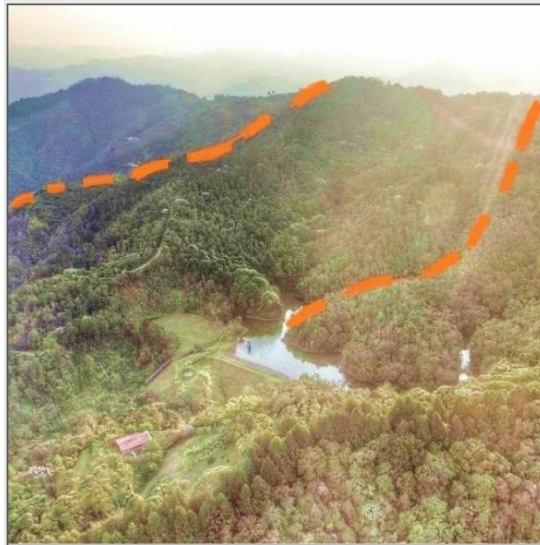


Figure 8. Geomorphological units. (Author's own elaboration.)

4.2.2. Geomorphological indices

Geomorphological indices were selected as the starting point for a physical description of the basin; therefore, morphometric parameters formed the basis for establishing the magnitude of the study area. In addition to these, altimetry parameters and channel slope were also included. Table 3 reports the calculated parameters, with their respective units and corresponding magnitudes.

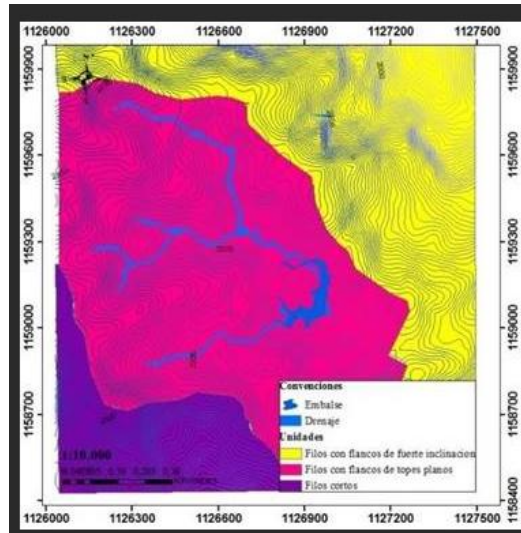


Figure 9. Map of geomorphological units. (Author's own work.)

Among the calculated parameters, the most important is the analysis of the average channel slope, which falls into the moderate category. However, the presence of deposits in the basin, which act as temporary water reservoirs, creates excess weight that can lead to mass wasting processes. As will be seen later in the soil assessment, there are sedimentary zones with veins of swelling clay. Furthermore, the unconfined compression test results show that events where the soil exceeds its saturation capacity, combined with the slope, could generate movements in the stream channels. Figure 10 shows that low to moderate slopes predominate in the Santa Mónica stream, while steep slopes are more prevalent in the La Nitrera stream.

To evaluate the shape of the basin, dimensionless indices such as Horton's index, which relates the basin's area and length, were used. In this case, the result of 0.45 indicates that the basin is at an intermediate point; therefore, it is neither elongated nor circular, despite being a reservoir. According to Horton's definition, it is a square-shaped basin with an outlet at one vertex. The Gravelius index is greater than 1, and higher values indicate more elongated basins and flatter hydrographs. The result in this case is 1.18, which indicates that the basin's shape is 18% more elongated on one side, using a circle as a reference. With a drainage density of 0.31, the basin is resistant to erosion, with stepped slopes and high permeability in terms of infiltration and runoff, but its drainage capacity is only moderate. This is because, with moderate slopes and a high presence of vegetation, the basin's response to high rainfall will be slower in terms of drainage. Figure 11 shows the order of the channels found; the higher the basin order, the more efficient the drainage for water removal (Hinds et al., 2013). This corresponds with the findings for drainage density, since, having a limited drainage network, evacuation in the event of high rainfall is very poor.

Table 3. Geomorphological index results (Source: Own elaboration.)

Parameter	Unit	Magnitude	
Average temperature	°C	17	
Reservoir area	m ²	13,952	
Average rainfall	(mm/year)	2,223	
Evapotranspiration	(mm/year)	1.15	
Basin length	m	4,465	
Main channel length	m	1,618	
Mean elevation (masl)	m	2,200	
Maximum elevation (masl)	m	2,250	
Average slope of the riverbed	%	20	
Basin area	m ²	1,158,305	
Perimeter	m	2,014	
Factor Horton	Dimensionless	0.45	
Gravelius Index	Dimensionless	1.18	
Length ratio	Dimensionless	1.21	
Drainage density	Km/km ²	0.31	
Time of concentration	(USDA method)	min	20
	Bransby-Williams	hr	0.20
	Kirpich	min	18

4.3 Soil

The selected points were located using ArcGIS software, and the results obtained for each of the evaluated properties are reported below. These properties were evaluated to determine the characteristics of the soil above the reservoir and its tributaries.

4.3.1 Particle size analysis

The samples were collected and analyzed for the period from the second half of 2015 to the first half of 2017, a period in which the extreme drought of early 2016 occurred. Spatial grain distribution was determined from the mean grain size (D50) (I.N.V.E-123, 2013), based on grain-size distribution curves. For the degree of sorting, the sorting index was used, based on percentiles supported by particle asymmetry.

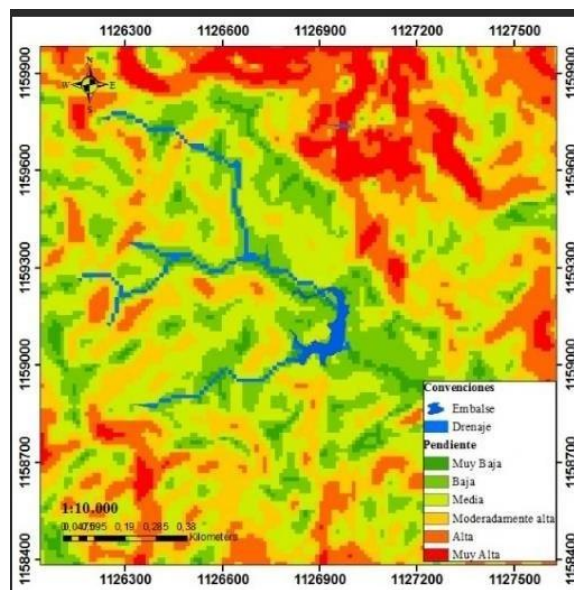


Figure 10. Type of slope. (Author's own work.)

Grain size particle distribution analysis shows that medium sand is the predominant fraction. In the area near the reservoir, medium sand also prevails, with a slight intrusion of fine sediments and low consolidation. Toward the northwest zone of the Natural Park, grain sizes correspond to gravel, associated with colluvial deposits identified during field surveys. Coarse sand is widely represented at the 50th percentile, an unexpected finding given its overall low abundance in several samples. The low content of silt and clay at the 50th percentile confirms that these fine sediments occur as interbedded layers, rather than forming the dominant fraction as initially hypothesized from field observations. In this research, the sorting index indicates moderately well-sorted sediments, reflecting an acceptable degree of particle homogeneity. Areas adjacent to the reservoir and lateral basins also show moderate sorting, which can be attributed to the fact that most particles in these zones fall within the medium sand grain size range. From the central area of the Natural Park eastward to the reservoir, poor sediment sorting is evident. This reflects high heterogeneity in the collected samples, which contain a high proportion of gravel and very coarse sand fractions.

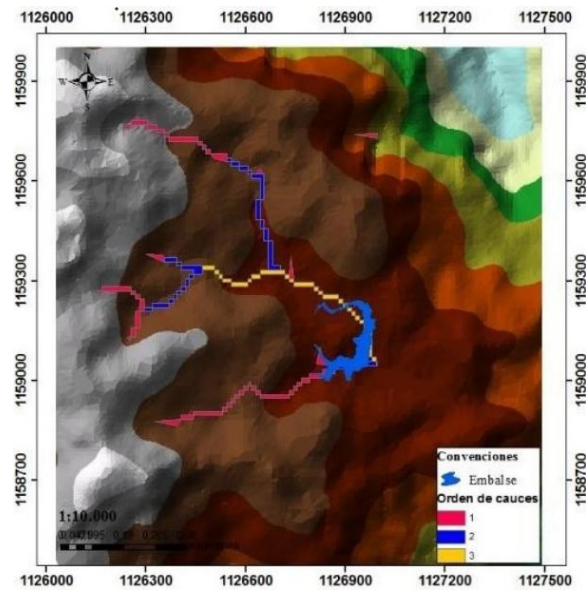


Figure 11. Channel order.

Created by the author using vector files from the Southwest Municipalities (Corantioquia, 2012).

The sieving of the samples revealed particles ranging in size from gravel to fines, with over 50% retained on the 200-mesh sieve and less than 5% fines present at all stations. At station 9, 40% was retained on the 4-mesh sieve (gravel size). These characteristics are fundamental not only for understanding the particle size distribution but also for a more accurate interpretation of the soil classification. To perform this classification, the uniformity coefficient (c_u) and curvature coefficient (c_c) were calculated (ASTM, 2006), yielding c_c values less than 1 and c_u values greater than 1 for 80% of the stations. Therefore, three soil group types were found according to the USCS classification: the largest proportion being well-graded sands with gravel and a low amount of fines (SW, Well graded Sand), this for the N-W zone; for the central part in the middle of the 2 ravines, there is a soil of the type of poorly graded sands with gravel and fines (SP, Poorly graded Sand); and for the part closest to the reservoir, it is found in the group of clayey sands, a poorly graded mixture of sands or clays (SM, Silty Sand).

4.3.2 Liquid and plastic boundaries

Looking back, it is clear that according to the USCS classification (ASTM, 2006), the soil has high sand characteristics; however, it was decided to conduct the evaluation based on field findings. As will be seen later in Table 4, the compilation of the 5 ranges of results presented within the analyzed samples shows that the results for the liquid limit

are not low; there are even results above 70%. This is why this test was reported and will be a topic of discussion in this research work.

The liquid limit of a soil is the moisture content, expressed as a percentage of the oven-dried soil, at the boundary between the liquid and plastic states. The plastic limit of a soil is the lowest water content at which it can be made. The plasticity index of a soil is the range of water content, expressed as a percentage of the dry mass of the soil, within which the material is in a plastic state.

Table 4. Liquid and plastic limit results.

Range	Liquid limit	Plastic limit	Plasticity index	Moisture content
1	49-51 %	45-47 %	4-5 %	30-35 %
2	51-53 %	42-43 %	9-10 %	15-20 %
3	53-54 %	40-41 %	10-11 %	25-30 %
4	61-63 %	45.45 %	16-17 %	20-25 %
5	72-74 %	62-65 %	8-9 %	35-40 %

Original work.

The report of these liquid limit data shows the distribution of these values within the study area. It is important to emphasize that, despite previous results indicating sandy soil, the lowest liquid limit value is 49%, which is a significant value for analysis using the Atterberg classification. Based on the results obtained and considering the plasticity index (I.N.V.E-123, 2013), liquid limit percentages above 50% in all areas indicate the presence of clay content among the predominant grain size, sand or silt. On the other hand, the plasticity index provides a very important clue for soil classification. All areas with a plasticity index below 10 indicate the presence of traces or little clay, indicating low plasticity. Areas with an index greater than 10% exhibit medium plasticity and are considered clay loam soils.

4.3.3. Colorimetry

Due to the presence of a large amount of leaf litter and vegetation cover (30-40 cm) in the area, a colorimetric test was applied to determine the level of potentially harmful organic components that could affect runoff and soil quality near the reservoir. Table 5 reports the data obtained from the test, and the methodology details the procedure outlined in INVIAS Standard 212. The results are presented on a scale of 1-5 in the colorimetric table, with 5 representing the highest level of harmful organic matter. Based on this, five well-defined zones were identified within the total number of samples. For zone 1c, the organic matter content was found to be standard (3), meaning that the zone is undisturbed and meets the minimum requirements for soil without harmful organic matter. Zone 2c shows a low amount of organic matter, indicating that the samples from this zone are minimally disturbed by the overlying vegetation cover. Ranges 3c and 4c contain a high content of potentially harmful organic fragments that should be evaluated under other parameters to verify the conclusions reached under this test.

Table 5. Colorimetry of La Nitrera Natural Park

Ranks	Color	Description
1c	3	Area with a low amount of organic matter.
2c	2	Area with low amount of organic matter, clear sample on the nitrate channel.
3c	4	Area with a high amount of organic matter.
4c	5	Area with a high amount of organic matter, contaminated soil.

Original work.

4.3.4. Unconfined compression

The test was conducted according to INVIAS standard 152 (I.N.V.E-152, 2008). The sample was acquired without lateral confinement, given the stability problems of the nearby walls in both the river basin and the reservoir during dry seasons. As defined by the standard used, the results obtained from the pressure press must be represented in a graph showing both deformation and load. Since five samples were analyzed from the five stations closest to the reservoir, an average was taken for each of the 16 readings obtained from the pressure press to obtain the result shown in Figure 12.

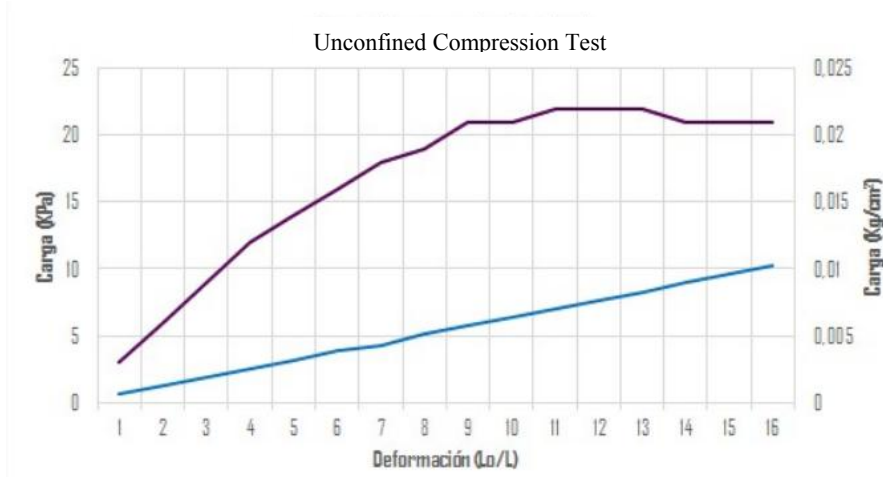


Figure 12. Unconfined compression test. (Author's own work.)

4.4 Toposequence or catena

As mentioned, the Barroso Formation and the Urrao Member of the Penderisco Formation are the soil-forming units found in La Nitrera Natural Park. Using regional literature and fieldwork to collect soil profiles, the soil characteristics of the area were determined. The Deere & Patton (1971) classification for tropical regions was used to create the profiles. Table 6 describes the zones for each profile.

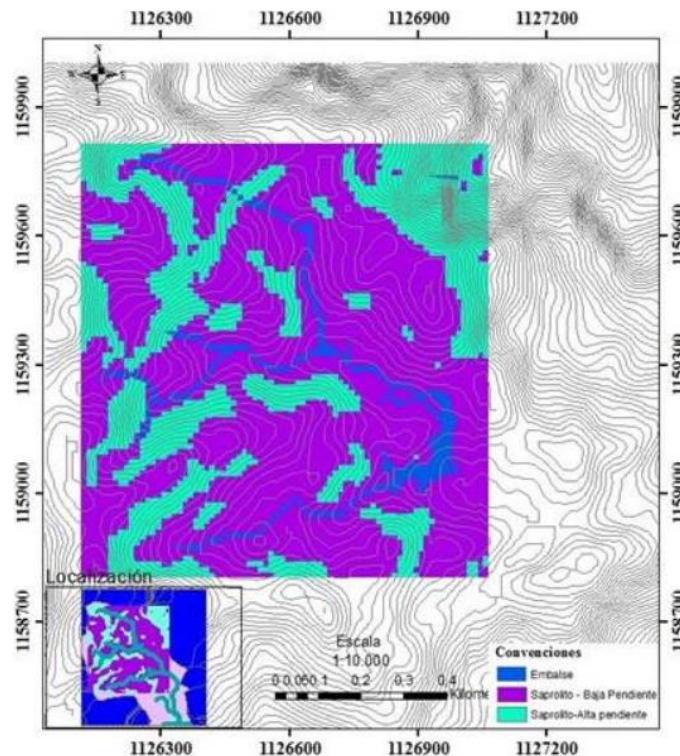


Figure 13. Residual soil and slope type. (Author's own elaboration.)

In Zone IA, all profiles do not exceed 30 cm in thickness. The other horizons in Zone I have dimensions that do not exceed 50 cm, and below this lies the bedrock, which is difficult to see in much of the Natural Park, but in the identified sites, it is highly fractured. Due to the amount of vegetation and the fact that many of these profiles were in areas with low visibility, the photographs are not clear, and therefore, the characterization is based on field data. The most important aspect of this study was to locate the saprolite, or residual soil, and relate it to the erosion magnitudes mentioned in the first chapter. Relating these variables would provide greater insight into the management of the reservoir and its water shortage problems. As has been discussed throughout this work, it was also mentioned that among the geomorphological indices, the slope of the terrain is of greatest interest.

Table 6. Description of toposequence profiles. (Original work.)

Profile	S1	S2	S3	S4	
Zona I	1A	Thin due to the steep slopes. Dark brown.	Thin organic matter, brown.	Organic matter ranging in color from black to dark brown.	Organic matter ranging in color from black to dark brown.
	1B	Presence of grayish gravels in a yellow-orange matrix.	Residual red color, high presence of clays and poorly compacted.	Composed of fine yellowish-brown material.	Yellowish-green material, presence of clay bands.
	1C	Reddish-yellow, sandy-silty material.	Sandy silty material, reddish-orange in color.	Saprolite with clayey silty material, reddish-yellow in color.	Light yellow, fine-granular matrix.
Zone II: Weathered rock	Sandy-silty matrix, greenish-brown in colour. Fractured.	With properties still of the parent rock, transitional material.	Gray blocks, clayey-sandy matrix. Blocks present at greater depths.	Transition level with parent rock properties and saprolite at the top.	
Zone III: Fresh Rock	Quite fractured, detrital, fine-grained, and chemical in a smaller proportion	Highly fractured, reddish-yellow in color.	High degree of fracturing, with a greyish-green color and aphanitic texture.	Highly fractured, greenish-yellow color, aphanitic texture.	

Figure 13 presents a map relating residual soil to slopes greater than 25%. The blue coloration indicates areas where, in addition to steep slopes, there is a higher concentration of residual soil. This dynamic suggests that these variables could be associated with mass movements that have occurred, and in areas closer to the riverbed, with erosion problems. The map also shows the exact location of this analysis within the watershed. It is worth noting that in the higher areas of the park, landslides could occur that obstruct the flow of water to the reservoir.

5 Discussion

The orientation determined by the boundaries of La Nitrera Natural Park shows a strong northwest tendency, modified by regional structures such as the Mistrato Fault. The specific consequence of these regional movements is that the change in direction alters the location of the blocks and the slope that currently define the framework of the channels feeding the reservoir. The indices chosen to determine the shape of the basin are widely used, but their classifications are not exact because they emphasize the basin's proximity to a circular shape. Accordingly, there is a clear need to integrate alternative methodologies — as adopted in this study — or to establish revised classification systems. The parameters selected for basin evaluation were defined on two main bases: firstly, the availability of complementary existing data, and secondly, the specific management needs of the reservoir. Based on the hydrological analysis, it is evident that the basin is in a mature

evolutionary stage. This condition is closely linked to its drainage pattern, which is governed by tectonic and lithological controls.

Soil property analysis provides a more detailed understanding of the area and its future behavior. Medium-sized sand particles were consistently found in all collected samples, along with clay, although in smaller proportions. Visual fieldwork revealed that sediment deposition in the reservoir is not uniform across its surface. The earliest and most visible deposits occur at the reservoir's inlet, due to the abrupt change in flow velocity caused by the vegetation change. This research employed a series of tests to understand this issue, revealing medium plasticity in the clay loam soil and low plasticity in the remaining soils, demonstrating how the presence of clay influences plastic behavior. This analysis raises the question of what other parameters should be evaluated for soil with these characteristics and under what circumstances its plasticity would reach its limit. Unconfined compression is used as a reference, showing that a drop can be observed under loads greater than 21 kPa. These analyses are considered in relation to reservoir management and the parameters that should be used for reservoir maintenance.

Determining the toposequence becomes a complex process in areas with dense vegetation, but it is crucial to evaluate the deposition patterns of the soil horizons and, where possible, quantify their thicknesses. The toposequence of the area shows that the characteristics of the profiles are similar across the different horizons. The organic matter layer, averaging 30 cm in thickness, is a noteworthy feature, raising questions about its management and the extent to which its excess weight or degradation affects reservoir management. Another key characteristic is the highly fractured bedrock. Given the lithology, in addition to characterizing it, what evaluations should be conducted are questions that lead to new avenues of research on the reservoir.

6 Conclusion

La Nitrera Natural Park is located on the Urrao Member of the Penderisco Formation, which has poorly consolidated deposits. It features a highly fractured sedimentary rock matrix with lenticular marine sediment bodies. The trace of the Mistrató Fault defines the foliation and direction of the ravine structures. The identified geomorphological units consist of three types of ridges: flat-topped, short, and steeply dipping, which define the drainage valley. The steep slopes of the streambeds (>25%) indicate that this area is subject to natural hazards, increasing the susceptibility of certain materials to erosion and mass wasting processes.

The geomorphological conditions of La Nitrera Natural Park jeopardize the future viability and lifespan of the reservoir and must be constantly evaluated, especially the structures affected by the Mistrató fault line. Furthermore, the morphometric assessment reveals that the watershed and reservoir responsible for supplying water to the municipality are very small, making it crucial to evaluate the intermittent watercourses and explore the possibility of making them permanent. The soil characterization reveals problems that, in the short term, could lead to greater supply difficulties than those already experienced during droughts. This is due not only to water scarcity but also to the observed characteristics: very soft soil under load, variability in plasticity, and irregular grain size classification. All of these factors will cause movement in the reservoir walls, and the accumulation of this movement will alter the flow velocity, leading to deposit buildup and reducing storage capacity.

7 Recommendations

Due to the surface processes that were evident in the fieldwork and the basic tests that were carried out to know the hardness and stability of the soil, a more in-depth analysis of these parameters is considered appropriate with the intention of protecting the reservoir and the trails of the Park.

It is necessary to analyze whether it is necessary to encourage in a controlled manner the fall of blocks or structures in

the steepest areas, which may pose a high hazard to visitors of La Nitrrera Natural Park in the future or damage the watercourses feeding the reservoir.

In areas showing scars from ancient landslides, it is necessary to establish a protocol that, without altering the fundamental purpose of the park as an ecological reserve, provides protection to prevent new landslides of the kind previously recorded in the area.

For the treatment of gravitational and mass processes, which do not require costly solutions, the use of shrub-type plants can be considered, which do not generate much excess weight on the walls, but whose roots are long enough to bind the soil.

Further analysis should be done of the soil surrounding the Santa Monica riverbed, which has a high presence of potentially harmful organic matter, since runoff effects could have alarming consequences for the water supply to the municipality's population.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Acuantioquia. (1996). Diseño de la presa de regulación. Informe final de diseño acueducto de Concordia. Integral Ingenieros consultores.

[2] Alcaldía de Concordia. (2015). Esquema de Ordenamiento Territorial. Alcaldía de Concordia Sistema de documentación e información Municipal. Recuperado de http://cdim.esap.edu.co/BancoConocimiento/C/concordia_-_antioquia_-_eot_-_2001/concordia__antioquia_-_eot_-_2001.asp

[3] ANH & Universidad EAFIT. (2007). Evaluación integral de la información geológica, geofísica y geoquímica de la cuenca Atrato y cuenca San Juan. Medellín: Agencia Nacional de Hidrocarburos. Recuperado de <http://www.anh.gov.co/Informacion-Geologica>
yGeofisica/Tesis/GEOLOGIA,%20GEOFISICA%20Y%20GEOQUIMICA%20CHOCO%202008.pdf

[4] ASTM D2487-11 (2006). Standard practice for classification of soils for engineering purposes (Unified soil classification system). ASTM International. <https://doi.org/10.1520/D2487-11>

[5] Cámara de Comercio de Medellín para Antioquia. (2015). Perfil socioeconómico de la subregión de Occidente. Antioquia, Colombia: Cámara de Comercio de Medellín. Recuperado de http://www.camaramedellin.com.co/site/Portals/0/Documentos/2017/Publicacionesregionales/153PerfilOccidente_Oct14.pdf.

[6] Cárdenas, J. I. & Restrepo, C. (2006). Patrimonio geológico y patrimonio minero de la cuenca carbonífera del suroeste antioqueño, Colombia. Boletín de Ciencias de la Tierra, (18), 91–102.

[7] Carvajal, J. H. (2012). Propuesta de estandarización de la cartografía geomorfológica en Colombia. Bogotá, Colombia: Servicio geológico colombiano. Recuperado de <https://www2.sgc.gov.co/Publicaciones/Cientificas/NoSeriadas/Documents/Propuesta%20de%20estandarizaci%C3%B3n.PD>

[8] Corantioquia. (2012). Actua, Plan de Acción 2012-2015. Administración Integral del Patrimonio Ambiental. Recuperado de http://www.corantioquia.gov.co/sitios/ExtranetCorantioquia/SiteAssets/Lists/AdministrarContenidos/AllItems/Plan_De_Accion_Corantioquia_2012-2015.pdf

[9] Deere, D. & Patton, F. (1971). Slope stability in residual soils. In Fourth Panamerican Conference on Soil

Mechanics and Foundation Engineering, American Society of Civil Engineers.

[10] FAO. (2007). Conservación de los recursos naturales para una agricultura sostenible. Recuperado de http://www.fao.org/ag/ca/training_materials/cd27-spanish/cp/introduction.pdf

[11] Flores, D. G.; Suvires, G. M. & Dalmaso, A. (2015). El análisis geomorfológico como base para el estudio de la vegetación nativa: Sierra Chica de Zonda, Precordillera Oriental de Argentina. Cuadernos de Investigación Geográfica, 41(2), 427–444. <https://doi.org/10.18172/cig.2710>

[12] Gobernación de Antioquia. (2015). Anuario Estadístico de Antioquia 2014. Antioquia, Colombia: Gobernación de Antioquia. Recuperado de <http://antioquia.gov.co/planeacion/anuario2014/anuarioestadistico-de-antioquia-2014.html>

[13] Gonzalez, F. & Soto, V. (2010). Estudio áreas de riesgo geomorfológico de la zona urbana y de expansión de la comuna de san antonio, V región. Universidad de Chile. Recuperado de <http://repositorio.uchile.cl/handle/2250/100669>

[14] Hernani, A. & Ramírez, J. J. (2002). Aspectos morfométricos y teóricos de un embalse tropical de alta montaña: represa La Fe, El Retiro, Colombia. Revista de la Academia Colombiana de Ciencias Exactas Físicas y Naturales, 26, 511–518.

[15] Herrera, J. & Toro, M. I. (2000). Lineamientos de la dimension física para el esquema de ordenamiento territorial del municipio de Concordia, Antioquia. Medellín: Universidad Nacional de Colombia sede Medellín.

[16] Hinds, A.; Legler, B.; Cravens, G.; Cunningham, B.; Distefano, R.; Draper, T. & Rimer, R. (2013). Watershed inventory and assessment. Missouri: Universidad de Missouri.

[17] I.N.V.E–121. (2007). Determinación del contenido orgánico en suelos mediante pérdida por ignición. I.N.V. E - 121-07. Instituto Nacional de Vías. Recuperado de ftp://ftp.unicauca.edu.co/Facultades/FIC/IngCivil/Especificaciones_Normas_INV-07/Normas/Norma%20INV%20E-121-07.pdf

[18] I.N.V.E–122. (2007). Determinación en laboratorio del contenido de agua (humedad) del suelo, roca y mezclas de suelo-agregado. I.N.V. E-122-07. Instituto Nacional de Vías. Recuperado de ftp://ftp.unicauca.edu.co/Facultades/FIC/IngCivil/Especificaciones_Normas_INV07/Normas/Norma%20INV%20E-122-07.pdf

[19] I.N.V.E–123. (2013). Análisis granulométrico de suelos por tamizado. I.N.V. E – 123 – 07. Instituto Nacional de Vías.

[20] I.N.V.E–125. (2013). Determinación del límite líquido de los suelos. I.N.V. E – 125 – 07. Instituto Nacional de Vías. Recuperado de ftp://ftp.unicauca.edu.co/Facultades/FIC/IngCivil/Especificaciones_Normas_INV-07/

[21] I.N.V.E–126. (2007). Límite plástico e índice de plasticidad de suelos. I.N.V. E – 126 – 07. Instituto Nacional de Vías. Recuperado de ftp://ftp.unicauca.edu.co/Facultades/FIC/IngCivil/Especificaciones_Normas_INV-07/

[22] I.N.V.E–152. (2008). Compresión inconfiada en muestras de suelos I.N.V. E – 152 – 07. Instituto Nacional de Vías. Recuperado de ftp://ftp.unicauca.edu.co/Facultades/FIC/IngCivil/Especificaciones_Normas_INV-07/Normas/Norma%20INV%20E-152-07.pdf

[23] ICONTEC. (2008). Calidad de suelo. Determinación del ph. Instituto Colombiano de Normas Técnicas y Certificación. Recuperado de http://www.icontec.org/Paginas/e_normas.aspx

[24] Marini, M. F. & Piccolo, M. C. (2005). Hidrogeomorfología de la cuenca del río Quequén Salado, Argentina. *Investigaciones Geográficas*, 59–71.

[25] Másmela, P. (2010). El paisaje como elemento de la ordenación territorial. Un análisis de paisaje desde su enfoque visual en el borde centro oriental de Medellín, Colombia (Doctoral dissertation, Universidad Nacional de Colombia. Sede Medellín).

[26] McCauley, A.; Jones, C. & Jacobsen, J. (2005). Basic soil properties. Soil and Water Management Module, 1(1), 1–12.

[27] Patiño, A. G.; Rivera, A. D. J. R.; Acosta, J. H. C.; López, A. A.; Rivillas, J. A. A. & Gallego, J. J. (2011). Estudio geológico-geomorfológico en el oriente cercano a Medellín, como apoyo a la búsqueda de actividad tectónica reciente. Boletín de Ciencias de la Tierra, (29), 39–54.

[28] Phillips, J. D. (2016). Landforms as extended composite phenotypes. Earth Surface Processes and Landforms, 41(1), 16–26.

[29] Piñeiro, D. A. (2015). Procesos hidrogeológicos en la cuenca de la quebrada de Tarapacá: análisis de las relaciones sedimentológicas con el abanico aluvial. Santiago de Chile: Universidad de Chile.

[30] Rincón, P. J. & Vegas, R. (2000). Aplicación de índices geomorfológicos de actividad tectónica reciente en el antepaís Bético. Geogaceta, 27, 139–141.

[31] Rojo, J. (2014). Estudio Topohidráulico e hidrológico sobre el río Altar. Universidad de Sonora. Recuperado de <http://tesis.uson.mx/digital/tesis/docs/8417/Capitulo3.pdf>

[32] Sánchez, J. (2015). Medir áreas y longitudes. Salamanca, España: Departamento de Geología. Recuperado de http://hidrologia.usal.es/Complementos/Medir_Areas.pdf

[33] Universidad de los Andes Venezuela. (2013). Geomorfología de cuencas. Recuperado de <http://ula.ve/ingenieria/oguerre/Geomorfologia.pdf>

[34] Villarroel, M. (2013). Determinación de parámetros y características hidrogeomorfológicas de una cuenca. Centro de Levantamientos Aeroespaciales y Aplicaciones SIG para el Desarrollo Sostenible de los Recursos Naturales CLAS. Recuperado de https://www.itc.nl/ilwis/documentation/_pdf/hidromorfologia_sp.pdf

[35] ICONTEC. (2006). Clasificación de suelos para propósitos de ingeniería (sistema de clasificación unificada de suelos). Instituto Colombiano de Normas Técnicas y Certificación. Recuperado de http://www.icontec.org/Paginas/e_normas.aspx

Notes

[1] Morales, D.; Vélez, F. & Guerrero, B. (2018). Caracterización hidrogeológica y geomorfológica de la cuenca y embalse del Parque Natural la Nitrera, Concordia (Antioquia). Rev. Fac. Cienc., 8(1), 73–99. DOI: <https://doi.org/10.15446/rev.fac.cienc.v8n1.71399>