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ARTÍCULOS / *ARTICLES*

IMPLEMENTATION OF A COLLABORATIVE GEOGRAPHIC INFORMATION SYSTEM (CGIS) IN A RESEARCH CAMPAIGN AT THE COROPUNA GLACIER (TROPICAL ANDES OF PERU)

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Abstract: Geographic Information Technologies offer significant potential as tools for designing, planning, managing, and disseminating research campaigns. Cloud-based digitalization saves time throughout all expedition phases—pre-fieldwork, fieldwork, and post- fieldwork —by facilitating the preparation, collection, and editing of data and maps.

This paper presents a cloud-hosted ArcGIS Online system developed to support, within a collaborative environment, a research campaign conducted on the glaciers of Nevado Coropuna (southern Peruvian Andes) during July and August 2022. The ArcGIS Online application provided the following functionalities: (1) preparation of data, maps and 2D/3D apps for fieldwork planning; (2) configuration of maps for collaborative, offline field use; (3) on-site data collection; (4) processing of the campaign's collected data; and (5) dissemination and publication of results. The tool requires no prior user experience and is applicable to any Earth science research project.

Key words: Nevado Coropuna, collaborative GIS, glaciology, glacial geomorphology, fieldwork, ArcGIS Online.

IMPLEMENTACIÓN DE UN SISTEMA DE INFORMACIÓN GEOGRÁFICA COLABORATIVO (SIGC) EN UNA CAMPAÑA DE INVESTIGACIÓN EN EL GLACIAR COROPUNA (ANDES TROPICALES DEL PERÚ)

AResumen: Las tecnologías de la información geográfica tienen gran potencial para su implantación como instrumento para diseñar, planificar, gestionar y difundir campañas de investigación. La digitalización en la nube permite ahorrar tiempo durante la preparación, recogida y edición de datos y mapas en todas las fases de la expedición: precampaña, trabajo de campo y post-campaña. En este trabajo se presenta un sistema alojado en la nube de ArcGIS Online para dar soporte en un entorno colaborativo a la campaña de investigación realizada en los glaciares del Nevado Coropuna (Andes tropicales del sur de Perú) en julio y agosto de 2022. Las prestaciones de la aplicación de ArcGIS Online para esa campaña se pueden desglosar en: (1) preparación de datos, mapas y apps 2D/3D para la planificación del trabajo de campo; (2) configuración de mapas para uso colaborativo en campo sin conexión; (3) recogida de datos sobre el terreno; (4) procesamiento de los datos recogidos en la campaña y (5) difusión y publicación de los resultados. La herramienta diseñada no requiere experiencia previa y puede aplicarse a cualquier otra disciplina de las ciencias de la Tierra.

Palabras clave: Nevado Coropuna, GIS colaborativo, glaciología, geomorfología glaciar, trabajo de campo, ArcGIS Online.

1. INTRODUCTION

Geographic Information Systems (GIS) offer numerous possibilities for technical support in geoscience research projects. The suite of desktop, web, and mobile GIS tools enables the storage, management, analysis, and organization of large datasets (Esri, 2012). Advances in GIS provide fieldworkers with advantages such as precise location tracking, real-time data visualization, and rapid data acquisition and recording. Nearly three decades after their emergence, GIS use has become widespread in geosciences, primarily in office-based work. Although digital fieldwork is expanding in geosciences (Phantuwongraj et al., 2021), on-site GIS applications remain largely limited to data recording. However, next-generation GIS tools are also valuable for fieldwork, displaying pre-planning on various maps and allowing field-collected data to be recorded on the same cartographic base. New online GIS applications facilitate the simultaneous integration of georeferenced data into the project's GIS system. With real-time internet connectivity, data can be integrated instantly.

Collaborative GIS (CGIS) has a long history (Balram & Dragicevic, 2006). CGIS system may possess a set of basic tools that permit shared view, control and object selection of geographical information; annotation and mark-up of geographic (map) features with multimedia data in the form of text, graphics, photos, and audio/video clips and interactive exploration of geographical data for spatial problems, as well as awareness of other collaborators and their outcomes. (Sun & Li, 2016).

Research on Peru's tropical glaciers presents an opportunity to test new GIS technologies. Here, geographic information is essential not only for efficient data capture but also to enhance researcher safety, for example, by locating crevasses on glaciers, even when fully or partially snow-covered.

Glaciers are hostile environments with hazards like crevasses, ice avalanches, and rockfalls. Sudden weather changes often force reduced work hours or even campaign suspension if risks escalate. Additionally, glacier snouts in southern Peru lie at extreme altitudes (RGI Consortium, 2017), between 4,900 and 5,500 meters above sea level (hereafter m). The distance and elevation gain from vehicle or pack-animal access points are also critical, given the weight of research equipment, climbing gear, and water/food supplies. Consequently, developing online GIS applications for glaciological research is a worthwhile challenge. Glacier studies, like other Earth Sciences areas, increasingly rely on GIS for mapping, data collection and processing, as well as results dissemination.

Although field personnel require some prior training, this is usually minimal, as modern online GIS tools are highly accessible and designed for smartphones, streamlining infield learning (Wang et al., 2017). Moreover, advanced smartphones integrate GPS and cameras, reducing campaign costs without compromising data quality. Today's smartphones achieve remarkable positioning accuracy, sufficient for many glacier studies. ArcGIS Online, a cloud-based platform with diverse functions, enables collaborative field-data georeferencing, making it valuable for both research and education (Esri, 2019a; Esri, 2019b).

This work presents results from a collaborative ArcGIS Online application in the Monitoring Tropical Ice in the Peruvian Mountains (MOTICE) project, funded by Spain's Ministry of Science, during three campaign phases developed in 2022: i) fieldwork planning, ii) mobile data collection during fieldwork (integrated into the project's CGIS), and iii) previous results dissemination to local authorities and stakeholders.

The 2022 MOTICE field campaign had the following general objectives:

I. Locate points at the glaciers' peripheries using differential GPS. Once linked to Peru's geodetic network, the point cloud, with an average error below 50 cm, was used to georeference satellite imagery and digital elevation models (DEMs). These DEMs and images were the base for multitemporal analysis of glacier surface/volume evolution and mass balance (Llanto et al., 2025).

II. Conduct subsurface geophysical surveys in three zones: clean ice, debris-covered ice, and proglacial areas with potential buried ice (rock glaciers/permafrost). Subsurface profiling used ground-penetrating radar (GPR) and vertical electrical sounding (VES).

III. Establish relative chronologies of deglaciated surfaces by measuring rock weathering with Schmidt hammer rebound and ultrasonic pulse velocity.

IV. Collect isotope samples from meltwater and snow to assess hydrological fluxes within the volcanic system.

2. STUDY AREA

Fieldwork was conducted over 31 days during July and August 2022 in the glacial and periglacial areas of Nevado Coropuna (15°32'S, 72°39'W; 6,377 m), located ~150 km northwest of Arequipa city and ~15 km northwest of Viraco village (Peru). Coropuna is a volcanic complex comprising several adjacent stratovolcanoes, with its summit area covered by the largest icecap in the tropics (Úbeda et al., 2018). By 2023, its total glacier surface area was ~41 km² (Úbeda, 2023). For this study, Coropuna was divided into four sectors: North-Cavalca, South-Unro, East-Quebrada Cospanja and West-Pallarcocha.

Coropuna lies in the arid tropical Andes, where glaciers depend to a greater extent on precipitation rather than on temperature (Sagredo & Lowell, 2012; Sagredo et al., 2014). Due to its extreme altitude, precipitation on Coropuna occurs exclusively as snow and is linked to the South American Summer Monsoon (SASM), which controls seasonal rainfall in tropical South America (Sylvestre, 2009; Nogués-Paegle et al., 2002; Vera et al., 2006; Zhou & Lau, 1998). The SASM includes several components: the South Atlantic Convergence Zone (SACZ), air convection over the Amazon Basin and the seasonal north/south shift of the Intertropical Convergence Zone (ITCZ) during the austral winter/summer.

Meltwaters from Coropuna's glaciers supply tens of thousands of people in its watershed, located in one of the driest regions on Earth. Additionally, Coropuna is an active volcano (Bromley et al., 2019; Úbeda et al., 2018). If meltwater was suddenly and massively released as a lahar (e.g., due to a volcanic eruption), it would become a serious threat to downstream populations. From Coropuna's summit to the Pacific coast, the elevation drops >6,000 m along a hyper-arid ramp where vegetation transitions from sparse to non-existent. Both this steep gradient and the lack of phyto-stabilization exacerbate hydrovolcanic hazards.

Below the glaciated area, permafrost has been detected in relation to topo-climatic factors like slope orientation and soil/substrate color (Yoshikawa et al., 2020) and it is currently being monitored. Monitoring methods include soil temperature measurements and geophysical profiling using electrical resistivity tomography (Úbeda et al., 2015). Permafrost is a significant feature, as it serves both as a reservoir of solid water and an impermeable layer. Its disappearance would alter the aquifers connecting frozen water reserves to the surrounding landscape.

3. METHODOLOGY

To achieve the objectives of the 2022 field campaign, a cloud-based workflow was designed in ArcGIS Online, integrating the three phases of glacial research (Fig. 1): precampaign, fieldwork, and post-campaign. The project's data ensemble combined aerial/satellite imagery, GIS layers previously created through office work and field collected data, all of them published in the cloud to enable map and application creation.

Phase I: Pre-Campaign

Data and map preparation were conducted using ArcGIS Pro (Fig. 2). A geodatabase with 11 layers was created (Table 1) in order to properly organize the data. This geodatabase excluded the DEM, which was stored separately. Layers were grouped into two categories: i) visualization-only data (yellow in Table 1), and ii) visualization, editing, and field data collection (red in Table 1).

From ArcGIS Pro, feature layers were hosted and published in ArcGIS Online with two advanced functions activated: i) attachments for photo collection and ii) synchronization, which enabled offline cartographic editing and representation. Also, a view was created to display editable field layers, synchronized and referred to the original data (editable layer) and shared publicly in read-only mode (2D/3D viewer in Experience Builder). This allowed synchronization between an internal layer (accessible only during fieldwork for data collection/editing) and a public view (displaying curated data).

Subsequently, a web map and 3D scene were generated (Fig. 3), allowing users to toggle the published layers. For field use on mobile devices (smartphones and tablets), a web map was configured for offline data collection/editing.

FIGURE 1.
ARCGIS WORKFLOW FOR FIELD CAMPAIGN PHASES

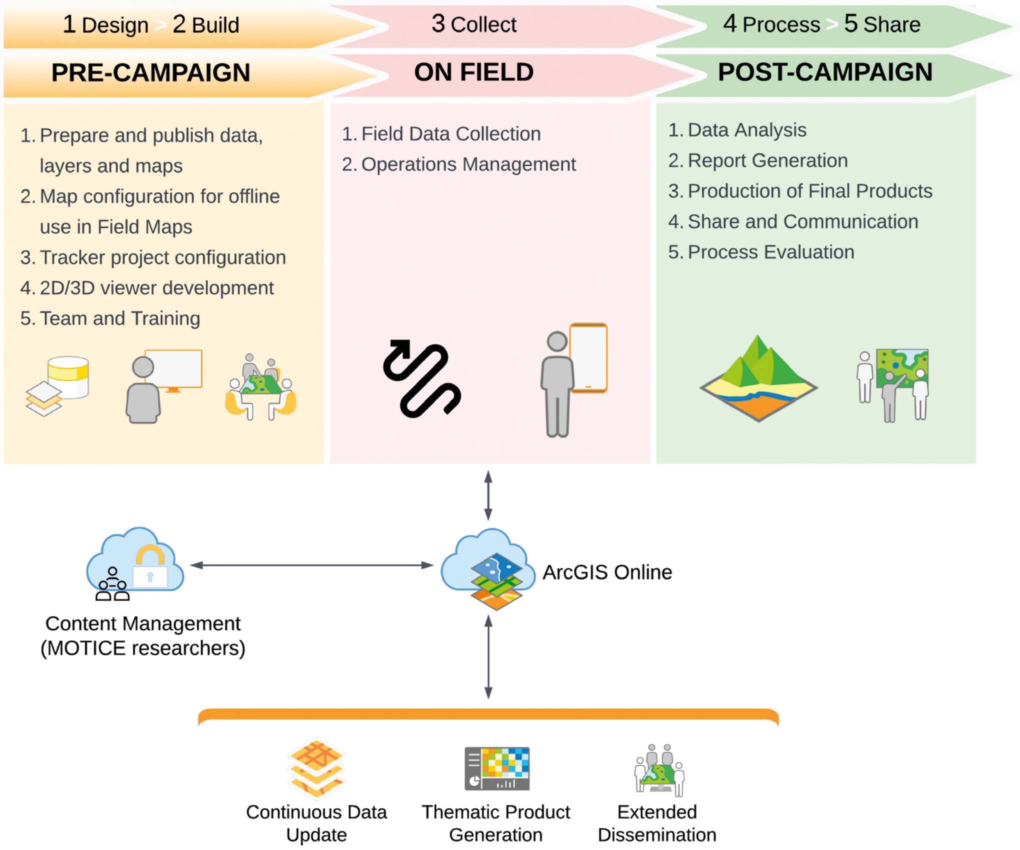


FIGURE 2.
DATA AND MAP GENERATION IN ARCGIS PRO

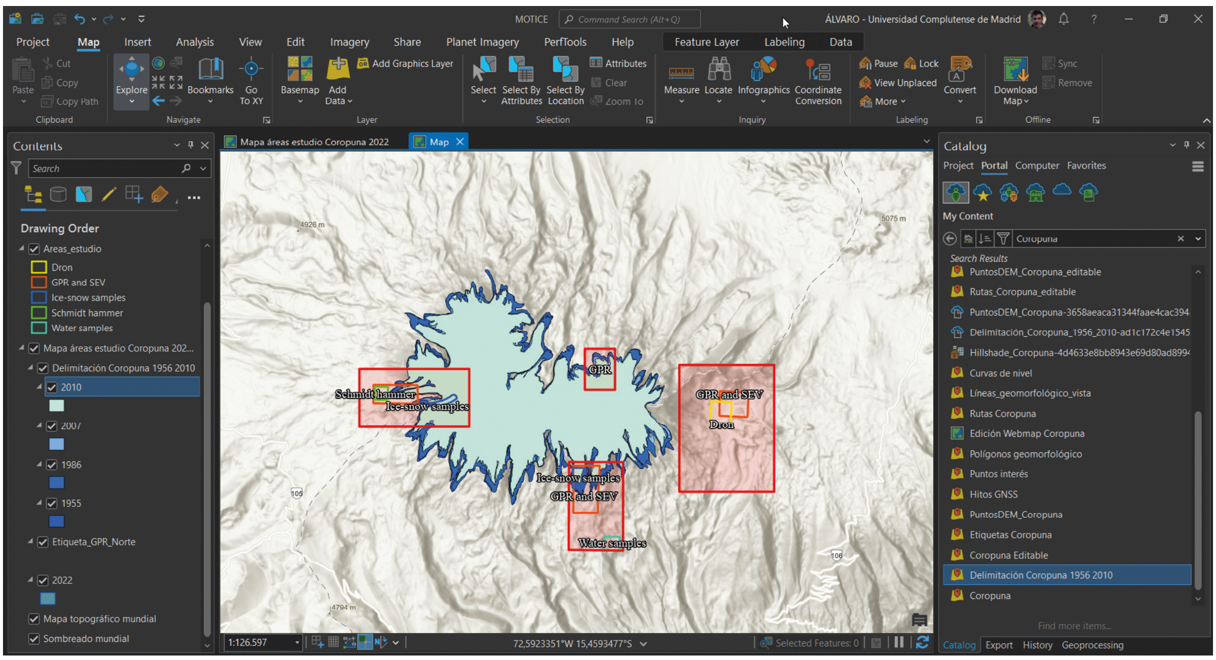


Table 1.
ENSEMBLE OF LAYER GENERATED FOR FIELD DATA COLLECTION.

Layers	Source	Main Use in the Field	Notes
Points of Interest	Camps, permafrost station…	Reference	-
DEM Points	INGEMMET	Reference	-
GNSS Points	INGEMMET	Reference	-
Approach Routes	Own production	Reference and data collection	Possible approach routes to the base and summit of Coropuna
Contour Lines	National Topographic Map (1:100.000)	Reference	-
2018 Tomography	INAIGEM	Reference	Data from a 2018 study on a rock glacier on the eastern side of Coropuna
Geophysics SEV and GPR	Own production	Reference and data collection	Point layer for SEV points and line layer for GPR profiles
Coropuna Delimitation 1956–2010	Úbeda (2011)	Reference	-
GPS Metadata	Own production	Data collection	Point layer on which the Add GPS Metadata Fields tool is applied to include GNSS fields and a description field for field notes.
Geomorphological Map	Own production	Reference and data collection	Polygon and line layers (moraines, glaciers, rock glaciers…). Manual digitization over Esri basemaps (Maxar imagery from August 2021, 1.2 m resolution).
DEM and Hillshade	Own production from SPOT6	Reference	DEM date: 23-11-2013

From the Field Maps web application (Fig. 4), the offline mode was set for the editable web map, defining the map extent to be downloaded in the mobile device, a minimum data capture precision (error<10 m), as well as automated tracking user on the go and recording of field routes.

A viewer capable of toggling between 2D and 3D views was programmed for data visualization over a map and for basic spatial analysis, in which additional layer could also be loaded. The viewer was designed to be web responsive, hence accessible on tablets/smartphones. It included widgets for coordinates conversion, elevation profile creation and area/distance measurement.

Phase II: In the Field

During fieldwork, Field Maps was critical for data collection using applied techniques (Fig. 5: VES, GPR, Schmidt Hammer), and capturing ancillary data (e.g., attached images, attributes) (Fig. 6).

Phase III: Post-Campaign

Field data were incorporated into the GIS-MOTICE system via ArcGIS Pro. Field Maps data were cleaned (errors identified/corrected) and organized into five thematic layers (Fig. 7): GPR, VES, Points of interest, GPS points and Hydrogeology points.

To disseminate results locally, the layers generated in ArcGIS Pro were exported to web applications (Fig. 8), once optimized for small screens (e.g., tablets/smartphones). An additional section was created in which imagery associated to each point was interactively shown. The information was displayed from a general location map, in which the four main fieldwork areas were highlighted.

FIGURE 3 .
WEB MAP (TOP) AND 3D SCENE (BOTTOM)

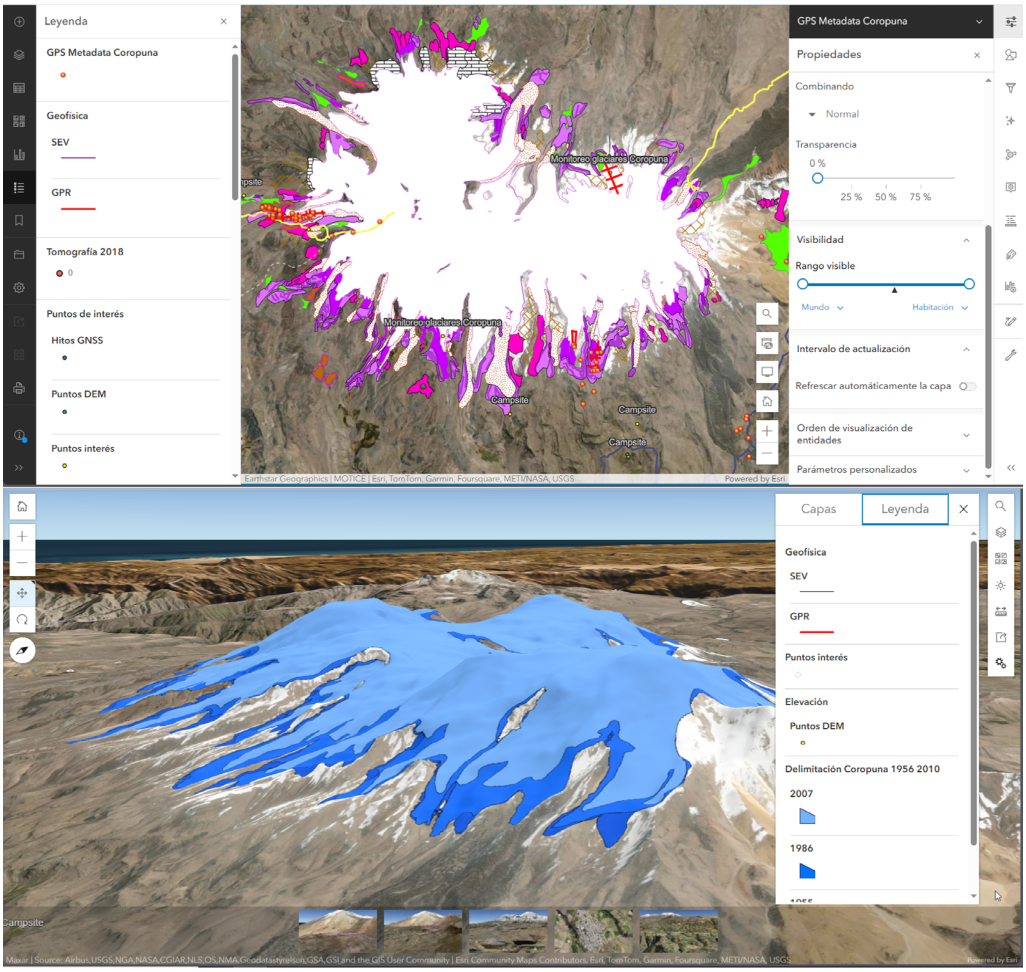


FIGURE 4.
OFFLINE LAYER CONFIGURATION IN FIELD MAPS

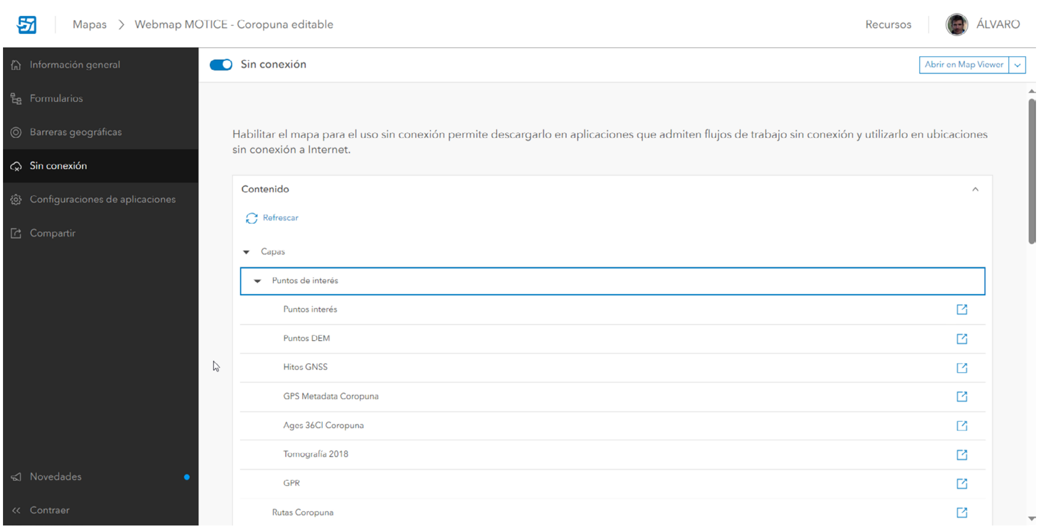


FIGURE 5.
FIELD TECHNIQUES APPLIED IN THE EAST QUEBRADA COSPANJA SECTOR

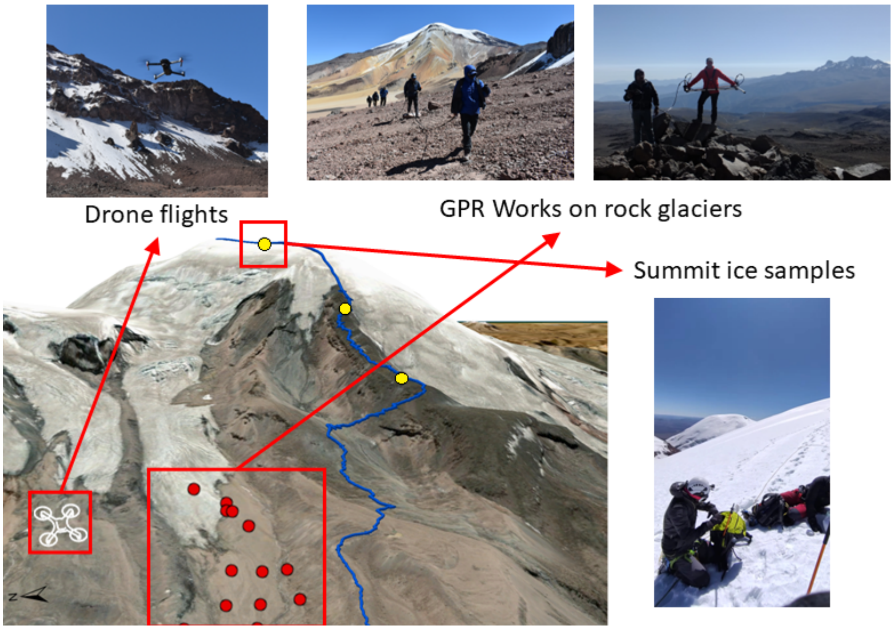


FIGURE 6.
MOBILE DEVICE SCREENSHOT DURING DATA COLLECTION AT POINTS AROUND AND ON THE COROPUNA ICECAP.

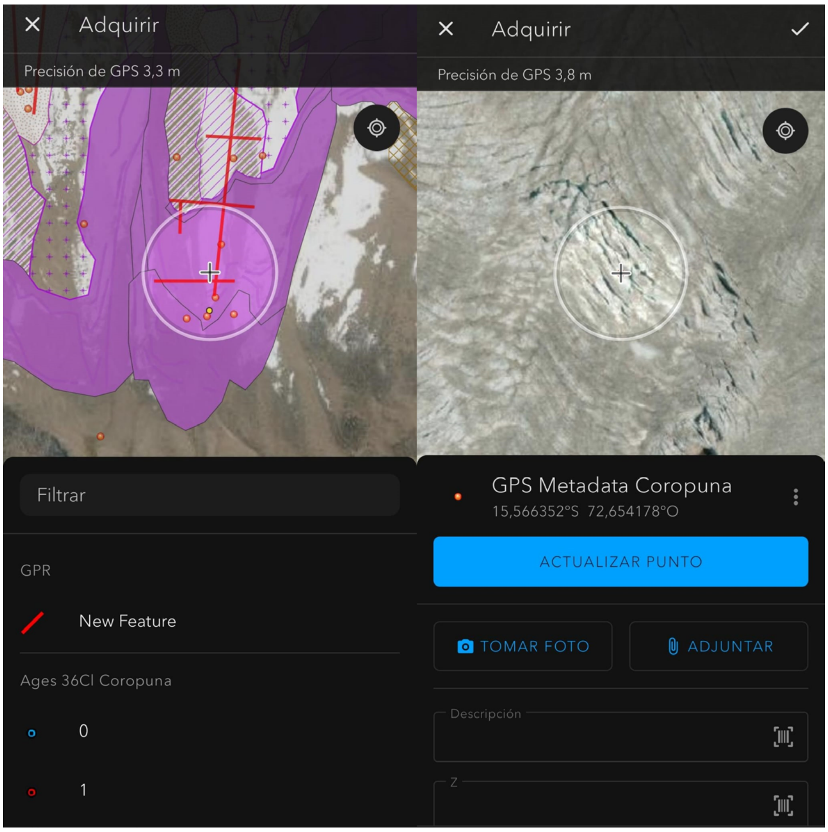


FIGURE 7.
FIELD DATA POST-PROCESSING IN ARCGIS PRO

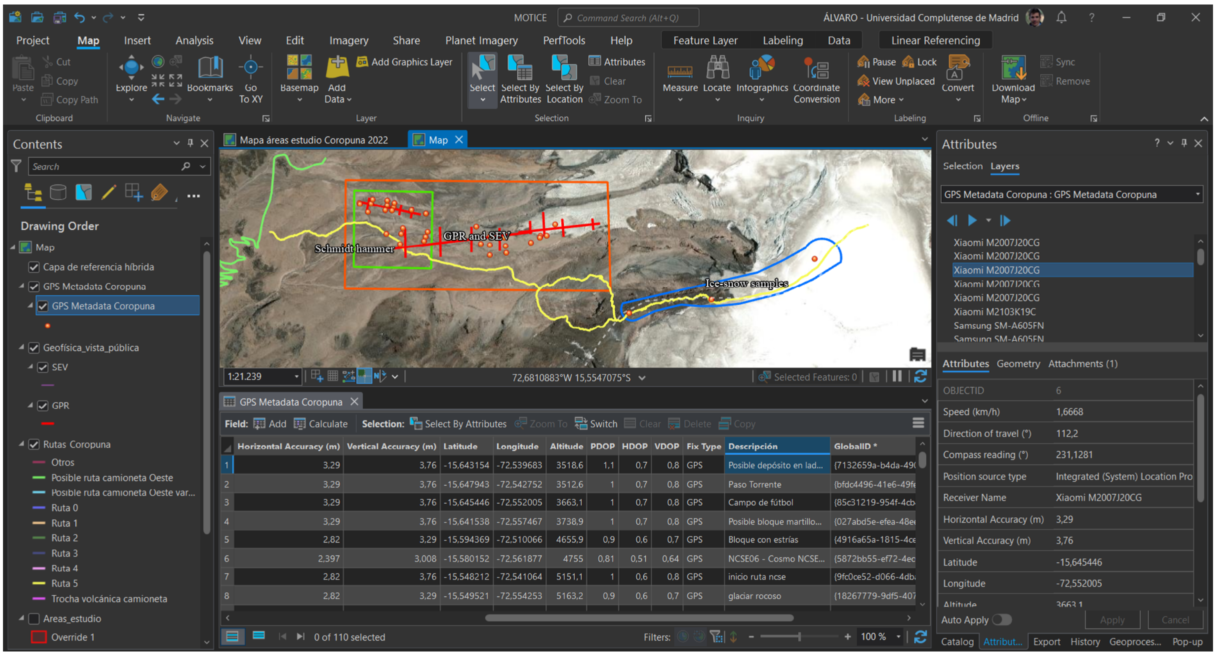
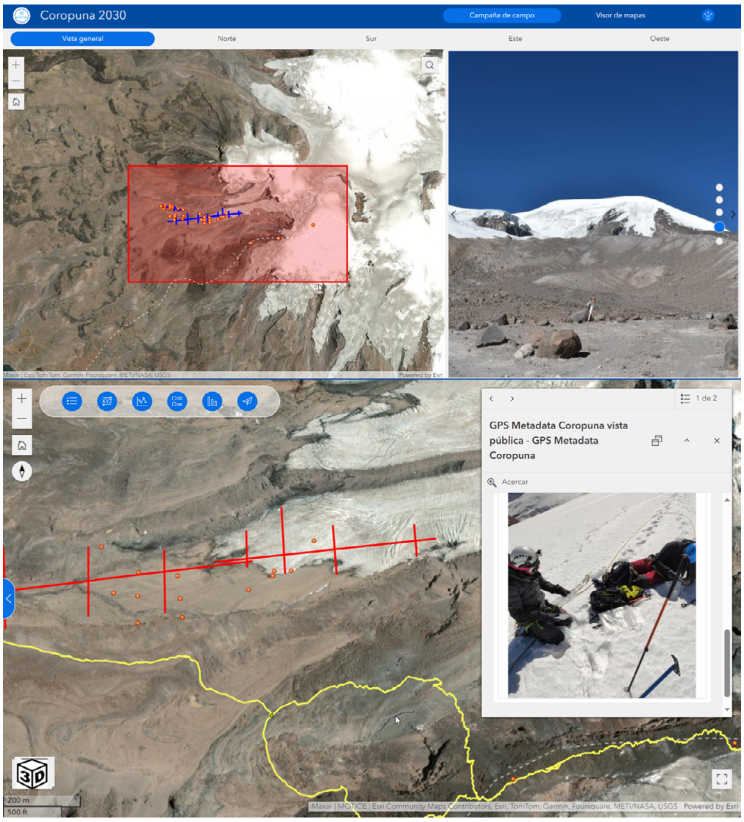


FIGURE 8.
WEB APPLICATION FOR FIELD CAMPAIGN RESULTS DISSEMINATION



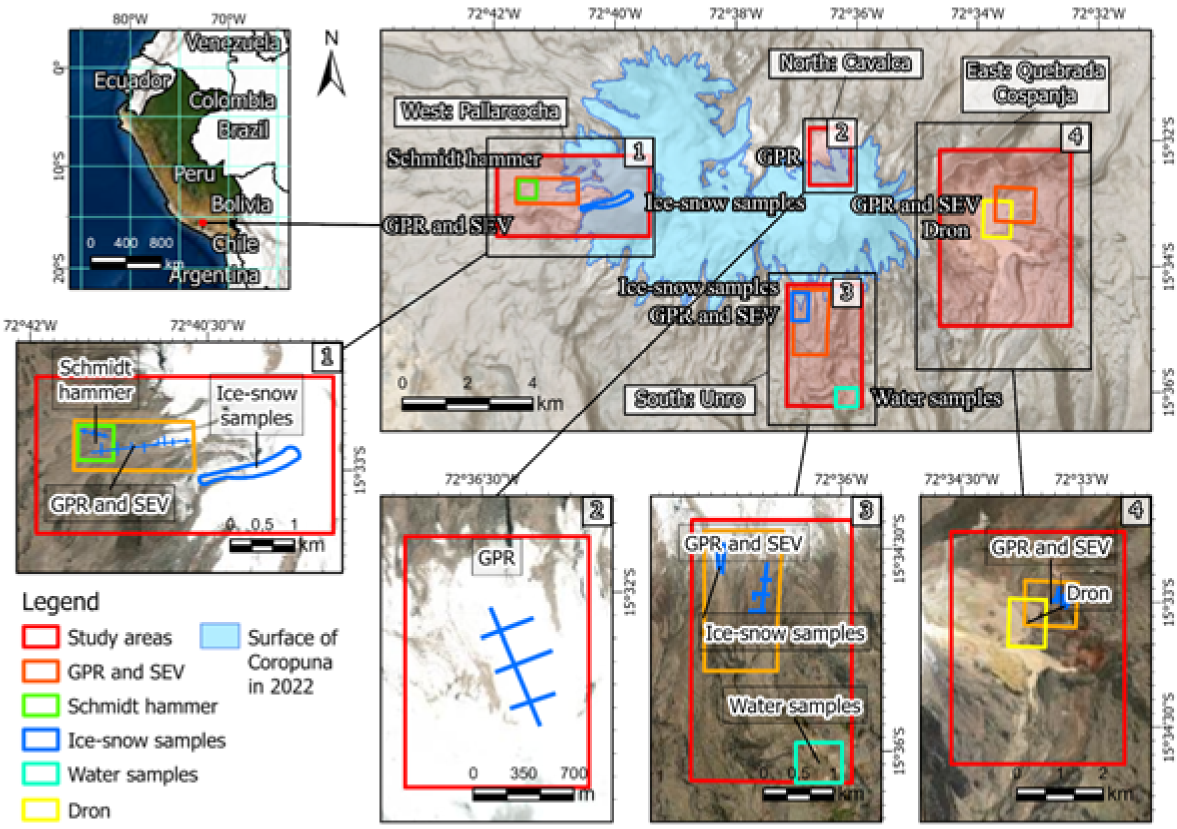
4. RESULTS

These are the results, organized by the type of product generated:

5. COLLECTED DATA

During fieldwork, more than 10 users (with and without GIS experience) recorded information at a total of 115 points of interest and generated ~20 km of tracks from their own smartphones. Additionally, the map downloaded on the devices served as a reference to check altitude and travelled distance, as well as to identify paths, trails, rocks and glacial crevasses, thanks to the high-resolution images of the base map. Likewise, the application also assisted in a) the identification of potential ground control points for differential GPS measurement (e.g., rocks), b) establish approach routes, c) prospect GPR transects and d) locate VES soundings in glacial and proglacial areas (Figure 9).

FIGURE 9.
LOCATION MAP OF THE FOUR STUDY AREAS AND APPLIED TECHNIQUES DISTRIBUTION



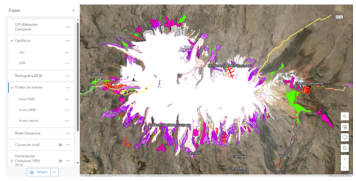
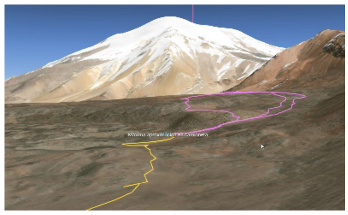
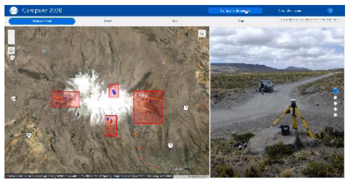
For each manually collected point, each device automatically recorded the X, Y, Z coordinates and GPS accuracy. Through reanalysis of the information in ArcGIS Pro, the points obtained in the field were classified into the following thematic fields:

- GPR trace vertices.
- Points of interest (e.g., water outcrops, ice caves, etc.).
- Ice and water samples.
- Schmidt hammer sampling points.
- Logistical information: base camps, maximum vehicle or support animal approach points.

6. MAPS AND APPLICATIONS FOR FIELD USE

The layers generated during the pre-campaign and the data collected during fieldwork allowed the creation of a series of products and tools adapted to the project's needs, compiled in Table 2.

TABLE 2.
LIST OF GENERATED PRODUCTS AND TOOLS.

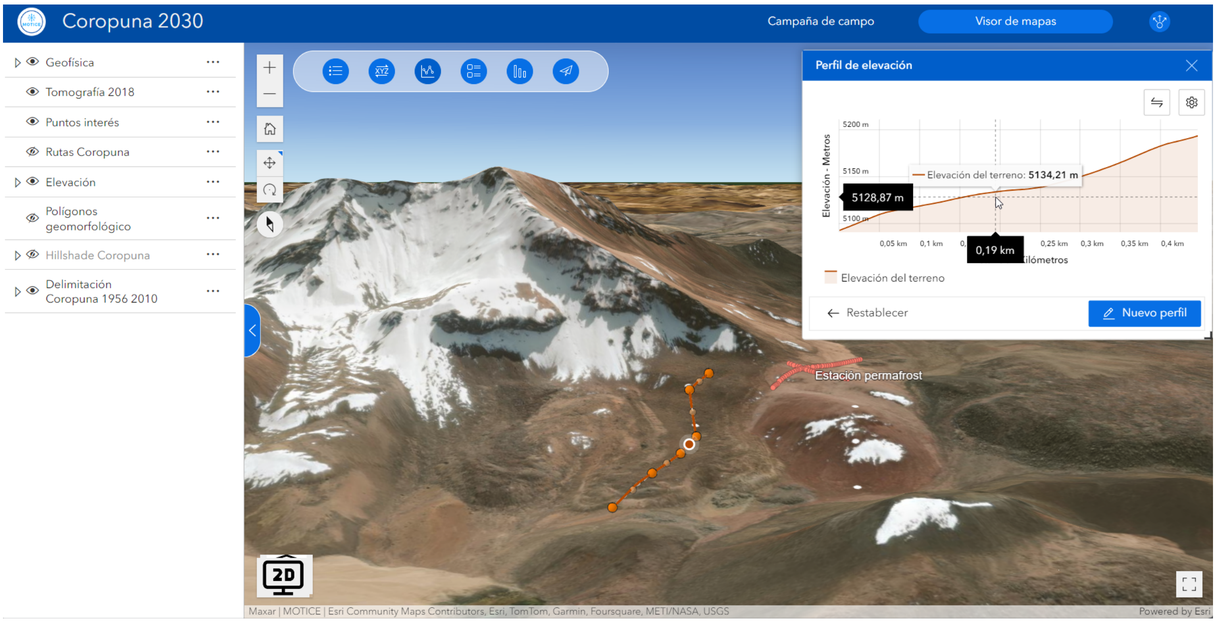
Name	Type	Main Use	URL	Screenshot
Coropuna Webmap	Map	Visualization	https://arcg.is/1ayyCa1	
Coropuna Offline Webmap		Visualization and editing	https://arcg.is/1nOm04	
Coropuna 3D	Scene	Visualization	https://arcg.is/9jCSb	
Experience Builder Viewer	App	Visualization	https://arcg.is/1fzaXy0	
Data Hub		Visualization and download	https://motice-ucmadrid.hub.arcgis.com/	

In the fieldwork-planning meetings (Figure 10), the viewer (Figure 11) was used to perform the following tasks for each of the four study areas defined on Nevado Coropuna (North, South, East, and West):

- Planning of vehicle approaches.
- Location of base camps.
- Definition of material transportation routes between the truck and base camp, and between base camp and sampling areas.
- Design of GPR profile itineraries.
- Location of VES prospections.
- Preparation of drone flights.
- Design of the ice sampling route for isotopes at Coropuna's summit.

FIGURE 10.
FIELDWORK PREPARATION SESSION SUPPORTED BY THE 2D/3D VIEWER, AT THE CEDER NGO FACILITIES IN VIRACO (AREQUIPA, PERU)

FIGURE 11.
2D/3D MAP VIEWER

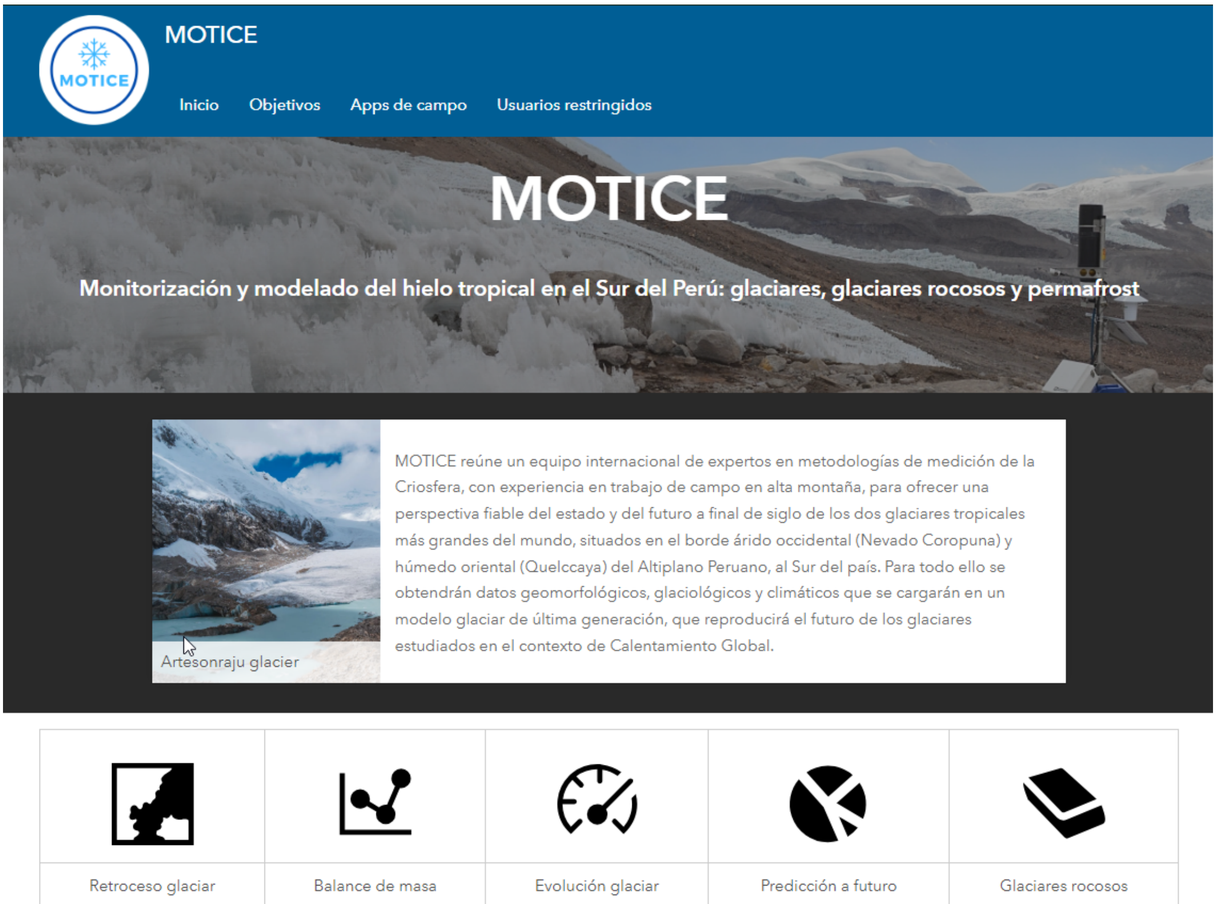


7. ACCESS, DISSEMINATION, AND COMMUNICATION

The set of maps and applications had received over 2,000 visits by the end of 2023. To disseminate the research results, the applications developed for this project can include further results from the various techniques conducted during the campaign (GPR, Schmidt hammer, GPS, VES). Additionally, in response to potential new needs suggested by the results, the set of maps and applications can be adapted to the project's new requirements, such as increased functionality for users, growth in data volume, or changes in information management permissions.

The information has been shared on a data Hub (Figure 12), which summarizes the MOTICE project and provides access to information through this CGIS system products: data, maps, scenes and applications. Furthermore, the Hub includes a restricted internal section exclusively for project researchers, which allows viewing and downloading data that has not yet been published.

FIGURE 12.
MOTICE PROJECT DATA HUB



The use of this CGIS environment allowed the rapid presentation of results in meetings with local stakeholders and decision-makers, as well as in official press conferences in Arequipa just three days after field data collection. This capacity for immediate information sharing enabled effective dissemination and communication of the progress of our research project.

8. DISCUSSION

The fundamental purpose of this work has been to present the design of the GIS-MOTICE system, which supported all stages of a glacier research expedition (precampaign, campaign, and post-campaign). The innovation of GIS-MOTICE lies in not being limited exclusively to the post-campaign phase but integrating the CGIS as a working tool in the initial phases (pre-campaign and fieldwork). In this way, GIS-MOTICE functioned as a "system of systems," interconnecting the set of GIS applications (ArcGIS Pro, Field Maps, Experience, Hub, among others...) to facilitate the creation of specific tools. GIS-MOTICE supported all expedition stages by integrating technologies and workflows under a common environment (ArcGIS Online). The design of a CGIS system like the one presented in this work can be extrapolated to digitize other field campaigns or projects which can benefit from the following advantages:

I. The applications can be used without prior GIS experience. However, preliminary training and/or the participation of a GIS-experienced administrator is recommended to facilitate information and application management tasks in ArcGIS Online.
II. The speed, reliability, and quality of the CGIS systems on mobile devices save time in remote work locations with difficult conditions and/or without connectivity. Mobile devices allow dynamic and interactive access to information.
III. Working in a collaborative cloud environment (ArcGIS Online) makes postprocessing and result dissemination much simpler. Additionally, it has the advantage of integrating into the Esri ecosystem and its desktop-cloud tools (Nétek et al., 2023).
IV. Developing a CGIS system like the one presented in this article allows researchers to collect and record reliable spatial data in a more uniform and efficient manner, saving time and avoiding errors and difficulties inherent to paper-based data collection.

Some potential drawbacks must be mentioned. One issue we found was not having downloaded the relevant maps on all devices from the last high quality internet location in Arequipa city, since connectivity in towns around Nevado Coropuna was slow and unstable. Fortunately, this was resolved using local entities' WiFi services, ultimately allowing proper map downloads on devices where the data was not available yet. However, this is an element to consider when implementing such systems. In this regard, a barrier or challenge associated with online GIS effectiveness arises from the need of a sufficient internet broadband for its use (Han, 2019). Likewise, another limitation when using field maps on mobile devices above 6000 meters is the need to remove gloves for data entry, which can be uncomfortable and even hazardous to users health in high-altitude environments. This drawback stems from smartphone touch interfaces requiring screen manipulation and is particularly accentuated when manually entering large data volumes. As alternatives, considering the importance of specific weather conditions when using mobile technologies at high altitudes, we propose creating pre-filled forms with selectable combos or voice/video input options instead of text fields. The use of smartphone-compatible touch pens could also be considered. Finally, the impact of low temperatures on batteries is something worth being considered here and common to any fieldwork campaign on glacial environments.

Despite the rapid growth in mobile mapping applications and increasing interest in them, the number of scientific articles containing information about them remains quite limited (Nowak et al., 2020). This article has demonstrated the functionality of the Field Maps mobile app for field data collection, even under extreme conditions at very high altitudes (4000-6377 m) and very cold temperatures (down to -20°C). Additionally, synchronizing mobile devices at the end of each field day enabled visualization of all acquired data in pre-configured viewers, helping assess objective achievement levels, allowing analysis and discussion of field outing results just hours after collection, and facilitating planning for subsequent days. Finally, the applications allowed nearly immediate dissemination of data to local communities and decision-makers with minimal post-processing. In this sense, we agree that mobile GIS systems are dramatically transforming fieldwork and solving or reducing many associated problems (Wagtendonk & De Jeu, 2005).

Teaching these CGIS applications to local community members around Nevado Coropuna—less familiar with new technologies but with deep environmental knowledge—all of them smartphone owners, proved very straightforward. They had the opportunity to learn and contribute data during the campaign from their own devices. This is one of the main benefits of such applications, as non-technical personnel can support data collection without needing to learn software or GPS device technical attributes (Randall et al., 2022). In fact, this infrastructure enables collaborative data gathering by local community residents (Panek & Netek, 2019) outside the project's main fieldwork season.

Adopting GIS-based fieldwork allows geospatial perspectives to positively impact geographic knowledge, as Healy & Walshey (2020) also affirm in their research on student training in this field. It is important for those without prior GIS knowledge to understand that not everything is perfect and precise. Because maps, even in their most advanced digital formats, show limitations, omissions, and distortions, being aware of these deficiencies is crucial. Addressing these challenges requires familiarization with and reliance on multiple information layers, using this approach to more comprehensively model and understand any studied phenomena (Kerski, 2008).

On the other hand, the availability of high-resolution imagery (Esri basemaps) has facilitated high-mountain tasks by enabling interpretation of relief above 6000 m altitude, pre-planning and monitoring of activities/routes, locating landforms of interest for study, or identifying potential hazards like glacial crevasses. GIS use not only streamlined data analysis and processing but also enhanced result visualization and understanding, promoting timely information exchange among project stakeholders. This rapid feedback approach reinforces CGIS relevance and utility in optimizing quick and effective scientific communication for glacial research.

9. CONCLUSIONS

This article presents a method for developing a geographic information system for coordinating and managing a research campaign on a glacier. During July-August 2022, an expedition was conducted to the glaciers of Nevado Coropuna, totaling 31 fieldwork days. In these activities, CGIS maps became one of the most important logistical tools, facilitating the organization of field outings, data collection and dissemination of results to local communities. A set of applications was programmed to enable the automatic collection, editing and updating of data directly on the same layers previously shared in the published viewers.

Additionally, the workflows and apps demonstrate an innovative cloud-based CGIS architecture, specifically configured for managing, monitoring and disseminating a research campaign on a glacial environment. Using GIS data and its associated web services, as well as the development of web maps and applications, it has been possible to create an information space that allows other users to access our research planning, data collection and result construction. Even during periods without mobile coverage (approximately 80% of time in the field), it was possible to quickly access layers, get real time geolocation and take advantage of high-resolution base maps.

Furthermore, working on Esri's cloud has been highly valuable for the project, as it has enabled synchronization of data, apps and offline devices, and has consistently provided nearly instantaneous response regardless of the number of connected users. It can be stated that this project is scalable and replicable to any other branch of geosciences requiring field mapping and collaborative fieldwork data collection.

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DECLARATION OF CONFLICT OF INTEREST

Los/as autores/as de este artículo declaran no tener conflictos de intereses financieros, profesionales o personales que pudieran haber influido de manera inapropiada en este trabajo.

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DECLARATION OF AUTHORSHIP CONTRIBUTION

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REFERENCIAS BIBLIOGRÁFICAS

Balram, S. & Dragicevic, S. (2006). *Collaborative Geographic Information Systems*. Idea Group, Inc. Hershey, USA.

Bromley, G.R., Thouret, J.C., Schimmelpfennig, I., Mariño, J., Valdivia, D., Rademaker, K., Vivanco, S.P., ASTER Team, Aumaître, G., Bourlès, D. & Keddadouche, K. (2019). In situ cosmogenic ^{3}He and ^{36}Cl and radiocarbon dating of volcanic deposits refine the Pleistocene and Holocene eruption chronology of SW Peru. *Bulletin of Volcanology, 81*, Article 64. https://doi.org/10.1007/s00445-019-1325-6

Esri. (2012). *¿Qué es ArcGIS?*: https://resources.arcgis.com/es/help/gettingstarted/articles/026n00000014000000.htm

Esri (2019a). *Recursos de ArcGIS Online*. https://trust.arcgis.com/es/security/arcgis-online-capabilities.htm

Esri (2019b). *Operaciones de campo*. https://www.esri.es/eses/arcgis/productos/field-operations/overview

Healy, G & Walshe, N. (2020). Real-world geographers and geography students using GIS: relevance, everyday applications and the development of geographical knowledge. *International Research in Geographical and Environmental Education*, *29* (2), 178-196. https://doi.org/10.1080/10382046.2019.1661125.

Han, R. (2019). Web GIS in Development: From Research and Teaching Perspectives. In S. Balram (Ed.), *Advances in Geographic Information Science* (pp 103–122). Springer. https://doi.org/10.1007/978-3-030-06058-97.

Kerski, J. J. (2008). The Role of GIS in Digital Earth Education. *International Journal of Digital Earth, 1*(4), 326–346. https://doi.org/10.1080/17538940802420879.

Llanto, J., Pellitero, R., Úbeda, J., Atkinson-Gordo, A. D. J., & Pasapera, J. (2025). 69-Year Geodetic Mass Balance of Nevado Coropuna (Peru), the World's Largest Tropical Icefield, from 1955 to 2024. *Remote Sensing*, 17(19), 3344. https://doi.org/10.3390/rs17193344

Nétek, R., Pohanková, T., Bittner, O., & Urbán, D. (2023). Geospatial Analysis in Web Browsers—Comparison Study on WebGIS Process-Based Applications. *ISPRS International Journal of Geo-Information, 12* (9), Article 374. https://doi.org/10.3390/ijgi12090374.

Nogués-Paegle, J., Mechoso, C.R. & Fu, R. (2002). Progress in Pan American CLIVAR Research: Understanding the South American Monsoon. *Meteorologica, 27*, 3–30.

Nowak, M.M., Dzióbʼ K., Ludwisiak, Ł. & Chmiel, J. (2020). Mobile GIS applications for environmental field surveys: A state of the art. *Global Ecology and Conservation*, *23*, e01089. https://doi.org/10.1016/j.gecco.2020.e01089

Panek, J. & Netek, R. (2019). Collaborative Mapping and Digital Participation: A Tool for Local Empowerment in Developing Countries. *Information, 10* (8), Article 255. https://doi.org/10.3390/info10080255

Phantuwongraj, S., Chenrai, P. & Assawincharoenkij, T. (2021). Pilot Study Using ArcGIS Online to Enhance Students' Learning Experience in Fieldwork. *Geosciences, 11*, 357. https://doi.org/10.3390/geosciences11090357.

Randall, J., Inglis, N. C., Smart, L. S. & Vukomanovic, J. (2022). From Meadow to Map: Integrating Field Surveys and Interactive Visualizations for Invasive Species Management in a National Park. *ISPRS International Journal of Geo-Information*, *11* (10), Article 525. https://doi.org/10.3390/ijgi11100525.

RGI Consortium. (2017). *Randolph Glacier Inventory—A Dataset of Global Glacier Outlines, Version 6 [Dataset]*. National Snow and Ice Data Center. https://doi.org/10.7265/4M1F-GD79.

Sagredo, E. & Lowell, T. (2012). Climatology of Andean glaciers: A framework to understand glacier response to climate change. *Global and Planetary Change, 86–87*, 101–109. https://doi.org/10.1016/j.gloplacha.2012.02.010.

Sagredo, E., Rupper, S.& Lowell, T.V. (2014). Sensitivity of the equilibrium line altitude across the Andes. *Quaternary Research, 81*, 355–366. https://doi.org/10.1016/j.yqres.2014.01.008.

Sun, Y. & Li, S. (2016). Real-time collaborative GIS: A technological review. *ISPRS Journal of Photogrammetry and Remote Sensing*, *115*, 143-152. https://doi.org/10.1016/j.isprsjprs.2015.09.011.

Sylvestre, F. (2009). Moisture Pattern during the Last Glacial Maximum in South America. In F. Vimeux, F. Sylvestre & M. Khodri (Eds.), *Past Climate Variability in South America and Surrounding Regions, Developments in Paleoenvironmental Research 14* (pp. 3-28). Springer.

Úbeda, J. (2011). El Impacto del Cambio Climático en los Glaciares del Complejo Volcánico Nevado Coropuna (Cordillera Occidental de los Andes, Sur del Perú). [Ph.D. Thesis], Universidad Complutense de Madrid, Madrid. Recuperado de: https://docta.ucm.es/entities/publication/17ae565b-8c8c-4729-ab70-b2e2e651e647

Úbeda, J. (2023). *Estudio Glaciológico. Proyecto Coropuna 2030. Fase de Formulación*.[Unpublished technical report].

Úbeda, J., Bonshoms, M., Iparraguirre, J., Sáez, L., De la Fuente, R., Janssen, L., Concha, R., Vásquez, P. & Masías, P. (2018). Prospecting Glacial Ages and Paleoclimatic Reconstructions Northeastward of Nevado Coropuna (16° S, 73° W, 6377 m), Arid Tropical Andes. *Geosciences, 8* (8), 307. https://doi.org/10.3390/geosciences8080307.

Úbeda, J., Yoshikawa, K., Pari, W., Palacios, D., Masias, P., Apaza, F., Ccallata, B., Miranda, R., Concha, R., Vasquez, P., & Cruz, R. (2015, April 12–17). *Geophysical surveys on permafrost in Coropuna and Chachani volcanoes (southern Peru)* [Paper presentation]. EGU General Assembly 2015, Vienna, Austria.

Vera, C., Higgins, W., Amador, J., Ambrizzi, T., Garreaud, R., Gochis, D., Gutzler, D., Lettenmaier, D., Marengo, J., Mechoso, C.R., Nogues-Paegle, J., Silva Dias, P. L. & Zhang, C. (2006). Toward a Unified View of the American Monsoon Systems. *Journal of Climate*, *19*, 4977–5000. https://doi.org/10.1175/JCLI3896.1.

Wagtendonk, A., & De Jeu, R. (2005). Mobile GIS and optimizing data collection methods in hydrological fieldwork. In **Remote Sensing for Agriculture, Ecosystems and Hydrology VII** (Vol. 5976, pp. 33–40). SPIE.

Wang, X, Van Elzakker, C.P.J.M. & Kraak, M.J. (2017). Conceptual Design of a Mobile Application for Geography Fieldwork Learning. *ISPRS International Journal of Geo-Information*, *6* (11), Article 355. https://doi.org/10.3390/ijgi6110355.

Yoshikawa, K., Úbeda, J., Masías, P., Pari, W., Apaza, F., Vasquez, P., Ccallata, B., Concha, R., Luna, G., Irraguirre, J., Ramos, I., De la Cruz, G., Cruz, R., Pellitero, R. & Bonshoms, M. (2020). Current thermal state of permafrost in the southern Peruvian Andes and potential impact from El Niño–Southern Oscillation (ENSO). *Permafrost and Periglacial Processes, 31,* 598–609. https://doi.org/10.1002/ppp.2064.

Zhou, J. & Lau, K.M. (1998). Does a monsoon climate exist over South America? *Journal of Climate. 11*, 1020–1040. https://doi.org/10.1175/1520-0442(1998)011%3C1020:DAMCEO%3E2.0.CO;2