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Research article

Water Sowing and harvesting application for water management on the slopes of a volcano

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ABSTRACT

The present study aims to elaborate a hydrogeological characterisation in the Water Sowing and Harvesting context. The study is focused on rural parishes in the Ecuadorian Andes that, despite their proximity to snow sources (Chimborazo glaciers), need more supply of this resource, to satisfy the demand of a population of 70,466 inhabitants. The study is based on hydrology and geomorphological analysis, a geophysical exploration, and a definition of water management strategies. The application of non-destructive geophysical methods and Geographic Information Systems support the hydrogeological study and the proposal of strategies for sustainable water management on the slopes of the Chimborazo volcano. An aquifer potential was identified (sand, gravel and fractured porphyritic andesites) with resistivity values between 51.3 and 157 Ω m at an approximate depth of 30 *m* from the geophysical characterisation addressed. This potential saturated zone is on the southern slope of the Chimborazo volcano within the hydrographic watershed, with favourable drainage networks for water accumulation. The aquifer shows a high-water saturation level but uncontrolled losses. As a consequence of these characteristics, alternatives for managing water resources are proposed, such as wells construction, using Water Sowing and Harvesting system methods ("camellones") based on Nature-Based Solutions, dam construction and environmental education. The different proposals are associated with the four sustainability axes of Brundtland (economic, social, environmental and cultural axis) and contribute to the sixth objective of the Sustainable Development Goal 2030 Agenda.

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1. Introduction

Climate change impacts on Earth are driven by variations in its climate system (e.g., temperature, precipitation), affecting the water cycle, atmospheric circulation, ocean, cryosphere, and biosphere [1]. The cryosphere, made up of snow, glaciers, permafrost, and lake and river ice, represents approximately 13% of the Earth's Surface [2,3]. According to the 2021 Intergovernmental Panel on Climate Change (IPPC) report [4], the cryosphere is undergoing rapid changes. Specifically, presenting loss of mass of frozen water (melt) in most regions. Even if global temperatures stabilise, glaciers will continue to lose mass for at least several decades, with the mass loss for the Greenland ice sheet sure and likely for Antarctica, during the 21st century [3].

Changes in the cryosphere have mainly impacted polar and high mountain ecosystems [5,6]. The cryosphere is an integral element of high mountain regions, which are home to approximately 10% of the world's population [7,8]. In addition to changes in the coverage of the components of the global cryosphere [9], the loss of the cryosphere generates changes in weather patterns [10], affects ecosystem functions [11], water security [12], originate geological hazards [13,14] and generate essential impacts on human activities (e.g., agriculture) [15,16].

Several scientific investigations have monitored physical disturbances in the mountain cryosphere [8]. Mountain glaciers, particularly in the tropics, are currently shrinking rapidly and are the leading indicator of climate change [17]. Beyond the physical impacts, cultural impacts are generated, such as how local people perceive and develop resilience to the loss of glaciers and snow in the Andes and the Himalayas [18].

Mountain glaciers comprise 85.2% of the world's glaciers [19]. These glaciers are essential in maintaining regional ecological stability and regulating runoff water supply [20]. In recent decades, numerous glacial lakes have formed throughout the tropical Andes as a result of a drastic receding of its glaciers since the late 1970s [21]. The Andes play an essential role in global ice cover, as it hosts the largest glaciated area in the Southern Hemisphere outside of Antarctica [22]. The retreat of the glaciers found in the tropical and dry Andes becomes a challenge for managing water resources and conserving the associated ecosystems during periods of drought, especially for the surrounding communities and the region [23].

The Tropical Andes is the world's most biodiverse hotspot, hosting numerous species-rich ecosystems. Millions of people depend on them as a source of fresh water, food, medicine and many other goods and services, including their cultural value [24]. The Andean páramos are unique and fragile high Andean ecosystems and provide many ecological services to human populations, such as water supply and carbon sequestration [25,26]. Carbon accumulation in these ecosystems is globally important for climate change mitigation and adaptation [27]. In the last decades, they have experienced striking alterations leading to biodiversity loss, including glacier retreat, the disappearance of water bodies and less foggy days [28]. These Andean ecosystems could lose about 31% of their current extent by 2050 [29]. In fact, melting glaciers are already causing water scarcity problems in the northern tropical Andes, especially in the Ecuadorian Andes [30,31].

The term "water harvesting" generally refers to the collection of runoff generated by rainfall in a particular area to provide water for human (potable), animal, or agricultural (non-potable) use [32]. Other authors define it as an ancient practice that involves the concentration of rainwater, snow melt or runoff in large areas for storage in the subsoil (sowing) and subsequent recovery (harvesting) in springs, wells, drainage galleries or water diversion courses [33,34]. Some examples of sowing and harvesting systems are the collection of roof water for domestic supply [35], atmospheric water collection [36], and structures such as dams or dikes for water abstraction and artificial groundwater recharge [37,38].

In response to the effects of climate change, it is common to find systems for Water Sowing and Harvesting (WS&H) in Latin America and the Iberian Peninsula. The WS&H systems of Ibero-America are water management models that apply Nature-based Solutions (NbS) and recover ancestral knowledge [34,39]. Among the most widely used (WS&H) systems in the Andes of Ecuador is qochas, or lakes (artificial wetlands), also called albarradas, atajados, jagüeyes andpataquis [34,40,41]. Another land and water use technique is the "camellones" or inka-wacho (complex canal networks), used as irrigation systems in agriculture in the highlands of Quito, Cayambe and San Pablo (Ecuador) [40].

The specific study area is the El Arenal sector (Guaranda-Ecuador). It is a páramo-type semi-desert region located on the slopes of the Chimborazo volcano in the Western Cordillera of the Andes [42]. The water resource is obtained mainly from the runoff from the Chimborazo glaciers, which form rivers and streams, and from the outcrops of groundwater located on the western flank of the volcano [43,44]. This freshwater is used for consumption and productive and industrial activities in rural communities and surrounding cities [43].

However, the sector is currently facing a water deficit associated with changes in the glacier of the Chimborazo volcano due to effects related to climate change, which include a reduction of the glacier, an increase in temperature and a decrease in rainfall [43,45,46]—added to anthropogenic factors such as the expansion of the agricultural frontier, deforestation, fires, water pollution, among others [43,47]. This factor generates a water supply problem, which becomes a challenge in the dry season (May–November), affecting the population of the communities in their daily lives, as well as directly affecting agriculture and livestock [44,48,49].

Due to the problem of scarcity of fresh water, civil works have been carried out to improve the water supply. However, the shortage has continued due to the low flows concerning the high demand for water [49]. For this reason, local governments seek alternative solutions that can comprehensively help water management.

The aim of the study is summarised in three aspects: i) carry out a geological survey of the El Arenal sector through Geographic Information Systems (GIS), in situ reconnaissance and rock/soil sampling to characterize the terrain and knowledge of the local geological setting, ii) develop geophysical prospecting studies using the apparent resistivity (Vertical Electrical Sounding (VES) to define hydrogeological interest areas. The Refraction Seismic (RS) method is also developed to classify the materials typology for use in a dam, iii) provide alternatives for water management considering ancestral techniques of WS&H based on the concepts of NbS and contribution to sustainability axes of Brundtland and Sustainable Development Goals (SDG).

Consequently, it is crucial to increase our scientific knowledge by adding ancestral knowledge with WS&H techniques, which lead to proposing new and innovative strategies for managing and conserving water sources in the Andean páramos since they represent important regional carbon reserves. The study methodology combines scientific techniques (geoelectric, refraction seismic, geological knowledge) and ancestral knowledge. This approach revitalizes the ancient NbS with sustainability criteria (SDGs), focused on Andean ecosystems in mitigation and adaptation to climate change.

2. Geographical and geological setting

2.1. Geographical setting

The study area includes the El Arenal sector, located east of the Guaranda canton, on the border between Bolívar and Chimborazo provinces. This sector is a páramo-type semi-desert region that extends towards the west slope of the Chimborazo volcano and which also belongs to the Chimborazo Faunal Production Reserve (RPFCH acronym in Spanish) [42,43] (Fig. 1a and b).

El Arenal is at a height greater than 3000 *m*. a.s.l. It presents hilly and mountainous reliefs, flattening surfaces, low terraces, and

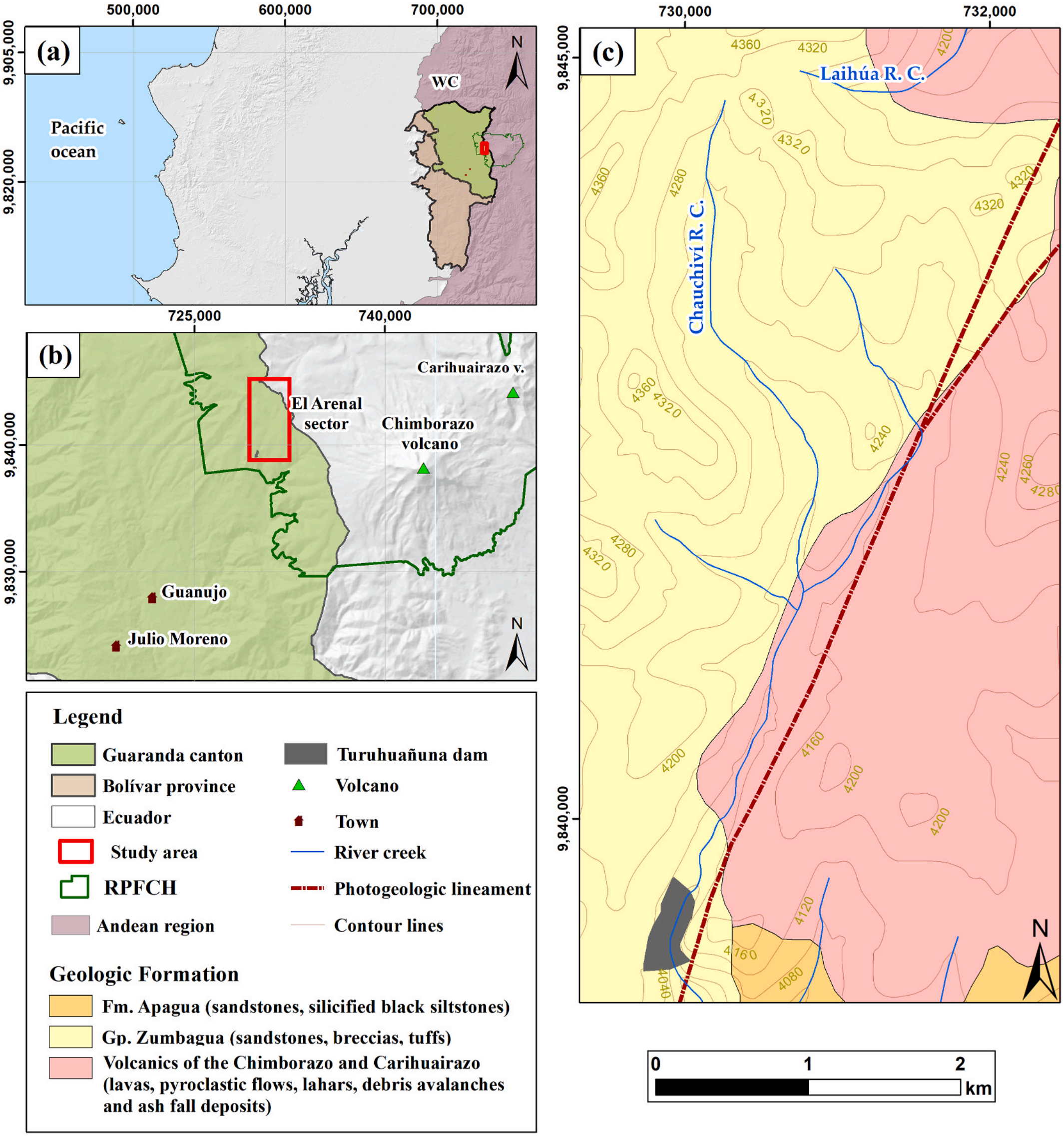

Fig. 1. Geographical and geological setting: (a) Bolivar province, Guaranda canton and Chimborazo Fauna Production Reserve area (RPFCH, by its acronym in Spanish) within the study zone; (b) "El Arenal" sector and principal towns mentioned in the study; (c) Geological map of the "El Arenal" sector.

depressed areas in the highlands of the páramo. The temperatures in El Arenal are the lowest in the canton, reaching average temperatures of up to 2 °C [50].

The direct beneficiaries of the study are the communities of the Guanujo and Julio Moreno parishes of the Guaranda canton, located to the southwest of the study sector (Fig. 1b). In these parishes, the total population reaches 55,374 and 2948 inhabitants, respectively, according to data from the last census (2010) [51]. With an estimated 66,905 inhabitants in Guanujo and 3561 inhabitants in Julio Moreno, according to the cantonal projections for the year 2022 [52]. The main economic activities linked to these parishes are agro-productive, livestock, fishing, tourism, manufacturing and crafts, and forestry [53].

2.2. Geological setting

Regionally, the province of Bolívar is located in the Andean zone, within the Northern Andes Mountain chain, in the Western Cordillera sector. The volcanic front of the Western Cordillera includes andesitic to dacitic composite stratovolcanoes, such as the El Chimborazo volcano [54] (Fig. 1a).

Locally, the geology of the sector is complex and diverse due to the presence of geological formations of volcanic and sedimentary origin, with alluvial deposits and unconsolidated glaciers [55]. The study area within the El Arenal sector includes three lithological terrains (Fig. 1c). The youngest lithology, located to the East, corresponds to the recent Quaternary Chimborazo Volcanics, which provides for lavas, pyroclastic flows, lahars, debris avalanches, and ashfall deposits of andesitic to dacitic composition located on the flanks of the Chimborazo volcano [56]. Followed by the lithology of the West, which corresponds to the Zumbagua Group from the Middle to Late Miocene, and includes coarse-grained sandstones, debritic breccias on a supported matrix, acidic to intermediate tuffs, and tuffaceous sandstones, characterised by their richness in lithics and quartz-feldspar-amphibole crystals [57]. The oldest lithology, located to the south, corresponds to the Paleocene-Eocene Apagua Formation, which includes fine-grained sandstones in fine to medium strata, interspersed with silicified black siltstones in the Bouma sequence and coarser-grained massive sandstones, characterised due to the high content of quartz, sericite and the absence of mafic minerals [58]. At a structural level, photogeological lineaments with NNE and NE directions are observed in areas that coincide with the prominent drainage directions and are probably associated with faults.

Regarding geomorphology, Guaranda has a very rugged topography due to the presence of the Western Cordillera of the Andes and small valleys (Guanujo, Guaranda, San Simón) and more extensive valleys (San Luis de Pambil) of the branch of the Cordillera de Chimbo [59]. The study area has also been modelled by glacial, periglacial and snowy morphoclimatic actions of the cold Quaternary, a time when the glaciers fell to 3200 and 3800 m above sea level [60].

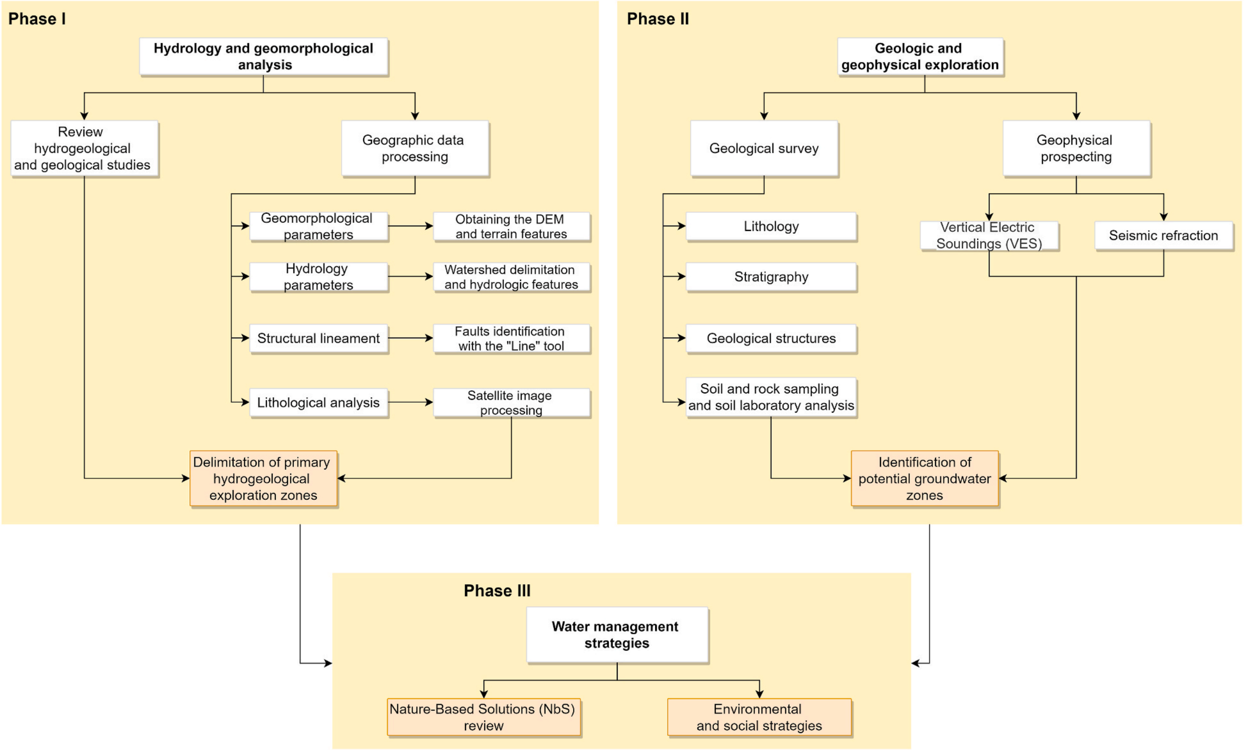

Fig. 2. Scheme of the methodology followed in this study.

3. Methods

To collect and use runoff water, hydrological analysis and geological characterisation of the materials that make up the terrain of the western flank of the Chimborazo volcano are required. Therefore, the work methodology was structured in three main phases (Fig. 2): i) hydrology and geomorphological analysis, ii) geologic and geophysical exploration using non-destructive geophysical methods, and iii) water management strategies. The procedure followed, and its limitations will be described in detail in each section of the study phases.

3.1. Phase I: hydrology and geomorphological analysis

Phase I consists of office work that includes geospatial analysis using GIS techniques, preparation of hydrological and hydrogeological base cartography, and evaluation of climatic conditions to obtain a first approximation of groundwater exploration zones in the study area. Additionally, in this phase, the primary hydrogeological exploration area was delimited by locating hydraulic works (e.g., Turuhuañuna dam) and identifying the drainage area or micro-watershed that supplies it. To obtain the size of the micro-watershed, the Digital Elevation Model (DEM) of the site, obtained from the ALOS PALSAR satellite image [61], was processed. The processing was carried out with the Hydrology tools of the ArcMap software, which uses the DEM as input data to calculate the flow direction and accumulation parameters by locating the point of discharge or outlet of the volume of water, obtaining the watershed in raster format.

For the multitemporal analysis, a statistical analysis was carried out from 1990 to 2019 using the precipitation data from the climatic data set of the Climatic Research Unit Temperature (CRUTEM) database [62]. First, the sequences of drought and humidity in the study area were determined by the calculated accumulated standard deviation.

Regarding the base cartography, the present research made maps of drainage order, slope, and structural guidelines and reviewed the geomorphological information of the study area. Specifically, the morphometric parameters (perimeter, area, length, Gravelius coefficient, drainage density and order of the drainage zone that feeds the dam) were obtained. In addition, the slope map was prepared to compare slope ranges and identify geoforms from the DEM of the study area.

Additionally, the structural guidelines were delimited using the LINE tool of the PCI GEOMATICA software, making known the possible existing faults and fractures. Lineaments greater than 500 *m* were only taken as they were more representative of the area. Phase I allowed us to obtain a vision of the hydrological environment and the terrain, which served to plan subsequent field campaigns and the delimitation of primary hydrogeological exploration areas.

3.2. Phase II: geologic and geophysical exploration

Phase II comprises two stages: i) geological survey and ii) geophysical prospecting.

For the geological survey, several field trips were made for the lithological and stratigraphic descriptions at the mesoscopic scale, as well as the taking of structural measurements (strike and dip), soil and rock samples, and subsequent laboratory analysis, to know the quality and characterisation of the materials of the sector. The selection of sites of interest was established in office work studies previously conducted. The tests carried out were granulometry, Atterberg limits, permeability and hardness (Los Angeles Abrasion). The information obtained allowed the correlation between the materials observed in situ with the geophysical interpretations that will be present later. In addition, the geomechanical studies intend to provide alternatives for using materials in situ for constructing hydraulic works (dams).

The second stage consisted of developing a geophysical survey, which was carried out in the areas close to the potential construction site of the dam, where the variations in the land's topography were less than 10%. Two geophysical methods were used, VES and RS, which are often used for subsoil studies, as they are non-invasive and low-cost methods [63].

VES delineated potential groundwater zones [64]. Specifically, 3 VES have been made with Schlumberger configuration with a maximum opening between electrodes of 5 *m*. The Schlumberger array was chosen because it provides better resolution and has greater probing depth than other methods [65]. An ABEM TERRAMETER SAS 1000 resistivity meter was used to measure the apparent resistivity at each VES station. Acceptable readings were obtained at a maximum standard deviation of 1%. At every station, the field data were converted to apparent resistivity by multiplying the resistances by the geometric factor [66] (Equation (01)) [67].

$$\rho = \mathrm{R} \text{ x } g \tag{1}$$

Hence:

ρ: resistivity of the subsurface material in ohms per meter (Ω.m).

R: electrical resistance of the conductor in ohms (Ω).

g: the geometric factor that depends exclusively on the arrangement of the electrodes.

The final apparent resistivity data was processed using the IPI2win software [68], with which the apparent resistivity curves were obtained. The geoelectric layers and their thicknesses were established according to the resistivities of the subsoil materials in the study area. The main limitation of the VES application in this study is the 1D vision of subsoil that the method provides, restricting the knowledge of lateral resistivity variability and the definition of the structural geometry of the subsoil (data resolution). However, in the present investigation, the knowledge and correlation of the local and regional geology of the area through in situ reconnaissance and laboratory tests allow for overcoming the limitations of this technique and carrying out an adequate interpretation of the subsoil.

On the other hand, the RS was used to determine the depth of the hard rock [69] for the future construction of the dam piles. The RS method is based on the generation of seismic energy from a point on the surface and the measurement of the travel times of seismic waves refracted at different speeds by the interfaces of the subsurface layers [69]. For this purpose, two seismic profiles were made, each one with a seismic laying distance between geophones of 3 *m*. An 8 kg hammer was used as the source of seismic movements for this study, as 24 geophones for detecting seismic signals and the ABEM Terraloc Pro2 equipment for measuring the travel times of the seismic waves.

On each profile, at least three shots were done in different positions of the seismic grid (one at each end and one in the centre) to improve arrival modelling and, at the same time, minimise data noise (windy weather). The data obtained from the arrival times of the waves were processed in the IXRefraX s/n 2015 Software [70]. The software allows modification of the waves' amplitudes to identify with better precision the arrival times of the seismic traces and generate demochrons of Dethe seismic laying and the velocity profile of P waves (Vp).

3.3. Phase III: water management strategies

Phase III includes integrating the results obtained in the previous phases, the areas preliminarily delimited for hydrogeological exploration and groundwater potential. Based on the hydrogeological investigations and review of NbS, a water management proposal was prepared considering the ancestral knowledge in the Andean community, which allows the infiltration and recharge of the identified aquifer, as well as the sustainability of the associated ecosystem. Specifically, the four pillars of sustainability established by Brundtland [71,72], the framework of components related to water of the 2030 Agenda for Sustainable Development of the United Nations and the SDG were analyzed [73,74], as well as the regulatory axes of Ecuador such as "Law organic water resources, uses and exploitation of water" [75] and other policies and their challenges around water that consider the NbS [76–78]. Strategies for water resource management were proposed according to the model adapted in this study of the three spheres of sustainability [79,80], shown in Fig. 3, contributing to the integral approach from the environmental, social, economic and cultural perspectives.

4. Results

4.1. Hydrological and geomorphological setting

The drainage watershed of the El Arenal community zone that descends towards the area where the Turuhuañuna dam is located

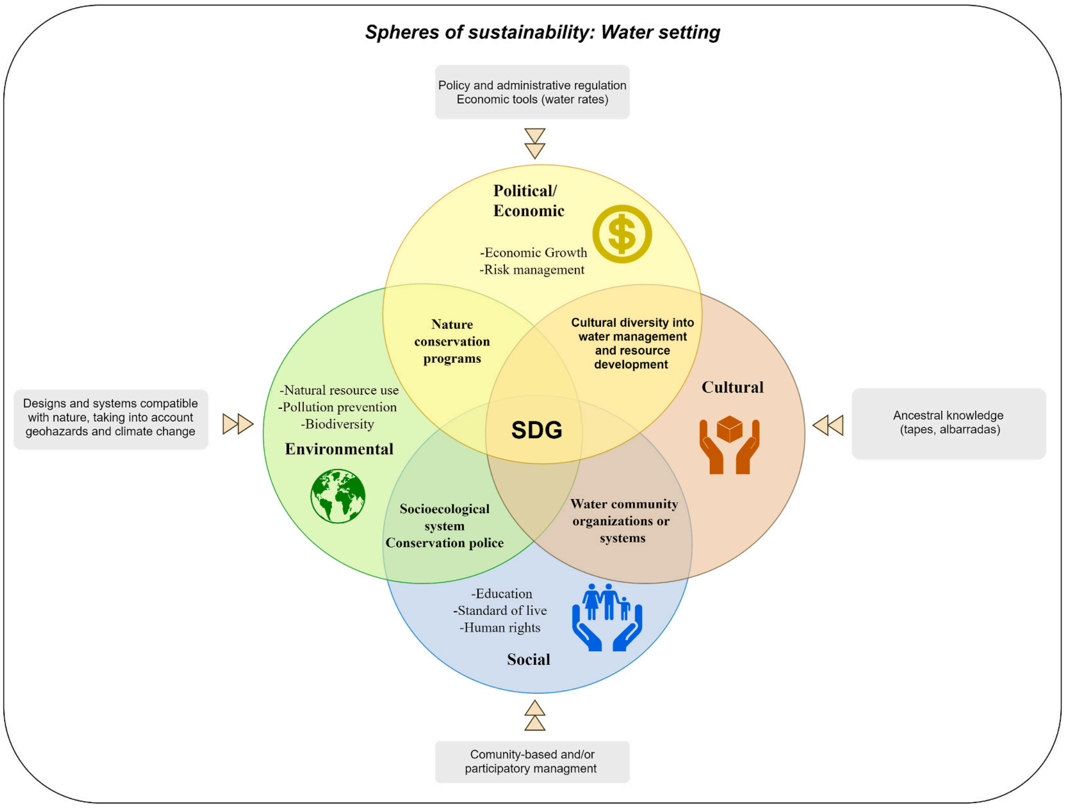

Fig. 3. Relationships between environmental, social, economic and cultural sustainability dimensions modified from Refs. [79,80]. Abbreviations: SDG: Sustainable Development Goals.

was determined, from which only the site of the drainage basin that feeds the dam was delimited (Fig. 4b). A summary of the morphometric parameters calculated for the drainage basin that feeds the dam is shown in Table 1. The morphometric parameters indicate that the watershed has an oval-oblong to rectangular-oblong shape (Gravelius coefficient >1.5), with a drainage network with fourth-order morphological classification and a high drainage density.

A raster of slopes of the study area was calculated. This raster was classified into five ranges (Fig. 5), for the comparison of slope ranges and geomorphological justification, according to Ref. [81] and Van Zuidam (1986) [82] (Table 2). From this classification, the variation of the slope in the study area was determined, where degradation of slope values from East to West is observed, from reliefs made up of steep slopes (slopes between 30° and 80°) to hills and inter-mountain plains (slopes <30°). Furthermore, the location of the optimal dam was identified (Fig. 5); it is located south of the basin, one of the flattest areas. Therefore, it will receive drainage runoff from the watershed due to its conditions.

Structural lines were determined in the study area by processing the DEM (Fig. 6). Fourteen lineaments over 500 *m* long were identified, with a predominant Northeast-Southwest direction. These guidelines can be associated with fractures or geological faults in place.

In the multitemporal analysis, a high value was identified in the precipitation cumulative deviation corresponding to the year 1998 associated with the event of the “El Niño" phenomenon (Fig. 7). In the dry sequence from 1998 to 2013, the lowest value of precipitation cumulative deviation stands out, coinciding with a 21% decrease in the ice-covered area on Chimborazo reported from 1968 to 2013 [83]. The study area generally presents low rainfall characteristics of a glacial environment.

4.2. Geologic and geophysical survey

4.2.1. Geological and geomechanical characterisation

Ten outcrops were geologically characterised along the drainage zone that supplies the Turuhuañuna dam (Fig. 8). The summarised lithology descriptions in the mesoscopic scale obtained at each point of the field survey are shown in Table 3. In general, sand deposits were found; deposits of materials of pyroclastic origin with pumice, lapilli and ashes; silt deposits; and massive outcrops of porphyritic andesites often weathered, heavily eroded and fractured. A typo stratigraphic column is showed in (Fig. 9) corresponding to Survey Station 3, it includes almost all lithologies identified in the study area, intercalations of sands, pumices, lapilli and ash at the top, and

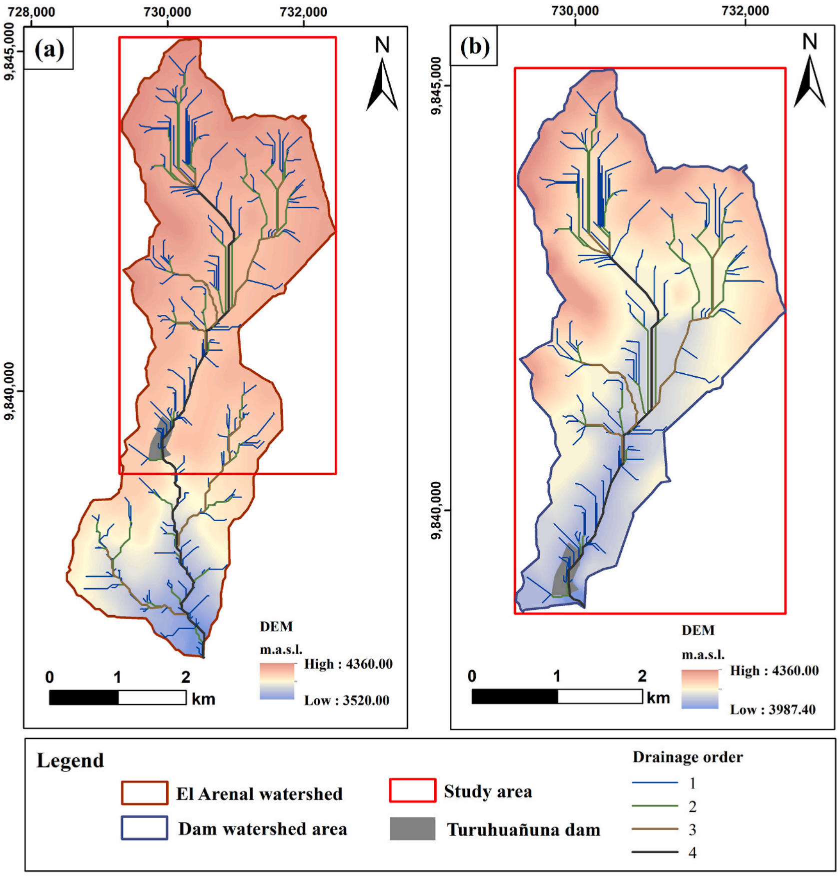

Fig. 4. Watershed delimitation and drainage: (a) El Arenal watershed; (b) Dam watershed area.

Table 1
Morphometric parameters of the drainage that supplies the Turuhuañuna dam.

Parameter	Value
Perimeter	17.66 km
Area	10.87 km^2
Watershed length	7.82 *m*
Gravelius coefficient	1.50
Drainage density	5.39 km/km^2
Watershed order	Fourth order

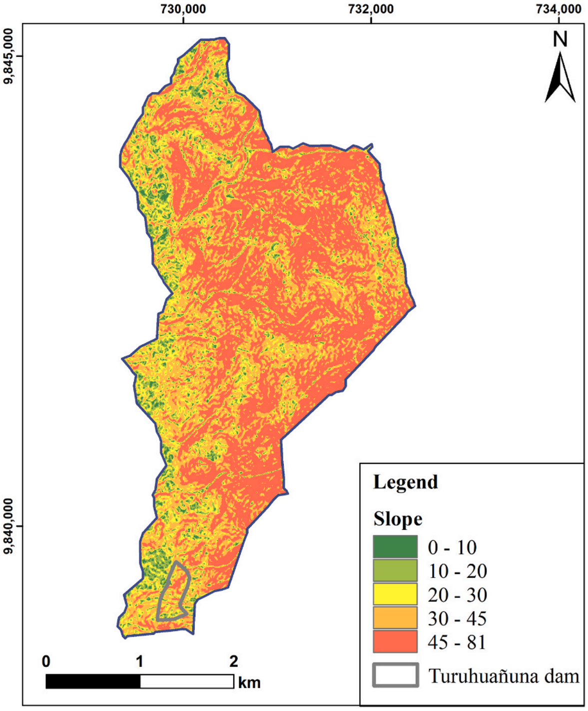

Fig. 5. The slope grade range in the study area classified according to Ref. [81] and Van Zuidam (1986) [82] in dark green as slope type "Moderate", light green "Steep slope", yellow "Moderately Steep", orange "Very Steep" and red "Cliff."

Table 2
Slope range and geomorphological unities classified according to (Araya-Vergara and Börgel, 1972) and Van Zuidam (1986) (Van Zuidam, 1986).

Slope grade	Slope type	Geoform
0–10°	Moderate	Intermountain Plain
10.1°–20°	Steep	High Hills
20.1°–30°	Moderately Steep	Mountainous Slopes with Steep Gradients
30.1°–45°	Very Steep	Steep Slopes
>45°	Cliff	Steep Slopes

fractured porphyritic andesites to the base.

Four points were determined for sampling materials in the areas with the most incredible abundance (Figura 8) to know the mechanical behaviour for its use as construction materials for the Turuhuañuna dam. The materials sampled and analyzed in the laboratory were: sand, silt and andesites. The tests carried out are within the ASTM D 422–63, ASTM D 1140, ASTM D2434 and ASSHTO T-215 standards of the American Society for Testing and Materials (ASTM) and included soil classification using the Unified Soil Classification System (USCS), wet (%W), plastic index (%PI), plastic limit (%PL), liquid limit (%LL) and permeability (P) in the silts; soil granulometry in the sands; and Mohs hardness (MH) in the andesites. The summarised result of the testing on each material is shown in Table 4. According to the test results, it was obtained that the fine materials correspond to silts and present low plasticity, according to SUCS. Dark silts have a moderate permeability with a value of P = 1.64 × 10-5 cm/s. The sand was classified as poorly

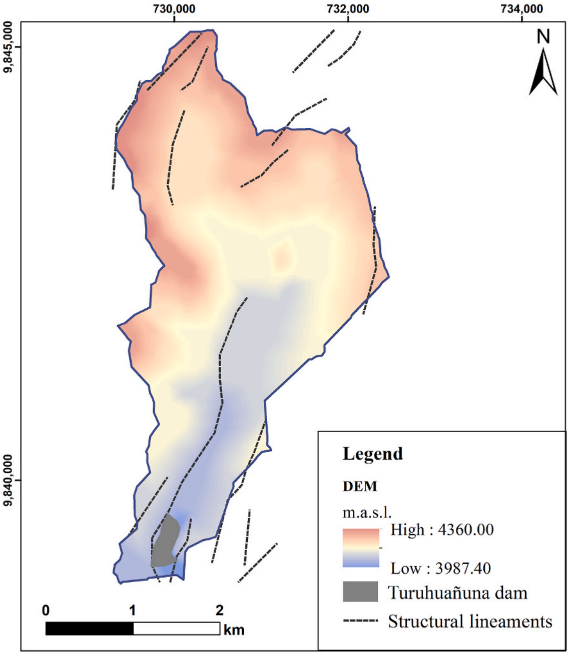

Fig. 6. Principal Structural lineaments in dam watershed area.

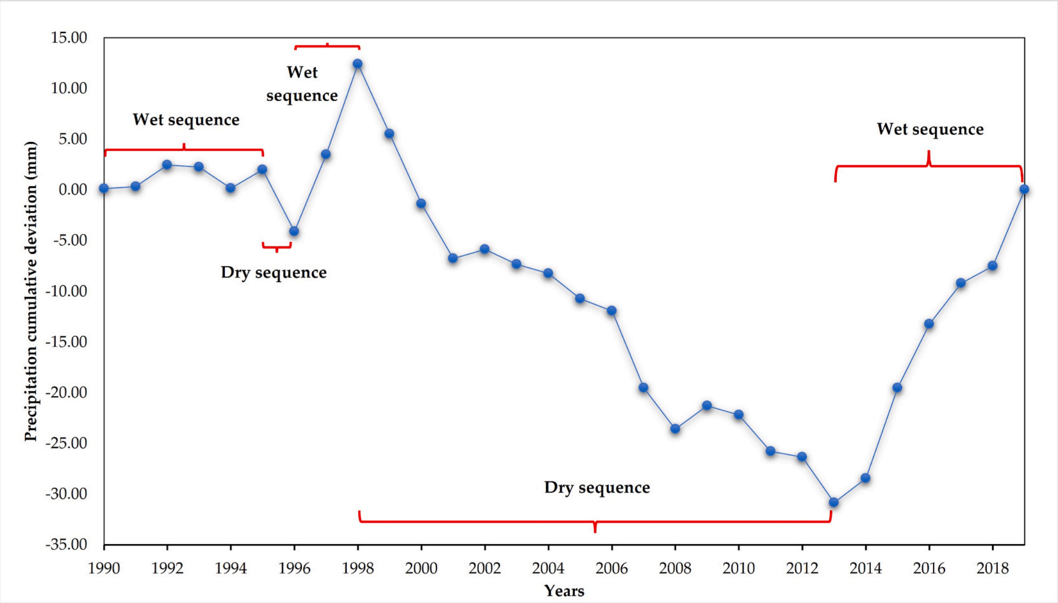

Fig. 7. Precipitation cumulative deviation of the "El Arenal" area in the period 1990–2019 using data from CRUTEM database showing wet and dry sequences.

graded sand with 4.8% of fine materials. And the porphyritic andesites presented an MH = 5 corresponding to medium hardness.

4.2.2. Geophysical interpretation

- Vertical Electrical Sounding

Three VES were conducted in the El Arenal sector study zone using Schlumberger electrode resistivity configuration (Fig. 10). The results were plotted to get a curve on a bi-log graph (Fig. 11a, b, 11c). The summarised result of the interpreted field data in software is

Table 3
Location and lithological description of the field campaign stations.

Station	Coordinates (m)	Height (m)	Lithological description
1	732147.17 E, 9841437.12 N	3.4	Lower unit of light grey coarse sand stratifications. Upper unit of light and dark brown stratifications of pyroclastic material (pumice, lapilli, ashes). Strike: N 166, Dip: 7°, Dip direction: SW
2	730911.05 E, 9840458.35 N	8	Massive porphyritic andesite rocks with plagioclase and lithic fragments and alteration by iron oxides. High erosion by artisanal mining.
3	730873.91 E, 9840427.77 N	7.5	Significantly eroded lower unit of massive porphyritic andesite rocks with plagioclase and lithic fragments and alteration by iron oxides. Upper unit of intercalation of stratifications of dark and light sands and pyroclastic material. Strike: N 233, Dip: 26°, Dip direction: NW
4	731870.49 E, 9843272.25 N	10	Massive porphyritic andesite rocks with plagioclase and lithic fragments and alteration by iron oxides. High weathering and erosion.
5	731899.86 E, 9843850.41 N	1.5	Stratifications of medium to coarse light grey sands interbedded with light brown pyroclastic material (pumice, lapilli, ashes). Strike: N 130, Dip: 20°, Dip direction: SW
6	730762.19 E, 9841094.07 N	5.7	Lower unit of lahar deposits with the presence of boulders. Upper unit of dark brown coarse sands. Strike: N 280, Dip: 7°, Dip direction: NE
7	730311.61 E, 9839965.31 N	8.5	Aeolian deposit of coarse dark grey sand.
8	730113.45 E, 9839758.86 N	4	Massive porphyritic andesite rocks with plagioclase and lithic fragments and alteration by iron oxides. High weathering and erosion.
9	729767.00 E, 9839223.36 N	28	Massive porphyritic andesite rocks with plagioclase and lithic fragments and alteration by iron oxides. High erosion, fracturing and weathering. Strike: N 144, Dip: 79°, Dip direction: SW
10	729911.06 E, 9839329.53 N	3.5	Deposit of black silts with alteration of iron oxides by weathering and presence of pebbles towards the base.

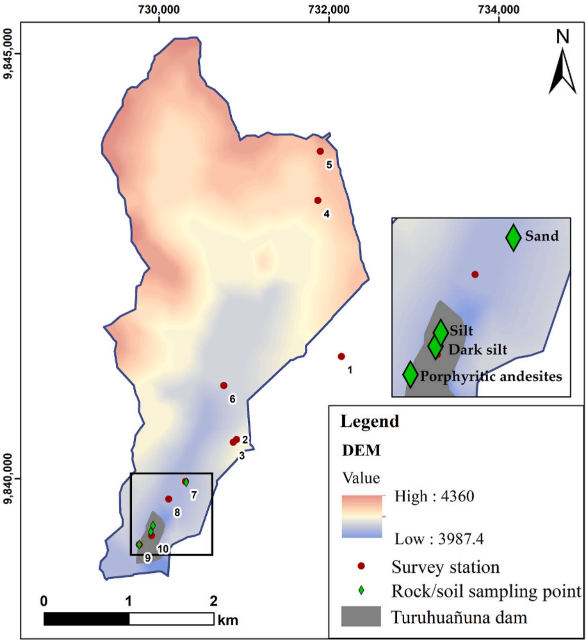

Fig. 8. Field campaign stations and sampling points in the dam watershed area.

shown in Table 5, with values of resistivity, thickness, depth, and correlated lithology. It is essential to clarify that the lithologies and their depths in the subsoil are approximations since there are no fixed ranges of resistivities. However, they vary depending on parameters such as fractures or water saturation.

In the VES01-CH and VES02-CH sounding, five similar lithological units were distinguished. The topsoil, composed of fractured porphyritic andesites, is relatively thin with various resistivity and thickness ranging from 403 to 648 Ω m and 1.08–1.12 *m*, respectively. The second layer has resistivity values between 601 and 880 Ω m and comprises porphyritic andesites, very fractured and compact, respectively. The third layer has resistivity values between 137 and 1203 Ω m and comprises porphyritic andesites,

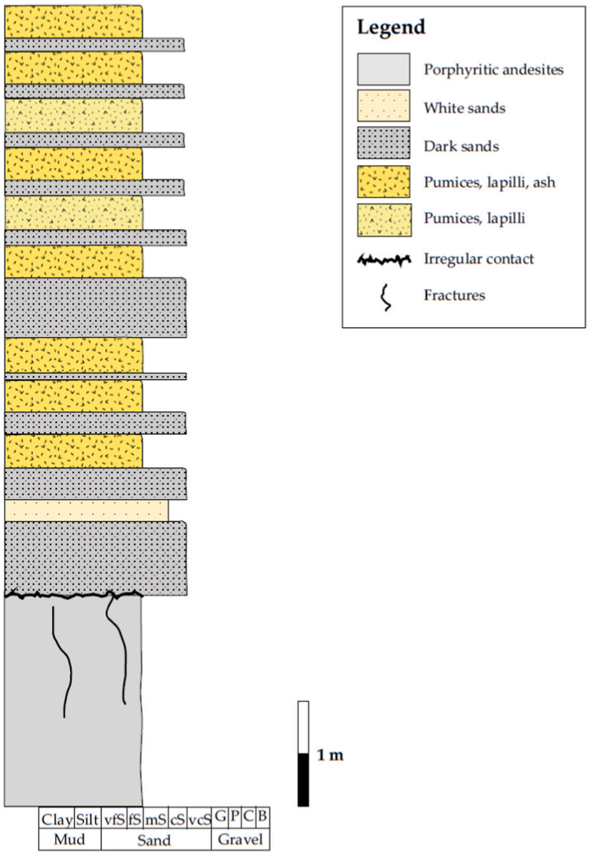

Fig. 9. Stratigraphic column from the outcrop at Geologic Station 3.

Table 4
Soil and rock testing results.

Material	Testing results
Silt	USCS: low plasticity silt (ML) %W: 43.55 %PI: 8 %PL: 36 %LL: 44
Dark Silt	USCS: low plasticity silt (ML) %W: 43.91 %PI: 6 %PL: 34 %LL: 40 P: 1.64×10^{-5} cm/s – clean, compact silt, suitable for drainage
Sand	Soil granulometry: 4.8% of fine materials (poorly graded sand)
Porphyritic andesites	MH: 5 (medium hardness)

compacted and fractured. The fourth layer has resistivity values between 22.1 and 106 Ω m and includes mainly sand and gravel with water saturation. Finally, the fifth layer has resistivity values between 161 and 195 Ω m and comprises very fractured porphyritic andesites with possible water saturation.

In VES03-CH, six lithological units were differentiated. In general, layers of very fractured porphyritic andesites interbedded with layers of gravel, sand, and silt, all saturated with water. The topsoil, composed of very fractured porphyritic andesites with water saturation, is relatively thin with resistivity and thickness of 142 Ω m and 1.14 *m*, respectively. The second layer has a resistivity value of 9.71 Ω m and comprises a fine layer of clay with water saturation. The third layer has a resistivity value of 180 Ω m and includes very fractured porphyritic andesites with water saturation. The fourth layer has a resistivity value of 51.3 Ω m and comprises mainly sand and gravel with water saturation. The fifth layer has a resistivity value of 157 Ω m and includes very fractured porphyritic andesites with water saturation. Finally, the sixth layer has a resistivity value of 65.6 Ω m and comprises sand and gravel with water saturation. The water saturation in all the VES03-CH units refers to a water-saturated zone where a possible aquifer can be characterised,

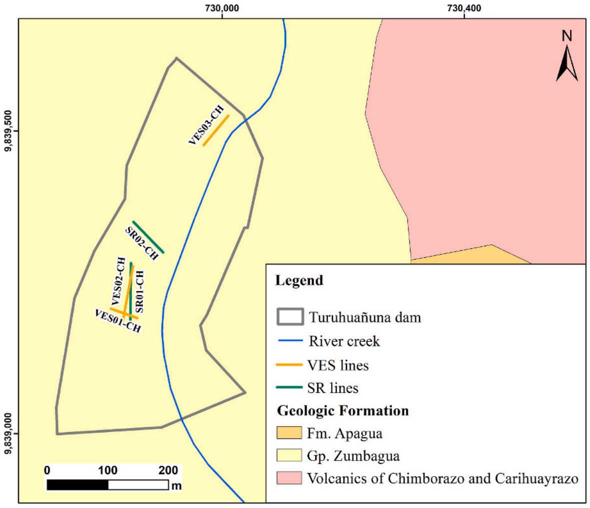

Fig. 10. Location of VES lines and RS lines.

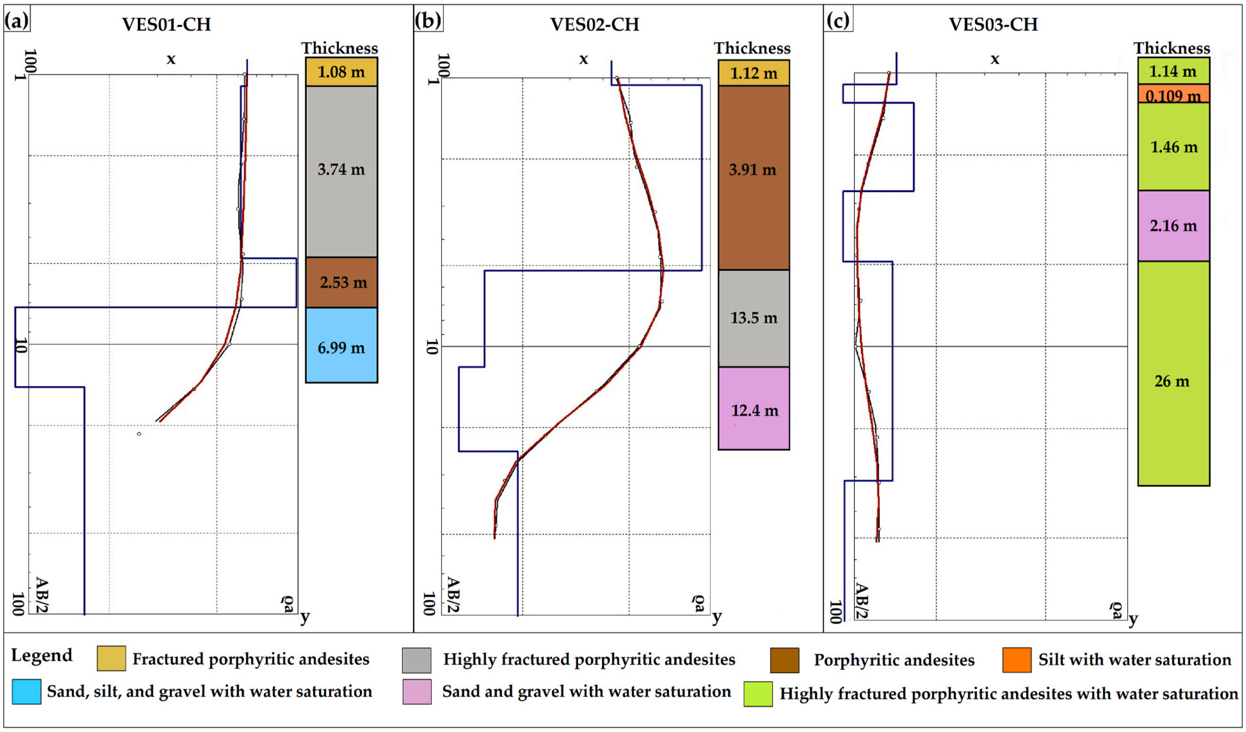

Fig. 11. VES modelled curves using the IPI2win software (a) Curve for VES01-CH; (b) Curve for VES02-CH; (c) Curve for VES03-CH.

beginning at a depth of 30.9 *m*. This potential aquifer (delimited for its water mirror in the surface) can be determined as a recharge zone for the dam's reservoir (Fig. 12).

- Refraction Seismic

Two RS lines were made in the study area of El Arenal (Fig. 10). Each line's velocity profile was determined based on the analysis of the obtained demochromes, which is a 2-D *P*-velocity distribution. The surveyed profile SR01-CH (Fig. 13a) reveals two layers of refraction. The first layer, with a thickness of 6.5 *m* and a velocity of 158 m/s, has been interpreted as a vegetal soil cover. The second layer, with a thickness greater than 6.5 *m* and a speed of 859 m/s, has been interpreted as consolidated pyroclastic materials with good density. The surveyed profile SR02-CH (Fig. 13b) reveal three refraction layers. The first layer, with a thickness of 1.2 *m* and a speed of

Table 5
VES Interpretation showing VES coordinates, layer resistivity, thickness and depth.

VES	Coordinates (m)	Layer resistivity $\rho 1$—ρn (Ωm)	Thickness $h1$—hn (m)	Depth $D1$—Dn (m)	Lithological Interpretation
1	729834.7 E, 9839200.2 N	648	1.08	1.08	Fractured porphyritic andesites
		601	3.74	4.82	Highly fractured porphyritic andesites
		1203	2.53	7.35	Porphyritic andesites
		22.1	6.99	14.3	Sand, silt, and gravel with water saturation
		161			Highly fractured porphyritic andesites with possible water saturation
2	729841.73 E, 9839226.56 N	403	1.12	1.12	Fractured porphyritic andesites
		880	3.91	5.03	Porphyritic andesites
		137	13.5	18.5	Highly fractured porphyritic andesites
		106	12.4	30.9	Sand and gravel with water saturation
		195			Highly fractured porphyritic andesites with possible water saturation
3	729991.05 E, 9839498.636 N	142	1.14	1.14	Highly fractured porphyritic andesites with water saturation
		9.71	0.109	1.25	Silt with water saturation
		180	1.46	2.71	Highly fractured porphyritic andesites with water saturation
		51.3	2.16	4.87	Sands and gravels with water saturation
		157	26	30.9	Highly fractured porphyritic andesites with water saturation
		65.6			Sands and gravels with water saturation

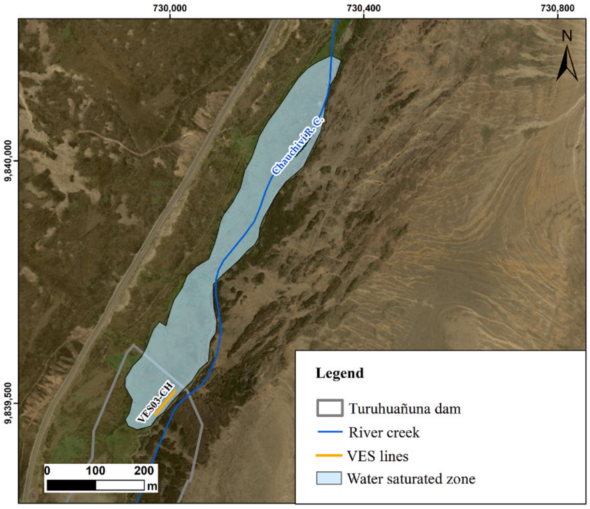

Fig. 12. Water saturated zone defined in the present study.

41 m/s, is associated with a vegetal soil cover. The second layer, with a thickness of 3.7 *m* and a rate of 755 m/s, corresponds to consolidated pyroclastic materials with good density. And the third layer, with a thickness greater than 3.7 *m* and a velocity of 1468 m/s, has been interpreted as a continuation of pyroclastic materials (porphyritic andesites). Based on these seismic profiles, it is interpreted that the hard rock would be found at a depth of approximately 5 *m* and would be made up of compact porphyritic andesites.

4.3. Water management proposal

The water management proposal of this study, once the hydrogeological model has been defined, is defined on five practices (Fig. 14) aimed at planning, developing and managing the use of available water resources in the area. In specific.

1. Drilling of wells. Drilling four wells is recommended to allow water extraction with an adequate flow to feed the dam's reservoir.
2. Construction of "camellones" to control the entry and exit of water and optimise water percolation into the aquifer. It is suggested to build four "camellones" (Fig. 15).
3. Construction of the Turuhuañuna Multipurpose Dam, which allows the use and distribution of fresh water.
4. Planning and execution of workshops/conferences aimed at environmental education to involve all the beneficiary communities to generate social awareness about water resources and their relationship with climate change and anthropogenic activities.

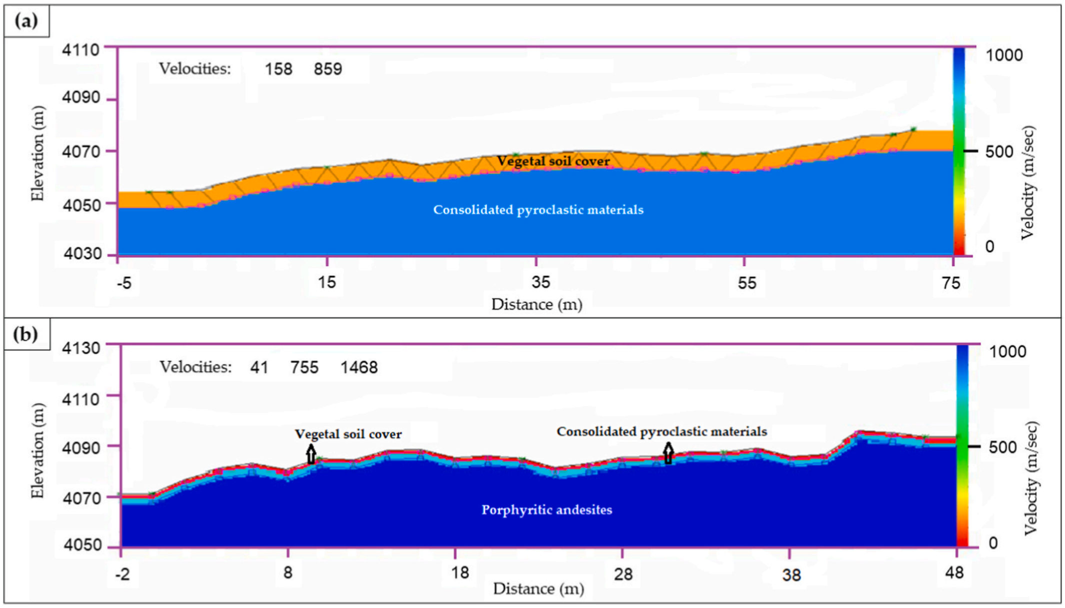

Fig. 13. Seismic line velocity distribution profiles using IXRefraX s/n 2015 Software. (a) SR-01 profile; (b) SR-02 profile.

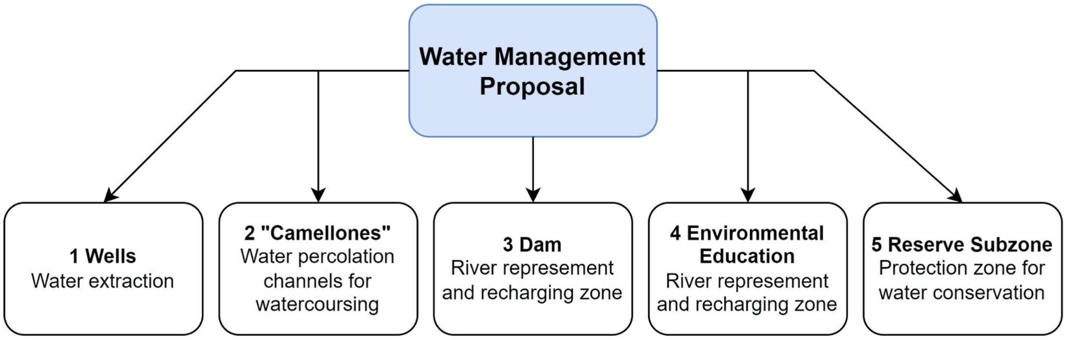

Fig. 14. The five water management proposals established for the "El Arenal" sector.

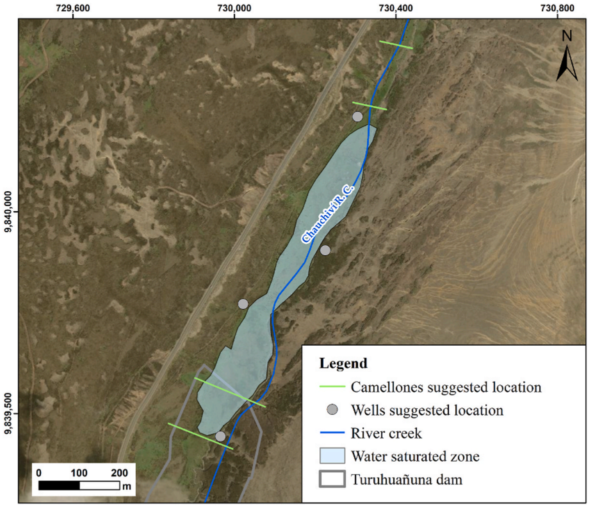

Fig. 15. Suggested location of "camellones" and wells as strategies for the management of water resources in the "El Arenal" area.

5. Expansion of the Chimborazo Faunal Protection Reserve subzone to protect the drainage zone that feeds the dam.

5. Interpretation of results and discussion

5.1. Aquifer characterisation and contribution of used tools

The combination of detailed specific studies, geological cartography and geophysical study (electrical resistivity, RS) and the generation of a DTM (GIS) on the slopes of the Chimborazo volcano (El Arenal) together with the available base information [42–44, 48,49,53,56–58], allowed the understanding of the hydrological and hydrogeological environment of the case study. Such as the case of the active Stromboli volcano in Italy, where they used Electrical Resistivity Tomography (ERT) and self-potential measurements to determine groundwater flow patterns [84], the application of electromagnetic (EM) and Audiomagnetotelluric (AMT) survey methods for the detection of aquifers with resistivities between 100 and 200 Ω m on the eastern flank of the Piton de la Fournaise volcano in France [85] and the application of VES to locate potential groundwater zones in The Deccan Volcanic Province, India [86]. These studies demonstrate the importance of combining geophysical methods to provide an overview of the aquifer system in volcanic areas. However, there are limitations in applying these methods that depend on the geomorphological and climatic conditions of the site. In this study, due to the ecological conditions of the area dominated by Andean paramos (reserve zones), VES was feasible because it is an inexpensive geophysical technique widely used in detecting groundwater [63,87,88] and counteracts the contact limitations of the surrounding vegetation.

The results of the geophysical exploration campaigns delineated areas of high groundwater potential in terms of the location and thickness of the aquifer (Table 5). The predominant materials that make up the free aquifer and allow the most significant accumulation and use of water resources are sand and gravel saturated due to their high porosity, in conjunction with very fractured porphyritic andesites with water saturation. In addition, the study serves as a scientific basis for the design of a water management system in sensitive semi-desert or desert páramo environments [89,90] such as El Arenal, which has witnessed the progressive melting of snowy Chimborazo [91,92], with domains of dry sequences for more than ten years (Fig. 7) and whose surrounding communities present difficulties in the supply of fresh water. The analysis of this work focuses on responding to the demand for water to establish a socio-ecological system [93–95].

For the characterisation of the aquifer studied, geophysical tools were used, this study offers the dual application of non-destructive geophysical methods combining VES and RS to obtain a 1D and 2D vision of the subsoil properties, identifying the saturated layers and the depth of the hard rock. However, the study recognises the limitation in the number of VES and RS lines since, being an indirect method, an additional number of geophysical studies would allow a better characterisation of the lateral heterogeneities of the subsoil. Therefore, in the future, it is recommended to carry out a more extensive VES campaign in the study area, in addition to the construction of a conceptual and geometric 3D model of the aquifer for a better understanding of the subsoil dynamics, creation and evaluation impact scenarios necessary for the decision-making based on the management of water resources and climate change of these natural ecosystems [96,97].

5.2. Water management proposals

The different practices proposed for water management (Fig. 14) can be associated with the four sustainability axes of Brundtland [71,72] and contribute to the sixth objective of the SDG 2030 Agenda. Which states, “ensure availability and sustainable management of water and sanitation for all” [73,74]. In addition, these proposals will be based on the work of cartography and geophysical studies carried out and described previously in this work.

Specifically, in the economic axis, the construction of the multipurpose dam is proposed, taking advantage of the stone materials removed in its design and its strategic location is defined, which will allow the use of surface and underground runoff to feed the dam reservoir. In the social axis, environmental education of rural communities is established as a pillar through participatory methodologies [98,99]. For the environmental axis, the extension of the reserve is proposed to protect the ecosystems associated with the dam construction area. Finally, in the cultural axis, the use of NbS is promoted (e.g., “camellones”). This last proposal presents challenges and opportunities from the perspectives of science, policy and practice [76]. In particular, in the management of NbS in a changing system characteristic of the northern tropical Andes that are experiencing the effects of climate change on the cover of their glaciers [26,30,31].

5.3. Concrete plans for optimising the use of water resources and practical implications in the NbS policy

The “camellones” in the present investigation were selected as NbS due to the hydrological and hydrogeological characteristics determined in the sector, with wetlands and abundant hydrophilic vegetation (natural pastures), which coincides with the passage of runoff from the melting of the volcano glacier. The construction of “camellones” a few meters upstream and downstream of the area of the water mirror (indicative of the aquifer) is proposed (Fig. 15). Traditionally, “camellones” or Waru-Waru were built to improve crop conditions and control excess winter water [34]. These “camellones” were widely used in the Andes, where páramo ecozones dominate [100].

The NbS in the study aims to intercept the stream that flows through the ravine in areas where the natural stagnation of water is limited but which, in turn, are close enough to the aquifer so that the water can infiltrate and recharge it. This practice is similar to other places where hydrophilic vegetation proliferates, such as the bofedales of the Andes (e.g., Chile [101]) or the borregales of Sierra

Nevada (Spain), where the "camellones" were built as networks of canals or ditches, to promote the growth of this type of vegetation and improve the water regulation capacity of the land [102]. The application of this NbS system allows the water to flow more slowly downstream, allowing its infiltration towards the subsoil [34].

Another approach to NbS for dam construction is using natural materials for dam building, such as rocks, soil, and vegetation [103]. This approach can help reduce dam construction's environmental footprint and improve the dam's resilience to natural hazards, such as floods and landslides [104]. The results of the geomechanical tests of Table 4 allowed us to establish the applications of the materials in situ due to their characteristics in the construction of the future dam. Specifically, i) porphyritic andesites, due to their medium hardness, can be used as a material for cyclopean concrete [105], which is characterised by mixing low-resistance concrete with large rocks; In addition, these rocks can be used as fill for spillways in the areas that acquire the shape of a box. ii) sand can be used in the preparation of concrete (mixture of sand, cement, gravel and water), which will be necessary for structures such as the dam wall, cyclopean concrete and gate. iii) clays may be used as compacting and levelling material for the ground to avoid possible infiltration. Additionally, for the construction of the access roads to the construction of the dam, roads will be opened in which materials such as crushed porphyritic andesites and clays will be used for the compaction of the road.

However, the páramos of the Andes are unique ecosystems that are often affected by the development of dams and other infrastructure. It is important to consider some examples found in the scientific literature that can be used to address the challenges related to dams in the páramos of the Andes include:

Restoring wetlands: Wetlands are important components of páramo ecosystems, but they can be impacted by dam construction. Restoring wetlands through re-vegetation and re-establishing natural hydrological processes can help mitigate these impacts [106,107].

Soil conservation: Páramo ecosystems depend on water, and dams can alter the natural water flow in the ecosystem. Implementing water management practices, such as rainwater harvesting and groundwater recharge [108], can help to maintain natural water flows and mitigate the impacts of dams.

> Sustainable land use: Encouraging sustainable land use practices, such as rotational grazing and agroforestry [109], can help to reduce the pressure on páramo ecosystems from human activities. This can help to reduce the need for infrastructure development, such as dams, and mitigate their impacts.

By implementing these NbS solutions, we can help to protect and preserve the unique and important páramo ecosystems of the Andes while still meeting our needs for water resources.

From this work, the alternatives of the use of applied geophysics to address water problems and the effects of climate change are exhibited from the perspectives of civil engineering, hydrogeology and environmental, integrating existing geophysical tools with ancestral knowledge through the suggestion for the implementation of the NbS models in search of the sustainability of the environment. Three practical barriers were identified within the political and social framework for the feasibility of water management proposals.

i) Lack of knowledge of the advantages of geophysical methods in sensitive environments such as protected areas or reserves.
ii) The "monitoring" is absent within the planning of execution of civil works related to NbS practices.
iii) The challenge of including the social factor and its connection with engineering designs within the environmental education campaigns and monitoring of the NbS.

These three barriers must be converted into strategies and pragmatic axes for managing public policies, highlighting that it is essential to guarantee the participation of multiple stakeholders (government, academia, community, and industries) to address ecosystem services. The study has limitations linked to the mesh of geophysical studies such as VES and SR carried out in the study area. However, the work establishes the bases of hydrogeological information so that it can be integrated into more extensive geophysical campaigns, which allow the definition of the geometry of the river-aquifer system and complement with isotopic analyses necessary to establish the recharge and the creation of predictive models of their dynamic behaviour in the face of the evident climate change that affects the páramo ecosystems.

6. Conclusions

On the slopes of the Chimborazo volcano, a subparallel drainage system of a micro-basin marked by lineaments/fractures that follow the downward trend of the slope has been recognized. With geophysics, a shallow, free, interior aquifer is recognized that reaches approximately 30 *m*. The aquifer becomes a key factor for the integral management of water by applying criteria of ancestral knowledge of WS&H techniques, which take advantage of the drainage of surface waters and the characteristics of the aquifer in the area. The results of the applied geophysics, in combination with other geological exploration tools, such as the geological survey, revealed the presence of permeable units in the study area, especially identified in the VES-03. The saturated material is composed of sands and gravels (low resistivity: 51.3 Ω m) and highly fractured porphyritic andesites (low resistivity: 157 Ω m). In addition, the RS allowed corroborating and determination of the characteristics of the hard rock, with P wave velocities between 755 and 1468 m/s, at an approximate depth of 5 *m* and of porphyritic andesites composition, according to the interpretations of the SR-01 and SR-02 seismic profiles.

The geotechnical study of the materials sampled and analyzed in the laboratory (Table 4, Fig. 8) allowed us to identify optimal characteristics of the materials in-situ (silts, sands and porphyritic andesites), which reflect their feasibility for use in the construction of the proposed dam, guaranteeing quality and reduction in the costs. The identification and characterisation of the porphyritic andesite will be useful for the construction of dams, due to its hard rock characteristics, benefiting the Guanujo (located 14.17 km from the possible aquifer) and Julio Moreno communities (19 km) from the water resource.

The application of GIS was necessary for the hydrological, geomorphological, and structural analysis and delimitation of the water mirror (indicative of the aquifer). In addition, it allowed the evaluation of the strategic areas for the construction of the future dam and proposals related to the construction of the "camellones".

The practices for water management are oriented to plan, develop and manage the use of the water resources available in the area, and consider the drilling of wells, construction of "camellones", construction of a multipurpose dam, environmental education and expansion of the subzone. These proposals are associated with the four Brundtland sustainability axes (economic, social, environmental and cultural) and contribute to the sixth objective of the SDG 2030 Agenda.

Using "camellones" as a WS&H system promotes the use of NbS, considered essential in fragile and changing scenarios such as the northern tropical Andes, which are experiencing the effects of climate change on their glaciers. Although these systems would contribute to the sustainability of the environment, they also represent challenges and opportunities from the political and social framework.

Our findings provide the opportunity to carry out specialized studies at four levels: geophysics (apply other complementary geophysical methods such as electrical resistivity imaging (ERI) technique, electromagnetic method, Ground-Penetrating Radar (GPR), to investigate the water content and distribution of materials of subsoil, the presence of subsurface water, and the flow of surface water), remote sensing (to study the dynamics of glaciers and snowfields in the páramos), hydrometric and isotopic studies (understanding the factors that control water storage in páramos ecosystems), implementing the NbS solutions (generation of design for the NbS systems proposed in this study with the least impact on the associated ecosystems).

Author contribution statement

Paúl Carrión-Mero: Maria Jaya-Montalvo: Joselyne Solórzano: Fernando Morante-Carballo: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Inés Tiviano: Edgar Hervas: Jenifer Malavé-Hernández: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Edgar Berrezueta: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Data availability statement

Data included in article/supp. Material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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