Journal of South American Earth Sciences 162 (2025) 105556

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Lithogeomorphological factors for wet meadows formation and sustenance in dryland setting in Domuyo mount, Patagonia, Argentina

Esteban Villalba [a,*], Silvina C. Carretero [a], María F. Lajoinie [b], Franco Tassi [c]

[a] Centro de Estudios Integrales de la Dinámica Exógena (CEIDE), Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata (FCNyM, UNLP), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Calle 64 #3, Ground floor, La Plata, Argentina

[b] Instituto de Recursos Minerales (INREMI), Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata (FCNyM, UNLP), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Calle 64 #3, First floor, La Plata, Argentina

[c] Dipartimento di Scienze della Terra (DST), Università di Firenze (UNIFI), Consiglio Nazionale delle Ricerche (CNR), Instituto di Geoscienze e Georisorse (IGG), Via La Pira #4, Firenze, Italy

ARTICLE INFO

Keywords:
Cold and thermal springs
Wetlands
Water discharge
Hydrothermal area
Geomorphological controls

ABSTRACT

Understanding the importance of wet meadows in dryland settings, which play a crucial role as a primary and sometimes unique resource of drinking water supply, is essential for their preservation and management. This study focuses on conducting a detailed examination of the geomorphological processes shaping the genesis of wet meadows in a hydrothermal area. The aim of this work is to assess the influence of lithogeomorphological factors for the formation and sustenance of wet meadows in dryland settings in Patagonia, Argentina. The investigation made possible the identification of geoforms of glacial and volcanic origin, along with substantial mass-wasting processes that have significantly influenced the landscape and hydrological system dynamics. The high peaks act as aquifer recharge zones, with meltwater infiltration through fissures controlled by the structuring of lithostratigraphic units. Intermontane wet meadows at stream headwaters exhibit steep slopes and elongated morphologies, predominantly generated on hillside deposits. Conversely, wet meadows in the lower basin develop on landslides and rock avalanches deposits displaying extensive surface coverage of low slopes. The geomorphological deposits described constitute an effective medium for water storage and are the main sustenance of the wet meadows in the Domuyo mount area, as well as being significant for the contribution to the streams and rivers that flow towards down watersheds. This study highlights the strong relationship between geomorphology, lithology, and structures in modelling the hydrological system of the Domuyo mount area. Moreover, the finding emphasizes the role of wet meadows as critical freshwater sources for local populations, native fauna, livestock, and irrigation, reinforcing the need for their preservation in these fragile environments.

1. Introduction

Drylands, encompassing arid, semi-arid, and dry sub-humid regions, constitute over 40 % of the Earth's surface, impacting roughly one-third of the global population (Feng and Fu, 2013; Huang et al., 2016; Lu et al., 2018). Water supply in these areas faces numerous challenges, stemming from low rainfall, high evapotranspiration, surface water salinization, desertification, limited vegetation cover, and soil degradation (Middleton and Thomas, 1997; Balugani et al., 2017; Prăvălie, 2016). Groundwater availability is also limited due to aquifer recharge constraints and the difficulty of accessing deep water reserves through drilling. Despite water scarcity in drylands, wetlands occasionally emerge as critical water sources for residents, livestock, and native fauna. In Patagonia, these wetlands are known as "mallines" (McClain, 2002; Mazzoni and Rabassa, 2013; Mitsch and Gosselink, 2015). However, wetlands in dryland environments are highly vulnerable to both natural and anthropogenic factors, including geogenic pollution (Minhas et al., 2017), climate change (Chasek et al., 2011), aeolic erosion (Duniway et al., 2019), urban development (Huang et al., 2016), industrial activities such as mining (Worlanyo and Jiangfeng, 2021), and livestock farming (McCartney et al., 2015). Recognizing the vital ecosystem services that wetlands provide, including the regulation of biogeochemical and water cycles, as well as contaminant assimilation, highlights the urgency of their study and conservation (Tooth and McCarthy, 2007; Tooth, 2018; Mitsch and Gosselink, 2015; Kundu et al., 2021). The vulnerability of wetlands in dryland settings underscores the

* Corresponding author.
E-mail address: evillalba@gsuite.fcnym.unlp.edu.ar (E. Villalba).

https://doi.org/10.1016/j.jsames.2025.105556
Received 19 March 2025; Received in revised form 22 April 2025; Accepted 26 April 2025
Available online 29 April 2025

importance of research aimed to understanding their natural development factors and establishing management guidelines for their preservation (e. g. Epele et al., 2022).

In this context, the Domuyo region emerges as a relevant case study for understanding the development and vulnerability of wetlands in dryland settings influenced by hydrothermal activity. The study area is located in the surroundings of the Domuyo mount (36°38′30.0″ S - 70°26′8.0″ W), within a Protected Natural Area in the extreme north of the Neuquén province, Argentina (Fig. 1a). Domuyo mount hosts a hydrothermal system which is considered the largest hydrothermal system in Argentina and the second largest advective heat flux in the world after Yellowstone (Chiodini et al., 2014). This hydrothermal activity significantly influences the quality of some surface watercourses and wet meadows used for water supply, introducing toxic elements, such as arsenic, and increasing salinity (Villalba, 2023). Additionally, although the study area experiences glacial and snow accumulation on its high peaks, this fresh water source is at risk due to interactions with hydrothermal water and vapors after entering the surface-groundwater hydrological cycle (Villalba et al., 2020). This study aims to examine the lithogeomorphological factors for the formation and sustenance of wet meadows in the Domuyo area, which are essential for assessing their role in the regional hydrological system and addressing water resource conservation efforts.

2. Study area

2.1. Geological setting

Domuyo mount is situated within the structural height of the Cordillera del Viento, part of the Northern Neuquén Precordillera (Bracaccini, 1970; Ramos et al., 2011).

The stratigraphy of the region consists of a Silurian-Devonian metamorphic basement, Permian volcanic rocks, and Triassic plutonic rocks (granitoids among which is the Varvarco Granodiorite) (Zanettini et al., 2001) (Fig. 1b). Subsequently, the sequence includes Triassic continental volcanic and sedimentary rocks (Precuyan Cycle), Jurassic marine sedimentary rocks and evaporites (e. g., Cuyo Group), followed by Jurassic-Cretaceous marine and continental sedimentary rocks (Zanettini et al., 2001) (Fig. 1b). Volcanic activity continued from the Cretaceous to Lower Tertiary, followed by an additional phase of Upper Tertiary volcanism (Narciso et al., 2004; Zanettini et al., 2001) (Fig. 1b).

The study area is characterized by intense Pliocene-Pleistocene volcanism, which is compositionally and temporally divided into the Lower Volcanic Cycle (LVC) and the Upper Volcanic Cycle (UVC),

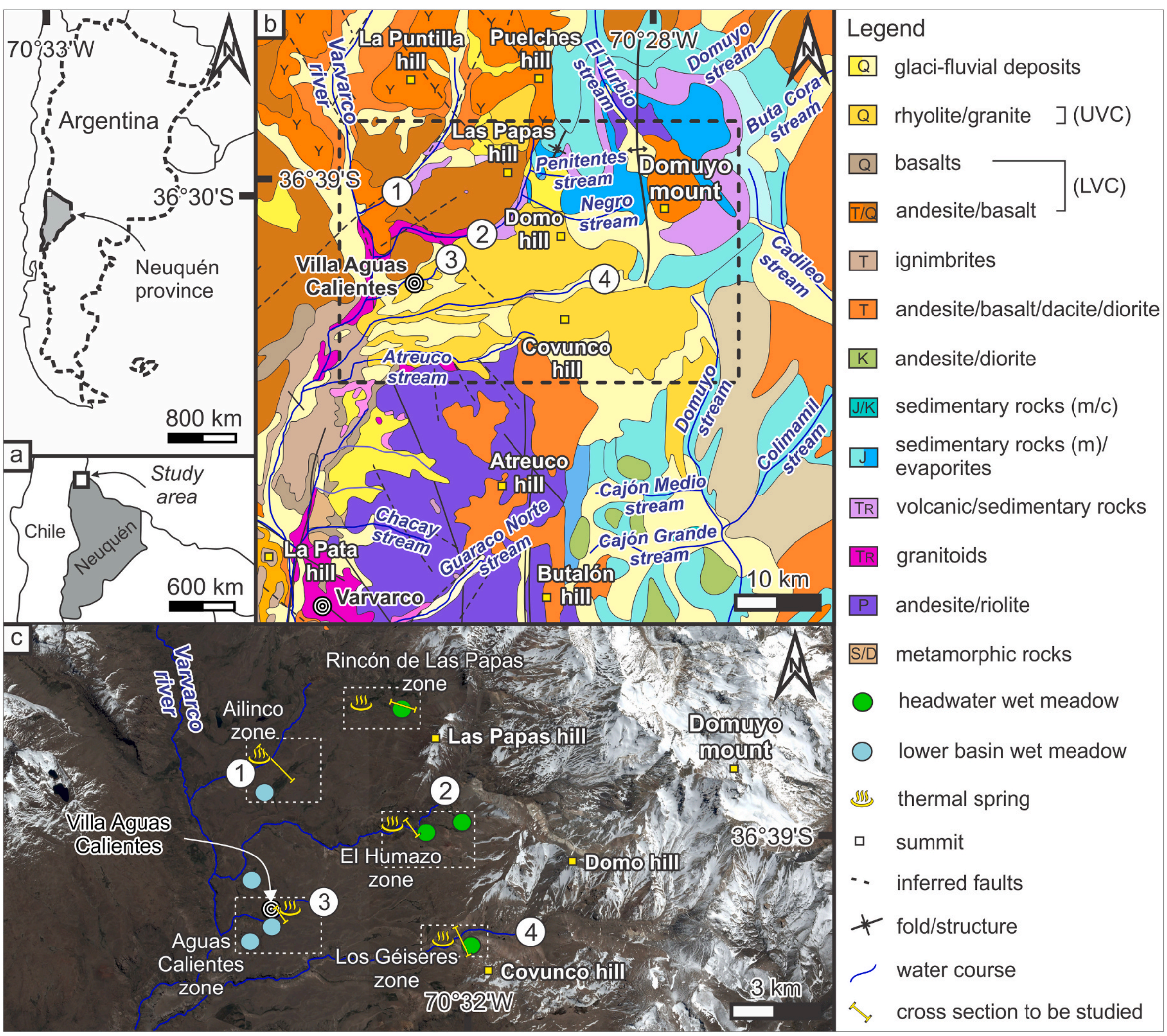

Fig. 1. Regional location (a), geological map (modified from Zanettini et al., 2001; Narciso et al., 2004) (b), and general satellite image (c) of the study area. The box with black dotted lines in (b) encompasses the Domuyo Geothermal System. The white dotted line boxes in (c) indicate the thermal discharge zones. The numbers inside the white circles in (b) and (c) indicate the Ailinco (1), Manchana Covunco (2), Aguas Calientes (3), and Covunco (4) streams. Marine and continental origin of sedimentary rocks in legend are indicated with (m) and (c), respectively. Symbols in capital letters in the legend indicate age according to International Union of Geological Sciences (IUGS) abbreviations.

separated by a stratigraphic discontinuity attributed to base-level changes (Páez et al., 2014; Brousse and Pesce, 1982; JICA, 1983). The LVC, dated to the Upper Pliocene-Lower Pleistocene, comprises basic calc-alkaline volcanic sequences assigned to the Tilhué Andesite and the Chapúa Basalt formations (Fig. 1b). These units include volcanic cones, necks, and lava flows, predominantly composed of grey to reddish andesites and basaltic andesites. They exhibit porphyritic textures with a glassy, vesicular matrix, and a mineral composition dominated by plagioclases, amphiboles, and pyroxenes (Stipanicic, 1965; Llambías et al., 1978; Brousse and Pesce, 1982; Zanettini et al., 2001). The UVC, formed during the Middle to Upper Pleistocene, encompasses calc-alkaline silica-rich volcanic rocks that constitute Domuyo mount. On the western flank of this volcanic centre, dome structures and associated deposits are present (Fig. 1b), including lava flows and phreatomagmatic rhyolitic deposits, and two eruptive episodes temporally differentiated. The first episode is represented by pyroclastic flow deposits composed of lapillitic tuffs. The second episode consist of lapillitic tuffs, monomictic breccias formed by the collapse of rhyolitic domes (block-and-ash deposits), and finally, rhyolitic to dacitic lavas forming domes and associated lava flows (Llambías et al., 1978; Páez et al., 2014).

Quaternary deposits in the area include moraines, glaciofluvial and fluvial terraces, gravitational deposits from mass-wasting processes, as well as alluvium, colluvium, and foothill accumulations. Furthermore, the landscape has been shaped by volcanism, mass-wasting processes, and glaciofluvial activity, resulting in an abrupt topography with elevations ranging from 1100 m a.s.l. to over 4700 m a.s.l. (Villalba, 2023).

The geological framework described above provides the foundation for understanding the complex interactions shaping the hydrological system in the study area.

2.2. Climate, population and water resources

The climate in the study area is mostly controlled by altitude, typically mountainous. The annual precipitation is approximately 655 mm, concentrated between May and August (Villalba, 2023). The average annual temperature for the abovementioned period was around 4.6 °C, with the highest temperatures in January and the lowest in July (Villalba, 2023). The hydrologic balance is characterized by a warm and dry season (from October to March) and a cold and wet season (from April to September). Water balance for the hydrological years 2014–2019 (Villalba, 2023) indicates precipitation of ~527.8 mm, of which 237.5 mm were excess, primarily during the cold and wet season (95.5 %). Likewise, towards the south of geothermal system (~20 km), average rate flows of 35.1 $m^3 s^{-1}$ Neuquén river and 72.9 $m^3 s^{-1}$ for the Varvarco river during the warm and dry season, while during the cold and wet season, averages of 34.3 and 64.6 $m^3 s^{-1}$ were recorded, respectively (Villalba, 2023). These values were associated with the hydrometric records for each seasonal period: as precipitation increases, high flow rates were observed at the gauging stations.

The study area contains small towns distributed along the main surface water courses, the most populous of which is Varvarco, located on the eastern bank of the namesake river (Fig. 1b). Varvarco together with the small settlements to the south (e. g., Invernada Vieja) have a population of around 700 inhabitants, according to the last population census in 2022 (www.indec.gob.ar). The main economic activities in the area are public sector employment and transhumance livestock farming. The latter is a traditional practice of indigenous peoples, involving the seasonal movement of livestock, mainly goats, in search of pastures towards higher-altitude lands near the summits in summer ("veranada") and towards snow-free lowlands in winter ("invernada") (e. g., Baied, 1989; UNESCO, 2023). The ascent typically begins between November 25th and January 1st, and the descent occurs after March 25th. According to information provided by rangers at the Domuyo Protected Natural Area, approximately 200 people take part in each pastoralism season, residing in other off-season locations, such as Chos Malal, around 300 km away. Tourism is also gradually expanding due to the numerous natural tourist attractions, which is reflected in the emergence of temporary residences and designated camping areas (e. g., Villa Aguas Calientes; El Playón, south of Domo hill; Fig. 1).

For decades, domestic water supply in the region has been compromised in terms of quality, with residents reporting health issues, including gastrointestinal pathologies (e. g., Río Negro Newspaper). Additionally, reports highlighting the presence of harmful chemical elements of natural origin in some water sources, such as arsenic from volcanic activity, further confirm concerns regarding drinking water quality (e. g., AIC; Litter et al., 2019; Villalba et al., 2020). Until 2022, the main water collection point was located at the final stretch of the Varvarco river, which receives inflows from streams sourced in the Domuyo Geothermal System area. However, in 2022 and after numerous negotiations, a filtration well was constructed downstream of the confluence of the Varvarco and Neuquén rivers (Fig. 1b), by the Provincial Water and Sanitation Entity (Neuquén Informa Newspaper). In line with the technical specifications of the pumping facilities, it has a maximum pumping capacity of approximately 60 l min^{-1}, although the consumed volume is unknown. Furthermore, according to interviews conducted with Varvarco residents for this study, more than half of the inhabitants consume water from a public access tap, for which they collect and transport water using barrels. This tap sources water from springs within wet meadows, which exhibit favourable organoleptic and visual characteristics, such clarity, odour and taste. Meanwhile, settlements located on the western slope of Domuyo mount use wet meadows for their water supply.

For the aforementioned reasons, it is important to understand the factors that determine the formation of wetlands and the dynamics of the natural hydrological system already used as a source of supply, and knowing safe alternatives is a priority.

3. Methodology

The geological and geomorphological characterization of the study area was initially conducted through the analysis of existing background information and the interpretation of satellite images. Subsequently, mappings were produced from the regional geological map available, including the SEGEMAR geological sheets "Las Ovejas" (3772-II) and "Barrancas" (3769-I), at a scale of 1:250000, produce by Zanettini et al. (2001) and Narciso et al. (2004), respectively. Satellite and aerial images from platforms like Google Earth Pro, USGS-EarthExplorer, and Bing Maps, featuring Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Global Digital Elevation Model (GDEM) data, were utilized for morphometric parameters measurements. The images had an original pixel size of 1 arc second resolution, references to the World Geodetic System (WGS84) and Earth's Gravitational Model (EGD96) as a geoid. Online satellite navigation facilitated detailed observations of optical terrain properties, aiding in the identification of lithological, geomorphological, and structural features, such as textures, colors, contrast, and morphologies. Furthermore, satellite images observations of the wet meadows studied in different periods of the year (cold-wet season such as May, and warm-dry season such as November) were made, to define whether there are seasonal morphometric variations. Field surveys were carried out during November 2018, aiming to describe (i) the different outcropping lithogeomorphological units and wet meadows, including the identification of contacts between units, (ii) possible stratigraphic relationships, and (iii) dimensional and morphometric parameters (e. g., in river courses, the thickness of banks). Georeferencing of field data was achieved using a high-sensitive GPS receiver (Garmin eTrex® H), and a Geographic Information System (QGis 3.28 Firenze LTR) facilitated the integration and analysis of collected information. This comprehensive methodological approach ensures a robust understanding of the geological, geomorphological, and hydrological dynamics of the study area.

4. Results

4.1. Geomorphological features of the headwater sectors

The Rincón de Las Papas (RP) zone encompasses the valley of the Ailinco stream (1; Fig. 1b and c) and extends across the eastern and western slopes of Puelches (3200 m a.s.l.) and Las Papas (3000 m a.s.l.) hills, respectively. Puelches hill exhibits a dome-like morphology of rhyolitic composition, whereas Las Papas hill is associated with andesitic lava flows (Zanettini et al., 2001). At the highest elevations of both hills, volcanic structures with pointed morphologies, positioned horizontally, are prominent. These structures feature a lower section distinguished by an initial scarp, from which gravitational movements originate (González Díaz et al., 2003; Villalba, 2023). The irregular topography of the uppermost sectors of these mountain ranges promotes the accumulation of snow precipitation, forming glacial snowfields that extend from oval to elongated shapes along the slopes (Fig. 2a). The persistence of these snow deposits during summer is likely to enhance erosive action, as evidenced by the presence of nivation niches on the bedrock. In the middle to upper sector of the slopes, starting scarps delimited by rock outcrops made up of LVC andesites are identified (Fig. 1b). These rock formations give rise to extensive rock-slides, while rock avalanches occur towards the lower sectors, steeper sections of the slopes (Fig. 2a). The combination of hills and geomorphological units in this area confer a semicircular morphology in plant view and a general concave-upward topography, positioning the watersheds in a way that promote centripetal drainage (see El Turbio, Penitentes, Negro, Cadileo, Buta Cora and Domuyo streams around Domuyo mount; Fig. 1b). More locally, wet meadows develop in the middle to upper section of the slopes, characterized by steeply sloping topography, small areal extent, and a longitudinal arrangement following the slope direction (Fig. 2a). They receive water from melting snowfields, which infiltrates the subsurface and, upon encountering topographic discontinuities, emerges as springs that discharge into the Las Papas stream valley. These wet meadows develop on the landslides caused by the mass-wasting processes. They receive water from melting snowfields, which infiltrates the subsurface and, intercepting topographic discontinuities, emerges as springs that discharge into the Las Papas stream valley. Nevertheless, the water discharge from headwater wet meadows generates flood surfaces when reaching the lower banks of the Las Papas stream, due to the presence of low-slope mass-wasting deposits since it is located toward the lower basin. Likewise, the slope of Las Papas hill is harbor to RP thermal discharges, consisting of small hot bubbling pools. Near these discharges, precipitates from hydrothermal fluids were recognized, covering an area of approximately 900 m^2. These deposits, composed of carbonate minerals (Villalba, 2023), develop into terraced travertine structures. In the plant view, these deposits exhibit an elongated semicircular morphology, distinguished by their ocher to whitish colorations and granular to laminate texture (Fig. 2b). Further northeast of the RP thermal discharges, rocky outcrops with a brownish-grey hue and brecciated structures emerge slightly above the topography shaped by gravitational movements.

El Humazo (EH; "The Big Smoke") is situated in the middle sector of the study area, and it is hosted in the Manchana Covunco stream (2; Fig. 1b and c). This thermal zone is the most renowned in the area due to the energetic and thunderous nature of its manifestations, composed

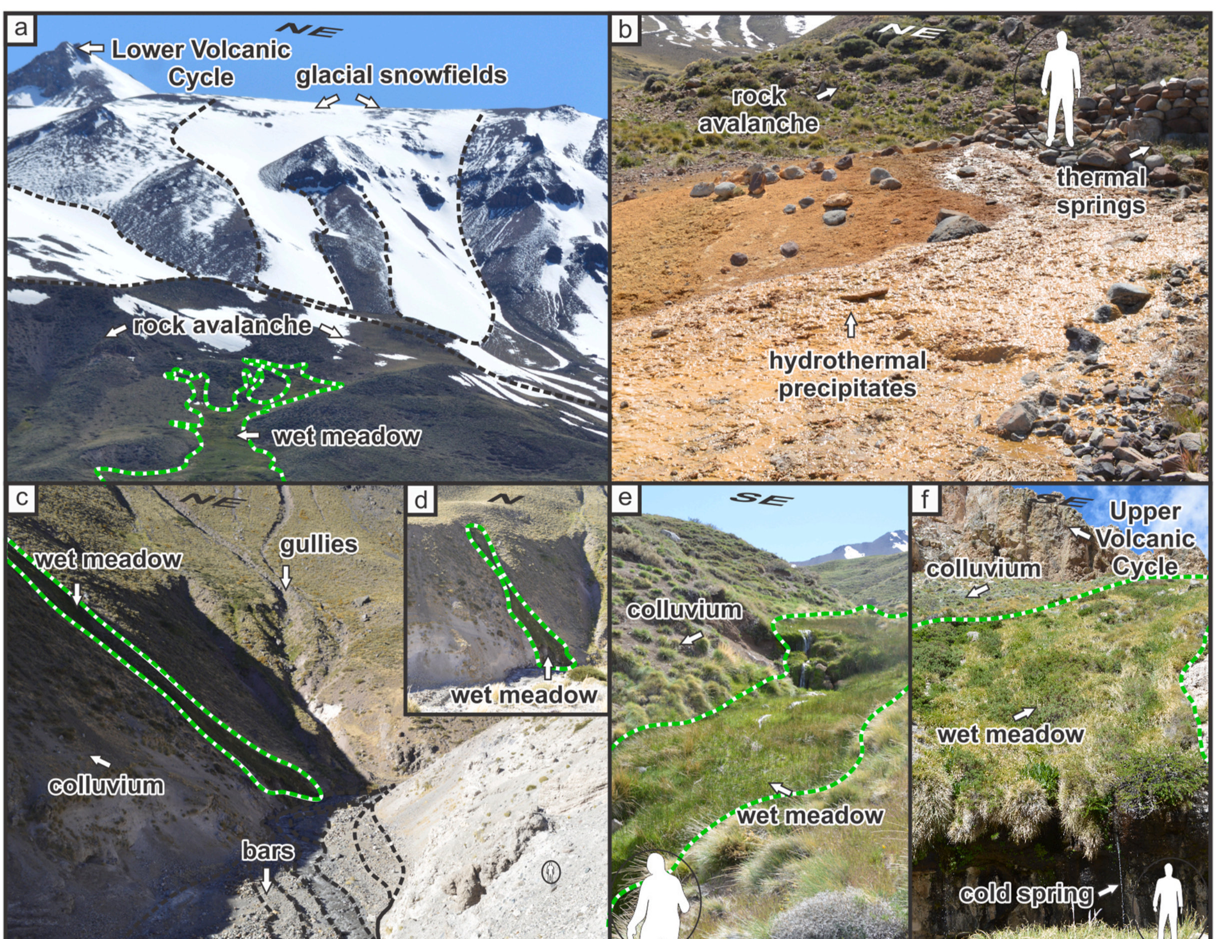

Fig. 2. Photographs of lithostratigraphic units and geoforms associated with wet meadows located in headwater sectors from Rincón de Las Papas (a, b), El Humazo (c, d), and Los Géiseres (e, f).

mainly of jet-like water-vapor emissions at water boiling temperature. Large hydrothermal explosions have occurred in the EH during the years 2003, 2007, and 2012, with the consequent formation of cone-shaped hydrothermal vents and short-lived eruption columns (e. g., D'Elia et al., 2020). Manchana Covunco streambed consists of granitoid outcrops, belonging to the Triassic Varvarco Granodiorite (Zanettini et al., 2001). To the southwest of the valley, stratified Triassic sedimentary rocks, assigned to the Neuquén Basin were recognized (Zanettini et al., 2001), while andesitic lavas (LVC) forming the southwestern part of Las Papas hill and rhyolitic lavas (UVC) constituting Domo hill occur to the north and south, respectively (Fig. 1b). In the Manchana Covunco stream valley, mass-wasting processes predominate, mainly originating from the slopes of Las Papas and Domo hills. Gravitational movements include a significant debris avalanche deposits from the north, extensive colluvial deposits covering slopes mainly from the south, and, to a lesser extent, debris flow from the east. The slopes exhibit multiple areas with rectilinear to concave profile, featuring gullies descending towards the valley floor. Collapses of colluvium deposits expand in a fan shaped pattern. Alluvial deposits become more frequent towards the south, indicating a flow towards lower areas with reduced vegetation. The steep slopes (>50 %) of the gravitational deposits allow them to accumulate vertically with a high angle of repose.

Towards the northeast direction, lobate surfaces formed by very poorly selected materials, resulting from debris flows, are observed and channeled in lower sectors close to the main valley of the stream. Wet meadows develop on small terrains, appearing where the slope is gentler due to dense flows, landslides, and hillside deposits. In extensive stretches of the Manchana Covunco stream, there is a relatively narrow alluvial plain, about 5 m wide, expanding to about 35 m in the sector close to the thermal discharges. Additionally, in the alluvial plain, bars are observed, superimposed on up to three levels (Fig. 2c and d). Narrow valleys with subvertical walls are identified at several, exposing hydrothermal deposits forming terraces, alteration rocks, and breccias. Near the EH thermal discharges, the aforementioned terraced precipitates are predominantly composed of travertines (Villalba, 2023), arranged horizontally. Breccias were recognized for distinctive textures, forming massive laminated packages, eruption cones, and rocks with hydrothermal alteration of light colorations and soft silicic and amorphous composition (Mas et al., 2000; D'Elia et al., 2020; Villalba, 2023).

The Los Géiseres zone is crossed by the Covunco stream (4; Fig. 1b and c). The upper sector of the Covunco stream valley follows a path between the Jurassic marine and continental sedimentary units (pelitic, calcareous and evaporitic rocks) and the UVC unit. This thermal zone is water-vapor type and is characterized by hot springs manifestations accompanied by large fumarolic emission. This valley exhibits numerous sectors laterally contained by steep sub-vertical to vertical walls that give rise to cascades. Colluvial and alluvial deposits predominate in these sectors, covering the slopes from the middle to the basal sector. These materials consist of gravel and polymictic blocks, arranged with a high angle of repose (>50 %). Wet meadows with an elongated morphology develop on colluvial deposits resulting from gravitational processes on the slopes. These wet meadows either drain towards the Covunco stream in the form of a subsurface flow or create waterfalls (Fig. 2e and f). Collapse structures deeper than 1 m are presented, generated by thermal action, leading to disintegration and subsidence of the land. The hydrothermal precipitates in this area are whitish and form robust terraced deposits with parallel lamination, mostly arranged horizontally, many of which are in a state of ruins. Additionally, conical-shaped rock accumulations were identified adjacent to the hydrothermal eruption craters, resembling those found in the EH zone but on a smaller scale (~4 m in diameter and ~2 m in height).

4.2. Geomorphological features of the lower basin sector

In the lower basin sector of the study area the Ailinco (Ai) and Aguas Calientes (AC) zones are present. The Ai zone is located downstream of the RP zone, between the volcanic hills La Puntilla and Puelches, within the valley of the Ailinco stream (Fig. 1b and c). Towards the lower basin of the aforementioned stream, there is a small and largely inactive hydrothermal zone, including a small lagoon with a subtle bubbling barely perceptible when the water temperature is a little higher than that of the surrounding watercourses and wet meadows (Villalba, 2023). The alluvial plain of the valley in this area is one of the widest, measuring up to ~50 m wide, associated with the low slope and widespread mass-wasting processes involving the rock avalanches of "Ailinco" towards the northeast of the river course, and "Las Papas" towards the southeast of it (González Díaz et al., 2003), originating at the foot of the hills of Las Papas (Fig. 1b). Subcircular landslides with a surface area of ~3 km^2 that occupy the river valley were also recognized, softening the topography as they exert a leveling effect on the terrain. In this area, the landslides were differentiated from the avalanches of adjacent rocks by the starting scar defined to the northwest, where the slope increases threefold to 14 %. Furthermore, minor movements occurred on large landslides, exhibiting an oval morphology in the upper sector and elongated shape in the lower sector, where some display secondary slump scars. These deposits from gravitational movements are characterized by very poor selection, materials with angular to sub-rounded shapes, and psephitic to coarse psammitic textures. Wet meadows develop on the substrate formed by mass-wasting deposits (Fig. 3a and b), mainly generated by landslides, with little development of Andosol-type soil (Ferrer et al., 1990). Precipitates derived from hydrothermal fluids are also present in Ai, with a high degree of physical break due to the lateral traction and mechanical action exerted by the large landslides in the area. These precipitates, occupying an area of ~130 m^2, are scarce in thickness and carbonatic in composition, and they make up terraced travertines (e. g., Villalba et al., 2020; Villalba, 2023). Additionally, outcrops of volcanic rocks and/or well-consolidated volcanic breccia with grayish, yellowish, orange, and whitish colors were also recognized. The cross-section perpendicular to the stream in this area is slightly asymmetric at the local scale. On the side composed of rocky outcrops, the slopes and heights are slightly greater (~1630 m a.s.l.), whereas on the opposite slope of the watercourse, consisting entirely of landslides, the slopes are gentler, and the elevation levels are lower (~1620 m a.s.l).

The AC zone is topographically subdivided by a southwest-northeast oriented scarp, exposing the UVC volcanic rocks (Fig. 1b). The scarp has an altitudinal range of approximately 500 to 1900 m a.s.l. with slopes reaching up to 58 %. Gravitational deposits cover part of the rock outcrops on this significant structure, including the middle and lower sections with predominantly colluvial deposits, and in the upper part featuring smaller crumbling formations. At the base of the scarp, a pediplain has developed, originating soils of the Andosol and/or Inceptisol type, characterized by poor development (Ferrer et al., 1990; FAO, 2015) (Fig. 3c). The Aguas Calientes stream traverses the deposits resulting from mass-wasting processes, except for the central sector where the channel bed consists of rocky terrain. In this specific sector, small waterfalls were observed, generated by stepped topographic breaks, each not exceeding 1 m in height. The river valley lacks a clearly defined path, primarily due to the limited lateral relief of the terrain through which it flows. Wet meadows occur in the lower sector of the Aguas Calientes area, specifically on its alluvial plain. This plain consists of deposits from gravitational movements, mainly consisting of colluvium, alluvium, and the previously mentioned pediplain (Fig. 3d and e). Conversely, in the central-lower sector of the scarp, hydrothermal discharges occur along with deposits of small precipitates from hydrothermal fluids (~550 m^2), primarily composed of amorphous siliceous material (Villalba, 2023), and denominated as sinter. These hydrothermal discharges consist of geysers and small pools.

4.3. General morphometric parameters of wet meadows

The data from the wet meadows in the study area surveyed are

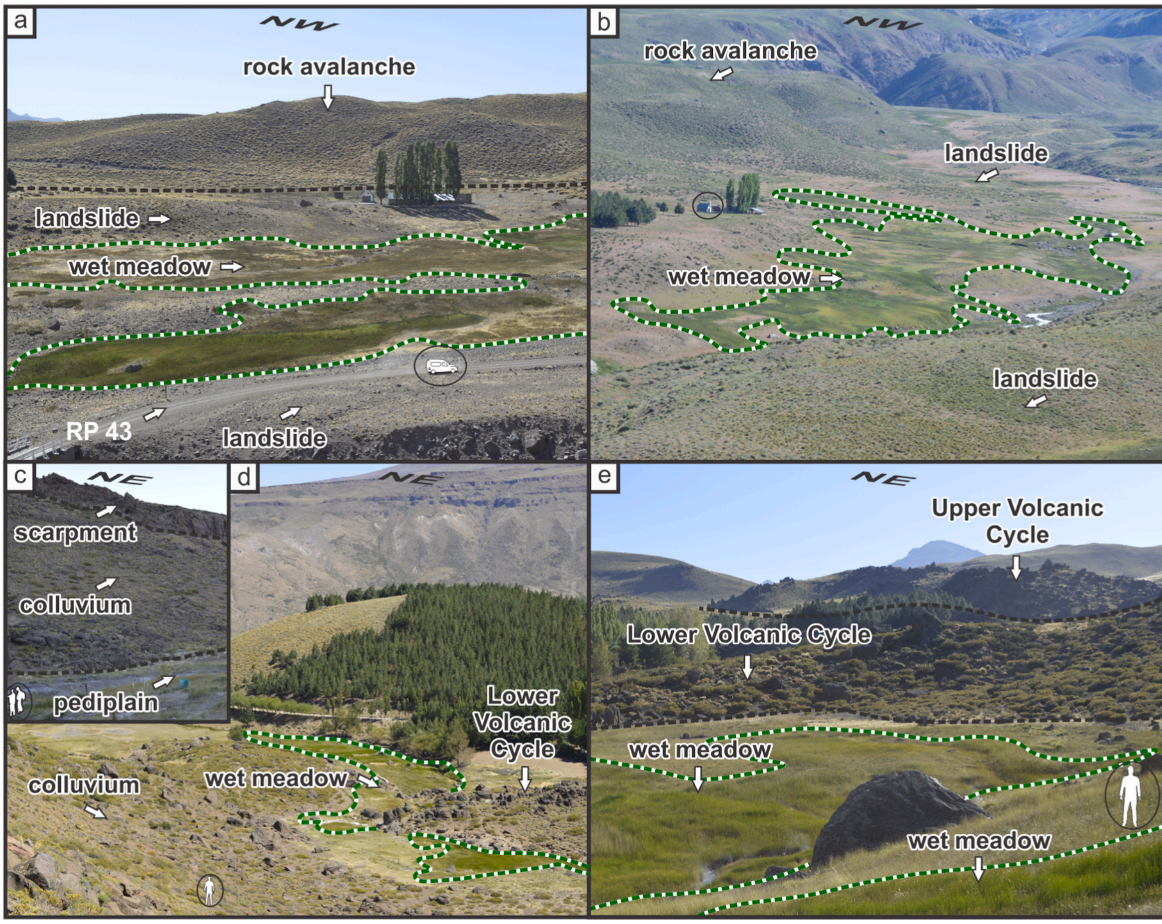

Fig. 3. Photographs captured in the field of lithostratigraphic units and geoforms of the lower basin sector. The areas of Ailinco (a, b), and Aguas Calientes (c, d, e) are observed.

presented in Table 1. A clear contrast is observed between the wet meadows located in the headwater sector and those in the lower basin. The headwater wet meadows register perimeters approximately 9.3 times smaller (~324 vs. 3004 m) and an areal extent 522 times smaller (~3006 vs. 156,934 m^2) compared to those in the lower basin. Besides, the land where the wet meadows from headwater developed has slopes 5.3 times higher than those of the wet meadows from the lower basin (~47.0 % vs. ~8.9 %). Elevation also differs significantly, with headwater wet meadows found at altitudes ranging between ~2332 and ~2376 m a.s.l., whereas those in the lower basin are situated between ~1713 and ~1778 m a.s.l. In addition, it should be noted that at observation scale used, no substantial fluctuations have been distinguished in the morphometric parameters of the wet meadows in dry-warm (e. g., November) and wet-cold (e. g., May) seasonal periods.

Table 1
Morphometric parameters of wet meadows in different locations of the Domuyo Geothermal System. In the name column is indicated the zone (RP, EH, and LG are in the headwater sector; Ai and AC are in the lower basin sector) and the number of each wet meadow measured. P: perimeter; A: area; S: slope; <h: minimum height; >h: maximum height. m a.s.l.: meters above sea level.

Zone/Number	RP/1	RP/2	RP/3	RP/4	RP/5	RP/6	RP/7	RP/8	RP/9	RP/10	EH/1	EH/2
P (m)	338	357	138	343	303	374	129	662	180	148	498	376
A (m^2)	1210	1342	360	2284	1901	2530	270	2670	299	329	13,404	2832
S (%)	48.5	40.7	34.7	49.1	52.1	38.0	38.6	35.0	69.2	46.3	47.2	38.2
<h (m a.s.l.)	2304	2299	2300	2276	2316	2263	2319	2200	2221	2273	2451	2379
>h (m a.s.l.)	2390	2349	2322	2309	2358	2332	2336	2330	2262	2292	2540	2410

Zone/Number	EH/3	EH/4	EH/5	LG/1	LG/2	LG/3	LG/4	LG/5	LG/6	LG/7	LG/8	Ai/1
P (m)	306	395	374	487	535	358	148	190	257	274	293	4097
A (m^2)	3705	7026	4090	5800	8707	3805	724	1620	875	1445	1915	254,451
S (%)	43.5	29.3	31.9	43.0	32.2	41.3	76.8	73.4	59.3	64.0	48.6	3.4
<h (m a.s.l.)	2374	2351	2323	2440	2477	2397	2377	2356	2358	2347	2238	1910
>h (m a.s.l.)	2401	2377	2350	2454	2551	2450	2394	2385	2402	2376	2287	1942

Zone/Number	Ai/2	Ai/3	Ai/4	Ai/5	Ai/6	Ai/7	Ai/8	AC/1	AC/2	AC/3	AC/4	AC/5
P (m)	4545	517	3161	3334	4311	3399	3524	2190	1735	3855	1353	3034
A (m^2)	471,403	9763	181,528	146,755	146,889	249,163	211,874	56,302	36,908	151,058	38,412	85,638
S (%)	3.2	8.2	10.2	6.1	4.6	7.4	9.4	11.0	13.5	10.0	16.9	11.9
<h (m a.s.l.)	1743	1659	1691	1665	1673	1817	1944	1720	1739	1575	1629	1501
>h (m a.s.l.)	1780	1675	1760	1719	1741	1897	2036	1797	1806	1624	1731	1603

5. Discussion

5.1. *Lithogeomorphology of high-lowlands and characteristics of wet meadows*

The formation and maintenance of wet meadows in the study area are strongly controlled by lithogeomorphological factors. The differentiation between endogenous and exogenous processes plays a key role in shaping the terrain, influencing both hydrological connectivity and groundwater recharge. The central-eastern sector is primarily controlled by volcanic structures and fault systems associated with Las Papas, Domo and Covunco hills, and Domuyo mount (Fig. 1), while the central-western sector is predominantly affected by mass-wasting processes and fluvial erosion (to the west of the Las Papas, Domo, and Covunco hills, Fig. 1c). The geoforms that originated from mass-wasting processes are particularly relevant for wet meadow formation, as they contribute to the deposition of unconsolidated materials with high porosity and permeability, facilitating subsurface water flow. Previous studies have indicated that gravitational movements in this region are influenced by historical seismotectonic activity (González Díaz et al., 2006; INPRES, 2012) and volcanic unrest, including inflation processes and hydrothermal eruptions (Hurley et al., 2020). These factors promote structural weaknesses that enhance infiltration and groundwater circulation, playing a key role in wet meadow recharge.

Mineralogical studies about precipitates from hydrothermal fluids in the study area (Villalba, 2023) suggested that they would be involved in the retention processes of elements transported by the hydrothermal fluids. This would occur due to co-precipitation and/or adsorption of the mineral phase of elements in solution, which is why they are of significance in reducing the chemical deterioration of waters (e. g., Alexandratos et al., 2007; Demoustier et al., 1998). Furthermore, rocks with hydrothermal alteration signs would evidence an increase in the porosity, which constitutes a factor that controls the hydrological functioning of the system, and the hydrochemistry of the waters (Tassi et al., 2016; Villalba et al., 2020; Álvarez et al., 2022; Villalba et al., 2022; Villalba, 2023). However, additional geochemical analyses would be required to assess the full impact of hydrothermal inputs on the long-term sustainability of wet meadows.

The relevant presence of ice cover in the high sectors of the north and east of the study area, guarantees not only the recharge of the hydrothermal aquifer but also constitutes the only contribution to surface runoff and sustenance of wet meadows (e. g., Palacios and Andrés, 2006). The infiltration of these waters is facilitated by the erosive processes resulting from glacial action, such as the removal of surface material, generation of mechanical fractures due to the movement of ice masses, as well as cryoclastic weathering (e. g., Jones and Willey, 2018). The streams would have generated a landscape of abrupt relief due to the development of valleys with irregular topography (Cotton, 1950), and where elevations differ of up to 400 m, between the channel bed and the top of the slopes, over a short lateral distance (200 m). Initially, the steep slopes were likely produced by retrograde erosion that generates slope gullies due to turbulent flow (Campbell, 1989), which were identified in the region (Salcedo and Solorza, 2010) and can currently be recognized incipiently in several sectors of the hydrothermal systems as in EH zone (Fig. 2c).

The RP zone structuring is represented by normal faults that affect the Varvarco Granodiorite and the folded and stratified sedimentary rocks of the Precuyano Cycle (Galetto et al., 2018), which allow the recharge of meteoric water from higher topographic levels by infiltration through the clastic deposits originated by the mass-wasting processes. Water that does not infiltrate feeds the surface flow and gives rise to wet meadows that eventually generate cold springs when the phreatic layer intercepts the topography, which is favored by the steep slopes and forms the wet meadows in headwaters (Fig. 4a and b). In the EH zone, the Manchana Covunco stream runs off, and cold springs occur from wet meadows caused by the outcrop of the water table due to the high slope

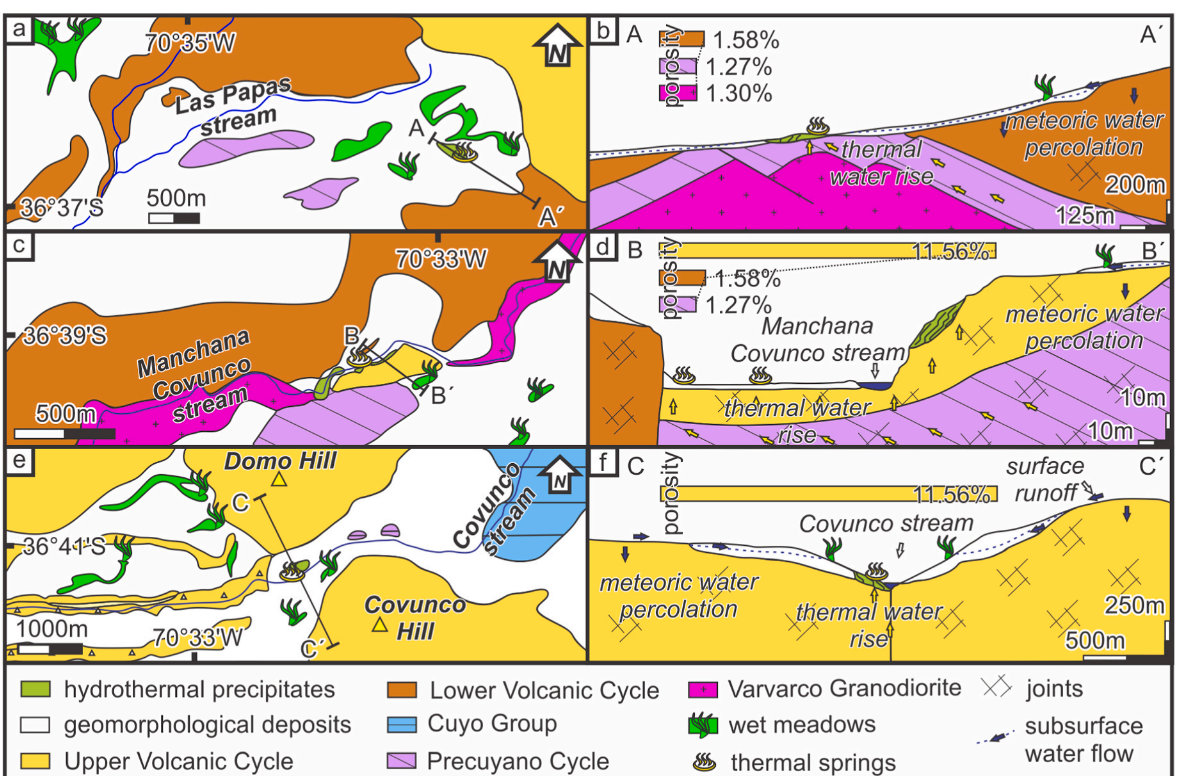

Fig. 4. Lithogeomorphological maps (a, c, e) and cross sections (b, d, f) in the headwaters sectors, where the springs occurrence (both from wet meadows and thermal) and the dynamics of the hydrological system are reflected. The cross sections are represented on the maps according to the segments A-A' (Rincón de Las Papas zone; Fig. 1c), B-B' (El Humazo zone; Fig. 1c), and C-C' (Los Géiseres zone; Fig. 1c). The porosity values are those reported by JICA (1983).

of the clastic deposits caused by mass-wasting processes along with their probable wedging. Meteoric water infiltrates through fissures in the rocks of the volcanic cycles, faults in Varvarco Granodiorite, and stratification planes in Precuyano Cycle (JICA, 1983; Galetto et al., 2018; D'Elia et al., 2020) (Fig. 4c and d). The Covunco stream in the LG zone coincides with the faulting that affects the UVC (Zanettini et al., 2001; Galetto et al., 2018), whereby structural control is referred to. As for wet meadows in LG, they predominate close to hydrothermal discharges which develop on thin alluvium and colluvium. These deposits harbor the phreatic layer, which emerges to form cold springs from wet meadows in the headwater sector. At the same time, part of the meteoric water that comes from topographic elevations circulates downward through the spaces generated by the characteristic columnar disjunction of this area, which causes secondary permeability due to the fissured medium (Fig. 4e and f).

The Ai zone presents an antiform type folding that affects the most basal units and faulting was also found that would coincide with the Ailinco stream (Galetto et al., 2018). Wet meadows in Ai zone are characterized by being on an esplanade occupying a large area with irregular to equidimensional shapes (Fig. 5a and b). Aguas Calientes stream has its origin mostly on the substrate caused by the mass-wasting deposits, although it later crosses the LVC. The wet meadows develop locally and on plains, and the subsurface flow discharges in the form of springs because the water table rises when it makes contact with the surface of the land. In addition, as occurs in the other hydrothermal zones, the rise of thermal water would occur fundamentally through the faulting whose position would coincide with the stream valley (Zanettini et al., 2001; Galetto et al., 2018) (Fig. 5c and d).

The low porosities of most of the lithological units involved in the stratigraphy of the study area, particularly the Varvarco Granodiorite (1.30 %), Precuyano Cycle (1.27 %), and LVC (1.58 %) (JICA, 1983), together with the structuring described in the literature, evidence that the storage and transmissibility of aquifer medium is generated by secondary permeability. Likewise, it is inferred that the greatest porosity of the UVC (11.56 %) is due to the fact that it corresponds to pyroclastic rocks with a low degree of welding, although it is fundamentally the columnar disjunction observed in field that gives it secondary permeability (Villalba et al., 2020). Moreover, thermal springs generate large accumulations of precipitates in the form of thick terraces in the EH and LG zones, which present a variety of structures and compositions similar to each other, coinciding with the Manchana Covunco fault. The expression of the terraces of hydrothermal precipitates is less evident in the thermal springs of RP, Ai, and AC, which are less thick and the manifestations are less effusive. The development of the precipitates would also reflect a structural type control in proximity to the headwaters, varying to a lithogeomorphological type towards the lower basin (Fig. 4b–d, f, and 5b, d).

5.2. Lithogeomorphological conceptual model

The meteoric water recharge zone is situated in the high peaks, towards the eastern region of the study area, while water discharge occurs in the western direction (lower basin). In the summits, an important structural control caused by the primary fault recognized as "Manchana Covunco" was identified (e. g., Miranda et al., 2006; Galetto et al., 2018). Towards the west of the study area, the lithology, and the geomorphological features are the predominant factors that control surface hydrological functioning (Villalba et al., 2020). The aquifer recharge likely occurs through the fissured medium near the hills, probably generated by the tectonic stresses of the region (e. g., Folguera et al., 2007). Unconsolidated volcanic deposits, columnar disjunction, stratification, or contact planes in sedimentary rocks, increases the hydraulic transmissivity and would be of significance for the sustenance of the groundwater system (Villalba et al., 2020). Once the water circulates at depth, it comes into contact with a heat source, likely formed by an intrusive igneous body, as suggested by existing evidence and previous investigations conducted by other authors (e. g., Llambías et al., 1978; JICA, 1983; Chiodini et al., 2014; Tassi et al., 2016; Silva-Fragoso et al., 2021; Galetto et al., 2018). Thermal water emerges to the surface due to the hydraulic pressure as hydrothermal manifestations such as geysers, bubbling pools, and fumaroles. Particularly, the geyser-type manifestations at the surface are caused by the boiling of subsurface water, which causes vapor overpressure and thus jet emission. These waters rise through the faults that are arranged coincidentally with the main streams of the area called "El Humazo" and "Covunco" faults, although fundamentally through the "Manchana Covunco" fault (Fig. 6), where the strongest manifestations (EH and LG) occur (Villalba, 2023). These thermal water discharges contribute to the streams in the study area or the wet meadows, where the previously mentioned geomorphological control dominates (Villalba et al., 2020). The wet meadows located in

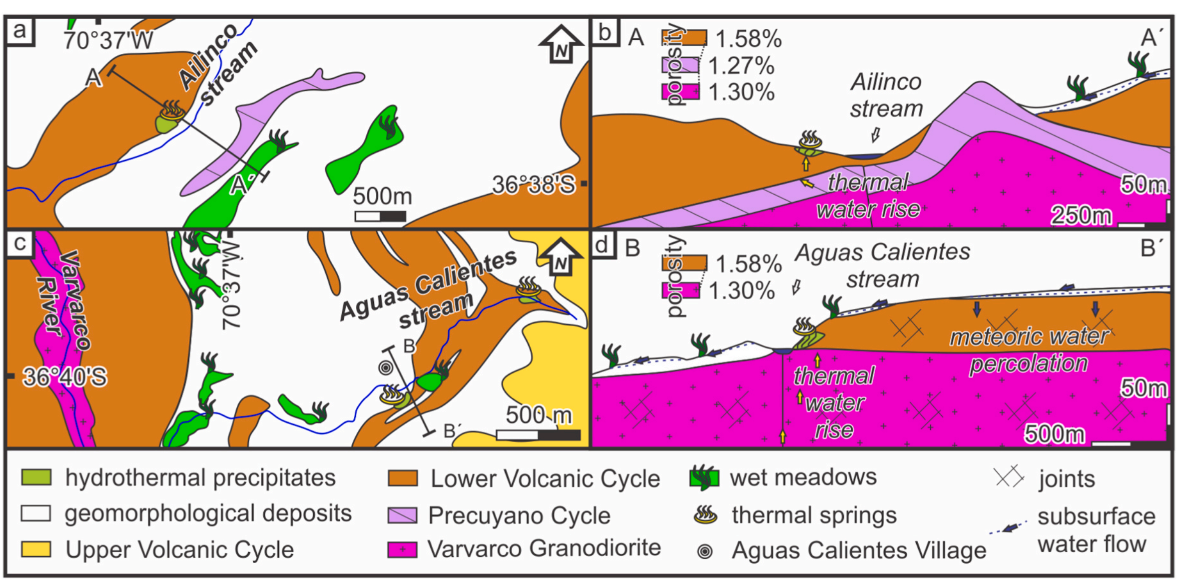

Fig. 5. Lithogeomorphological maps (a, c) and cross sections (b, d) in the lower basin sectors, where the dynamics of the hydrological system are reflected. The cross sections are represented on the maps according to the segments A-A' (Ailinco zone; Fig. 1c), and B-B' (Aguas Calientes zone; Fig. 1c). The porosity values are those reported by JICA (1983).

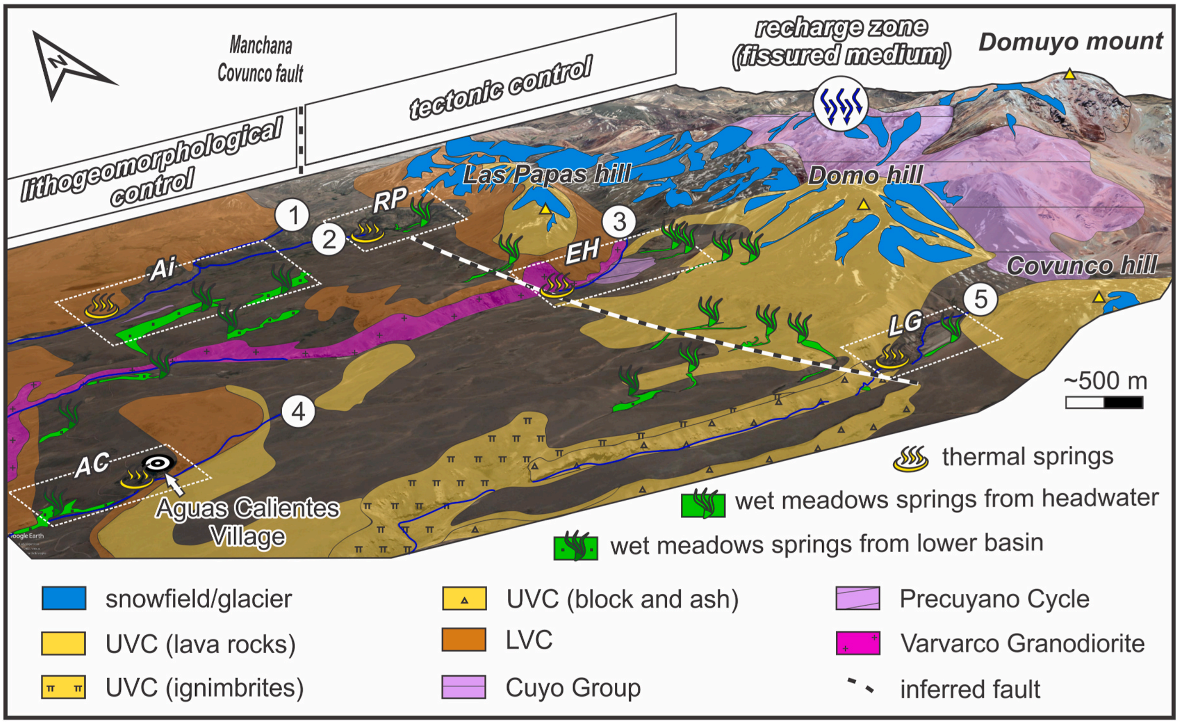

Fig. 6. Panoramic view and general conceptual model of the study area, where the main lithostratigraphic units and global distribution of wet meadows are represented. Satellite image in brown without trails indicates geomorphological features or units (except snowfields/glaciers), where deposits generated by mass-wasting processes predominate. Numbers 1 to 5 correspond to the Ailinco, Las Papas, Manchana Covunco, Aguas Calientes, and Covunco streams, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

headwaters develop in valleys on a relatively thin substrate, with a limited area, on steep slopes and elongated morphologies. These wet meadows are supported by (i) the shallow subsurface circulation of water from precipitation and snowmelt, and (ii) the water excess previously mentioned. Although detailed estimates of the input and source of water feeding the wet meadows are not available, future studies should focus on establishing precipitation, infiltration, or thermal water contribution relationships to improve the understanding of the hydrological cycle. The wet meadows situated in the lower basin developed on a thicker substrate, occupy more extended areas of less relief, and their morphologies tend to be irregular to subrounded since they occur in foothill sectors or distally with respect to the mountain ranges. Taking into account how the studied cold springs occur, the hillslope type predominates in the case of wet meadows from headwaters, while exposure springs, helocrene and rheocrene types, also occur in the lower basin (see Springer et al., 2008).

6. Conclusions

The dryland setting of the study area and its surroundings is a determining factor in socio-economic and population development. From villages to small towns, hundreds of people surrounding the study area require suitable water. This resource is obtained mainly from a filtration well situated on the bank of the Varvarco river, although some reports have pointed to quality problems on that water course, resulting from the input of thermal water, which poses risks to public health. In this context, high mountain wet meadows without thermal influence constitute a key source of water supply for populations, native fauna, livestock, and irrigation in the region. Wet meadows, in addition to providing abundant ecosystem services, such as regulating biogeochemical cycles and retaining water, also represent a safer and better quality water source for human and animal consumption. In fact, according to interviews conducted in the area, a significant part of the inhabitants of Varvarco access drinking water by capturing from springs located in these wet meadows.

This study shows that the hydrological system of the Domuyo mount area is strongly linked to geomorphology, lithologies, and tectonic structures. Groundwater recharge occurs at high altitudes due to the melting of glacial units and the subsequent water percolation through a structural control, such as fracture systems. In turn, part of the water flows down as a subsurface flow in headwater wet meadows, which have a limited areal expression and elongated morphologies due to the geoforms on which they develop. Eventually, springs from wet meadows discharge where the water table intersects the topography, which arises due to the features of the lithogeomorphological units that contain them, such as contact surface, cross section morphology, contrast of permeability, etc. In the lower basin sectors, wet meadows are significantly larger (two orders of magnitude) than those in headwaters and developed on deposits generated by low-slope mass-wasting processes. The information presented in this work constitutes new data that contributes to the knowledge of the lithogeomorphological factors for wet meadow formation and sustenance in dryland settings. Furthermore, the importance of these ecosystems as sources of quality water for populations is highlighted, reinforcing the need for their conservation and management. Given the increasing environmental pressure and climate variability affecting arid and semi-arid regions globally, the Domuyo case provides valuable insights into the geomorphological and lithological settings influencing wetland hydrology. This information is useful for resource management strategies and wetland conservation policies in other mountain drylands facing similar challenges.

CRediT authorship contribution statement

Esteban Villalba: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Silvina C. Carretero:** Writing – review & editing, Visualization, Validation, Supervision, Investigation, Data curation, Conceptualization. **María F. Lajoinie:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation, Data curation, Conceptualization. **Franco Tassi:** Writing – review & editing, Visualization, Validation, Supervision, Data curation, Conceptualization.

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.

Acknowledgements

The authors are grateful to the authorities of Áreas Naturales Protegidas de la Provincia de Neuquén (ANPN) for the permits granted to carry out fieldwork in the Domuyo System. We also thank the park ranger Daniel Castillo from Varvarco for his interview and help in collecting demographic information and his vision of the problems of the communes regarding of water supply. The authors would also like to give special thanks to Dr. Enrique Fucks for providing suggestions to improve this work. It is very appreciated to the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), and the Facultad de Ciencias Naturales y Museo (FCNyM) of the Universidad Nacional de La Plata (UNLP) of the Argentine Republic for the economic (N114/22) and technical support to carry out the research tasks concerning the completion of this work. Finally, we truly appreciate the careful reading, constructive comments, and valuable suggestions made by the editors and reviewers, given that their feedback has helped us improve the clarity and scientific quality of the work.

Data availability

Data will be made available on request.

References

Alexandratos, V.G., Elzinga, E.J., Reeder, R.J., 2007. Arsenate uptake by calcite: macroscopic and spectroscopic characterization of adsorption and incorporation mechanisms. Geochim Cosmochim Ac 71 (17), 4172–4187.
Álvarez, M.P., Carol, E.S., Pasquale Pérez, M.P., Melendi, E., Villalba, E., 2022. Hydrochemistry of Patagonian wet meadows (Mallines) under different geological frames environmental assessment of Patagonia's water resources. In: Environmental Assessment of Patagonia's Water Resources. Springer Nature, Switzerland, pp. 1–16.
Baied, C.A., 1989. Transhumance and land use in the northern Patagonian Andes. Mt. Res. Dev. 9 (4), 365.
Balugani, E., Lubczynski, M.W., Reyes-Acosta, L., Van Der Tol, C., Francés, A.P., Metselaar, K., 2017. Groundwater and unsaturated zone evaporation and transpiration in a semi-arid open woodland. J. Hydrol. 547, 54–66.
Bracaccini, O., 1970. Rasgos tectónicos de las acumulaciones mesozoicas en las provincias de Mendoza y Neuquén, República Argentina. Rev. Asoc. Geol. Argent. 25 (2), 275–284.
Brousse, R., Pesce, A.H., 1982. Cerro Domo: Un volcán Cuartario con posibilidades geotérmicas. Provincia del Neuquén. In: Proceedings, 5th Congreso Latinoamericano de Geología, vol. 4. Servicio Geológico Nacional, Subsecretaria de Minería, Buenos Aires, pp. 197–208.
Campbell, I.A., 1989. Badlands and badland gullies. In: Thomas, En D.S. G. (Ed.), Arid Zone, first ed., Geomorphology. Belhaven Press, pp. 159–183.
Chasek, P., Essahli, W., Akhtar-Schuster, M., Stringer, L.C., Thomas, R., 2011. Integrated land degradation monitoring and assessment: horizontal knowledge management at the national and international levels. Land Degrad. Dev. 22, 272–284.
Chiodini, G., Liccioli, C., Vaselli, O., Calabrese, S., Tassi, F., Caliro, S., Tassi, F., Caliro, S., Caselli, A., Agusto, A., D'alessandro, W., 2014. The Domuyo volcanic system: an enormous geothermal resource in Argentine Patagonia. J. Volcanol. Geotherm. R. 274, 71–77.
Cotton, C.A., 1950. Tectonic scarps and fault valleys. Geol. Soc. Am. Bull. 61, 717–758.
D'Elia, L., Páez, G.N., Hernando, I.R., Petrinovic, I.A., López, L., Kürten, G., y Vigiani, L., 2020. Hydrothermal eruptions at El Humazo, Domuyo geothermal field, Argentina: insights into the eruptive dynamics and controls. J. Volcanol. Geoth. Res. 393, 106786.
Demoustier, A., Castroviejo, R., Charlet, J.M., 1998. Clasificación textural del cuarzo epitermal (Au-Ag) de relleno filoniano del área volcánica de Cabo de Gata, Almería. Bol. Geol. Min. 109 (5–6), 449–468.
Duniway, M.C., Pfennigwerth, A.A., Fick, S.E., Nauman, T.W., Belnap, J., Barger, N.N., 2019. Wind erosion and dust from US drylands: a review of causes, consequences, and solutions in a changing world. Ecosphere 10 (3).
Epele, L.B., Mazzoni, E., Iturraspe, R., León, C., Díaz, E.D., Miserendino, M.L., Mataloni, G., 2022. Patagonian wetlands: Vertientes, Vegas, Mallines, Turberas, and Lagunas. In: Mataloni, G., Quintana, R.D. (Eds.), Freshwaters and Wetlands of Patagonia: Ecosystems and Socioecological Aspects. Natural and Social Sciences of Patagonia. Springer, Cham, pp. 267–294.
FAO (Food and Agriculture Organization), 2015. Informe de diagnóstico de los principales valles y áreas con potential agrícola de la Provincia del Neuquén. (Documento de trabajo N° 2. Aspectos físicos: suelo, clima y agua). Desarrollo institucional para la inversión 32.
Feng, S., Fu, Q., 2013. Expansion of global drylands under a warming climate. Atmos. Chem. Phys. 13 (19), 10081–10094.
Ferrer, J.A., Irisarri, J.A., Mendía, J.M., 1990. Estudio regional de suelos de la provincia de Neuquén. Consejo Federal de Inversiones, Argentina.
Folguera, A., Ramos, V.A., Zapata, T., Spagnuolo, M.G., 2007. Andean evolution at the Guañacos and Chos malal fold and thrust belts (36° 30′-37° S). J. Geodyn. 44 (3–5), 129–148.
Galetto, A., García, V., y Caselli, A., 2018. Structural controls of the Domuyo geothermal field, southern Andes (36° 38′ S), Argentina. J. Struct. Geol. 114, 76–94.
González Díaz, E.F., Costa, C.H., Giaccardi, A.D., 2003. El complejo deslizamiento de Ailinco-Cerro Papas-Las Olletas (Departamento Minas, norte del Neuquén, Argentina). Rev. Asoc. Geol. Argent. 58 (2), 194–200.
González Díaz, E.F., Folguera, A., Costa, C.H., Wright, E., Ellisondo, M., 2006. Los grandes deslizamientos de la región septentrional neuquina entre los 36°– 38° S: una propuesta de inducción sísmica. Rev. Asoc. Geol. Argent. 61 (2), 197–217.
Huang, J., Yu, H., Guan, X., Wang, G., Guo, R., 2016. Accelerated dryland expansion under climate change. Nat. Clim. Change 6 (2), 166–171.
Hurley, M., Colavitto, B., Astort, A., Sagripanti, L., Rosselot, E.A., Folguera, A., 2020. Mass-wasting deposits in the Domuyo volcanic center, northern Neuquén Andes (Argentina): an analysis of the controlling factors. J. S. Am. Earth Sci. 103, 102760.
AIC (Autoridad Interjurisdiccional de las Cuencas del Río Limay, Neuquén y Negro), 2015. Monitoreo de arsénico en aguas superficiales de la Cuenca del Río Neuquén, pp. 19.
INDEC (Instituto Nacional de Estadísticas y Censos) 2022. Cuadro poblacional, Provincia del Neuquén. Argentina.
INPRES (Instituto Nacional de Prevención Sísmica), 2012. Mapa de sismicidad en Argentina. Ministerio de Obras Públicas.
JICA, 1983. Argentine Republic. Final Report on the Northern Neuquén Geothermal Development Project. Japan International Cooperation Agency (inedited).
Jones, M., Willey, L., 2018. Eastern Alpine Guide: Natural History and Conservation of Mountain Tundra East of the Rockies. University Press of New England.
Kundu, S., Pal, S., Talukdar, S., Mandal, I., 2021. Impact of wetland fragmentation due to damming on the linkages between water richness and ecosystem services. Environ. Sci. Pollut. Res. 28 (36), 50266–50285.
Llambías, E.J., Palacios, M., Danderfer, J.C., Brogioni, N., 1978. Petrología de las rocas ígneas Cenozoicas del Volcán Domuyo y áreas adyacentes, Provincia del Neuquén. In: Proceedings, 7th Congreso Geológico Argentino: Neuquén, vol. 2. Asociación Geológica Argentina, pp. 553–568.
Litter, M.I., Ingallinella, A.M., Olmos, V., Savio, M., Difeo, G., Botto, L., Farfán Torres, E. M., Taylor, S., Frangie, S., Herkovits, J., Schalamuk, I., González, M.J., Berardozzi, E., García Einschlag, F.S., Bhattacharya, P., Ahmad, A., 2019. Arsenic in Argentina: occurrence, human health, legislation and determination. Sci. Total Environ. 676, 756–766.
Lu, N., Wang, M., Ning, B., Yu, D., Fu, B., 2018. Research advances in ecosystem services in drylands under global environmental changes. Curr. Opin. Env. Sust. 33, 92–98.
Mas, G.R., Bengochea, L., Mas, L.C., 2000. Hydrothermal alteration at El Humazo geothermal area, Domuyo volcano, Argentina. In: Proceedings of the World Geothermal Congress. Tohoku, Japón.
Mazzoni, E., Rabassa, J., 2013. Types and internal hydro-geomorphologic variability of mallines (wet-meadows) of Patagonia: emphasis on volcanic plateaus. J. S. Am. Earth Sci. 46, 170–182.
McCartney, M., Rebelo, L.M., Sellamuttu, S., 2015. Wetlands, livelihoods and human health. In: Finlayson, C., Horwitz, P., Weinstein, P. (Eds.), Wetlands and Human Health, Wetlands: Ecology, Conservation and Management, vol. 5. Springer, Dordrecht.
McClain, M.E., 2002. The ecohydrology of South American rivers and wetlands. In: International Association of Hydrological Sciences. No. 6).
Middleton, N.J., Thomas, D., 1997. World Atlas of Desertification. UNEP, Arnold, London.
Minhas, P.S., Rane, J., Pasala, R.K., 2017. Abiotic stresses in agriculture: an overview. In: Abiotic Stress Management for Resilient Agriculture. Springer, Singapore, pp. 3–8.
Mitsch, W.J., Gosselink, J.G., 2015. In: Wetlands, fifth ed. John Wiley & Sons Inc.
Miranda, F., Folguera, A., Leal, P.R., Naranjo, J.A., Pesce, A., 2006. Upper Pliocene to lower Pleistocene volcanic complexes and upper Neogene deformation in the south-central Andes (36° 30' – 38° S'). Geol. Soc. Am. 407, 287.
Narciso, V., Santamaría, G., Zanettini, J.C.M., 2004. Hoja Geológica 3769-I, Barrancas. Provincias de Mendoza y Neuquén, vol. 253. Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino. Boletín, Buenos Aires, p. 60.
Neuquén Informa Newspaper. El EPAS ejecuta una obra para garantizar el agua potable en Varvarco.https://www.neuqueninforma.gob.ar/noticias/2022/05/15/192966-el-epas-ejecuta-una-obra-para-garantizar-el-agua-potable-en-varvarco.
Páez, G.N., D'Elia, L., Hernando, I., Petrinovic, I., Villarosa, G., Borzi, G.E., Varela, S.S., 2014. Evolución y dinámica eruptiva del Complejo Volcánico Domuyo, provincia de Neuquén, Argentina. XIX Congreso Geológico Argentino. Córdoba, Argentina.

Palacios, D., Andrés, N., 2006. El significado geográfico de la nieve en la dinámica natural de la Sierra de Guadarrama. In: Grupo de Investigación en Geografía Física de Alta Montaña. Universidad Complutense de Madrid.
Prăvălie, R., 2016. Drylands extent and environmental issues. A global approach. Earth Sci. Rev. 161, 259–278.
Ramos, V.A., Mosquera, A., Folguera, A., García Morabito, E., 2011. Evolución tectónica de los Andes y del engolfamiento Neuquino adyacente. In: Leanza, L. (Ed.), Relatorio de la provincia de Neuquén. XVIII Congreso Geológico Argentino, Neuquén, Argentina, pp. 335–348.
Río Negro, Newspaper. La comunidad de Varvarco reclama el agua potable. https://www.rionegro.com.ar/la-comunidad-de-varvarco-reclama-el-agua-potable-CGHRN05032713271015/.
Salcedo, A.P., Solorza, N.R., 2010. La degradación de tierras mediante análisis fisiográfico y la aplicación de técnicas de teledetección en la cuenca del Río Guañacos, Departamento Minas, Neuquén. Bol. Geogr. 32, 23–54.
Silva-Fragoso, A., Ferrari, L., Norini, G., Orozco-Esquivel, T., Corbo-Camargo, F., Bernal, J.P., Castro, C., Arrubarrena-Moreno, M., 2021. Geology and conceptual model of the Domuyo geothermal area, northern Patagonia, Argentina. J. Volcanol. Geotherm. R. 420, 107396.
Springer, A.E., Stevens, L.E., 2008. Spheres of discharge of springs. Hydrogeol. J. 17 (1), 83.
Stipanicic, P.N., 1965. El Jurásico de la Vega de la Veranada (Neuquén). El oxfordiense y el distrofismo divesiano (Agasiz – Yaila) en Argentina. Rev. Asoc. Geol. Argent. 20 (4), 403–475.
Tassi, F., Liccioli, C., Agusto, M., Chiodini, G., Vaselli, O., Calabrese, S., Pecoraino, G., Tempesti, L., Caponi, C., Fiebig, S., Caliro, S., Caselli, A., 2016. The hydrothermal system of the Domuyo volcanic complex (Argentina): a conceptual model based on new geochemical and isotopic evidences. J. Volcanol. Geotherm. R. 328, 198–209.
Tooth, S., McCarthy, T.S., 2007. Wetlands in drylands: geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa. Prog. Phys. Geogr. 31 (1), 3–41.
Tooth, S., 2018. The geomorphology of wetlands in drylands: resilience, nonresilience, or…? Geomorphology 305, 33–48.
UNESCO (United Nations Educational, Scientific and Cultural Organization), 2023. Transhumance, the seasonal droving of livestock. Retrieved from. https://ich.unesco.org/en/RL/transhumance-the-seasonal-droving-of-livestock-01964.
Villalba, E., Tanjal, C.V., Borzi, G.E., Páez, G.N., Carol, E.S., 2020. Geogenic arsenic contamination of wet-meadows associated with a geothermal system in an arid region and its relevance for drinking water. Sci. Total Environ., 137571
Villalba, E., Santucci, L., Borzi, G.E., Pasquini, A.I., Páez, G.N., y Carol, E.S., 2022. Geothermal influence on the hydrochemistry of surface streams in Patagonia neuquina. In: Environmental Assessment of Patagonia's Water Resources. Springer Nature, Switzerland, pp. 57–73.
Villalba, E., 2023. La interacción agua-roca en ambientes hidrológicos asociados a fluidos geotermales. Aplicaciones en calidad de aguas de abastecimiento. Universidad Nacional de La Plata, Facultad de Ciencias Naturales y Museo. Doctoral dissertation , pp. 171.
Worlanyo, A.S., Jiangfeng, L., 2021. Evaluating the environmental and economic impact of mining for post-mined land restoration and land-use: a review. J. Environ. Manag. 279, 111623.
Zanettini, J.C., Santamaría, G.R., Leanza, H.A., 2001. Hoja Geológica 3772-II, Las Ovejas. In: Provincia del Neuquén. Servicio Geológico Minero Argentino, vol. 263. Instituto de Geología y Recursos Minerales. Boletín, Buenos Aires, p. 67p.