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Augmented reality for innovation: Education and analysis of the glacial retreat of the Peruvian Andean snow-capped mountains

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ABSTRACT

Mountain glaciers are considered great reservoirs of water, and their importance lies in the fact that many of our ecosystems and numerous communities depend on them; Peru has one of the largest extensions of Andean snow-capped mountains, which have been affected by the decline in their glacier coverage and that is warned, will disappear due to environmental conditions and alterations in the current global temperature. This problem has increased due to ignorance, misinformation, indifference, and lack of solidarity on the part of the population who favors this discouraging situation. Taking advantage of the current technological immersion, in which we live, the development of a mobile application was proposed as a pedagogical resource to raise awareness among educational institutions about the glacial retreat of the Peruvian Andean snow-capped mountains, showing the current situation of some of the snow-capped mountains of the Andes that have suffered a greater impact, implementing augmented reality technology to obtain an interactive link. To provide greater detail of the situation, previous studies were carried out on glacial retreats in two Peruvian snow-capped mountains over the last 40 years, where it was found that, of the snow-capped mountains considered, Chicon had a decrease of 32.5% of its glacier cover, and Pumahuanca had a decrease of 56.9%. Such results are exposed within the application to provide realistic data on the glacial conditions of both Peruvian snow-capped mountains, as well as the consequences and conservation techniques to mitigate and cope with deglaciation. Taking into consideration that environmental education from an early age turns out to be key to forming an informed and participatory society about climate change.

1. Introduction

The global increase in temperature and the reduction of rainfall as a result of climate change has been accelerating the loss of glaciers worldwide and mountain glaciers are no strangers to this devastating fact, covering an approximate extension of 7,06 * 10^5 km^2 worldwide and with an estimated volume of 1,7 * 10^5 km^3 are considered water reservoirs of humanity, which after their excessive melting are contributing to a considerable rise in sea level (Zemp et al., 2019; Huss and Farinotti, 2012). According to studies conducted by the University of Zurich, Switzerland (Zemp et al., 2019), the greatest loss has occurred in Alaska, followed by the Greenland glaciers and the glaciers of the southern Andes, with an accelerated loss that has increased in the last 30 years.

The Andes mountain range is where most of the great cultures and economies have been forged, chosen for its numerous water sources which supply to this day both the surrounding population centers and the cities, besides being essential for productive activities in the valleys and coastal areas (María Paz Aedo and Montecinos, 2011). However, it is being affected not only by global warming but also by mining activity on glaciers, mainly in Chile and Peru, being the most harmful human

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activity that favors the increase of glacial retreat of the Andean snow-capped mountains (María Paz Aedo and Montecinos, 2011; Bernex and Tejada, 2022; Chile Sustentable, 2022).

According to Bernex and Tejada (Bernex and Tejada, 2022), 71% of tropical 71% of the tropical glaciers in the South American Andes are in Peru; 22% in Bolivia; 4% in Ecuador, and 3% in Colombia, where, although some snow-capped mountains still have glacier coverage, it is evident that they are now in considerable decline; other glaciers have simply lost their coverage completely. According to the Sustainable Development Goals (SDGs) number 13 (Naciones Unidas Cambio, 2022), measures are required to combat climate change and its evident consequences to protect the planet, safeguard resources for future generations, and contain the negative impact on the economy, communities, and countries; given that the constant emissions of greenhouse gases have increased the global temperature causing the continued warming of the oceans and therefore the increase of melting ice (United Nations Goal 13, 2022). This ends up affecting millions of people in terms of reduced access to water, in addition to obtaining it with a very poor quality, which brings us to SDG 6 (United Nations Goal 6, 2022) which talks about ensuring the availability of water and its sustainable management and sanitation for all, since it is estimated that 40% of the world's population is affected by the scarcity of this resource, which will continue to worsen after the accelerated melting of glaciers.

Recent studies have shown that tropical glaciers in the Andes are retreating at an alarming rate (Kozhikkodan Veettil et al., 2016). Likewise, previous studies (Bulege, 2016; Schauwecker et al., 2014) observed increases in air temperature of approximately 0.31 °C/decade between 1969 and 1998 and 0.13 °C/decade between 1983 and 2012 in the Cordillera Blanca of Peru. During the dry season, the Andean countries, especially the more populated areas of Bolivia and Peru, depend on water from glacial basins (Kozhikkodan Veettil et al., 2016). Glaciers in the Andes of Peru provide an important environmental and economic service by releasing meltwater for the arid western part of the country during the dry season, especially between the months of May and September, when there is little or no rainfall. Much of the water resources consumed for agricultural, domestic, and industrial purposes on the arid west coast of Peru originate in the snow and ice of the Andes. Glaciers effectively buffer runoff by storing much of the precipitation that falls as snow on the glaciers during the wet season (Vergara et al., 2022), from October to April, and releasing it throughout the year, even during the dry season, when it is most needed (Vuille et al., 2008). Modeling studies project that glaciers in mountain ranges will continue to shrink significantly over the next few decades and could disappear completely in some basins by 2080, with drastic changes (Bulege, 2016; Juen et al., 2007). These reasons lead us to raise awareness and take action in the face of climate change based on the importance of addressing the link between water security and glacier protection, considering that these are particularly fragile ecosystems that are directly dependent on environmental conditions. It is necessary to take action to ensure the living conditions of populations and guarantee a sustainable future for new generations (Mayo, 2022).

Projects are currently being developed for the conservation of the Peruvian Andean snow-capped mountains, as well as new policies for the conservation of water resources (Iza and Rovere, 2006; Instituto Geológico, 2023), however, little has been done to raise awareness among the population about the current hydrological situation and glacier coverage of these important mountain ranges that are key to our subsistence and to the ecosystems associated with the ice masses. Taking into account that in arid and high-altitude environments such as the Andes, the only way to maintain "bofedales" (ecologically diverse and socially important wetlands for crops and raising livestock) is through glacial runoff (Park, 2022). Therefore, learning to understand how quickly glaciers are being lost could be a contributing factor to the protection of people who depend on them (Yun et al., 2023; Rocchetta et al., 2014).

While it is clear that we are about to suffer a serious problem of the water crisis, it is more than proven that ignorance, indifference, and lack of solidarity on the part of the population favor this discouraging situation, which makes us aware of the lack of urgent measures that manage knowledge and promote education to build a sustainable future, encouraging them to assume proactive attitudes that help mitigate and avoid problems, leading to efficient and integrated management of water resources (Bernex and Tejada, 2022). Education is the key to promoting a culture of water and environmental awareness (Lee and Yoon, 2020) which implies knowing our environment, acquiring experiences, values, attitudes, and social memory, even from childhood, which hand in hand with educators and the right tools could promote best practices for the management and optimization of water, as well as promoting an informed and participatory society (Bernex and Tejada, 2022; Lee and Yoon, 2020) being aware not only about how to manage water resources but also consider the ecosystems that depend on it, which is part of SDG 6 (Lee and Yoon, 2020; UNESCO Educación y Cultura Del Agua).

Currently, the use of ICT (Information and Communication Technologies) is being applied in different fields of study and at all levels of our society (Angarita López, 2018), in the area of education is where it has had successful results, different technological tools allow teachers to reinforce knowledge and cognitive development in students (Marín et al., 2020). Computerized educational materials often attract children's attention by allowing them to capture their attention through images, forging a friendly relationship (Angarita López, 2018), being the case of 3D models, which through the use of Augmented Reality (AR) technology provide the user with a dynamic experience in the teaching-learning process (Zapata-Paulini et al., 2023), achieving the implementation of virtual objects in the real environment (Kudale and Buktar, 2021). Therefore, the main objective of this research project is to provide an interactive pedagogical resource that serves as a means to raise awareness among educational institutions about the glacial retreat of the Peruvian Andean snow-capped mountains, to generate environmental culture not only in children but also in parents against the rational use of water resources, through the use of AR.

This research work is organized as follows. Section (2) Bibliographic study: this section helps to situate the research by supporting it with other research previously carried out. Section (3) Materials and methods: explains the tools, approaches, and designs considered for the development of the research. In Section (4) Development of the solution: this is based on the chosen methodology, detailing the procedures carried out to reach the proposed solution, as well as the final result obtained. In Section (5) Discussions: the previous study is related to the research. Section (6) Conclusions: provides a final reflection on the findings obtained. Finally, in Section (7) Limitations and future recommendations: the limitations of the study are presented, as well as proposals for future related work.

2. Bibliographic study

The Peruvian Andes are made up of 18 mountain ranges with glacier coverage and two extinct ones distributed along the length of the mountain range in the country, which originate from three hydrographic basins: the Pacific, Atlantic, and Titicaca. The formation of glacier cover in our mountain range is directly related to climatic and atmospheric conditions; in addition, solar radiation has unequal effects on glacier formation (Instituto Nacional, 2022) (pp. 13–18). All these factors cause the mountain range to have a rugged geomorphological composition, which with the presence of glaciers has as a consequence that the water courses can be exploited with the installation of hydroelectric power plants that collaborate with the sustainability and development of the country.

2.1. Anthropogenic impacts

The use of environmental resources as a result of human intervention leads to the degradation of the ecological environment, destruction or modification of landscapes (Csorba, 2010; Placencia, 2012), as well as climatological alterations that damage the balance of sensitive environments (Tóth, 2010); therefore, the integration of environmental management is important for the simultaneous protection of ecological values (Rózsa, 2010; Lóczy, 2010).

Over the years, anthropogenic activities have caused excessive air pollution in the Andes Mountains in Peru (Broussard), and traces of different chemicals have been found (UN Environment programme; Grondona et al., 2022). According to the findings of research conducted by the National Institute for Research on Glaciers and Mountain Ecosystems (INAIGEM) in Peru, it was concluded that the black carbon (soot) that originates in the cities and valleys from different causes, such as forest fires, burning of pastures, vehicular traffic and others, is increasingly present at the summit of the snow-capped mountains in small quantities, influencing the melting of snow, such as forest fires, burning of pastures, vehicular traffic and others, is increasingly present at the summit of snow-capped mountains in small quantities, influencing the melting of snow or ice in the glaciers of the Cordillera Blanca (UN Environment programme; Diario El Comercio). This occurs because black carbon absorbs sunlight and raises the air temperature, which favors the melting process (Diario El Comercio; Torres et al., 2018; Musacchio et al., 2021).

Glacier melt is vital for water supply, which is essential for various commercial activities, directly affecting the national economy (Torres et al., 2018). According to research in recent decades, populations below glaciers and/or snow-capped mountains may have enjoyed a period of abundant water supply because glaciers released their meltwater. However, it is being corroborated that most glaciers are reaching their maximum water production or will do so in the coming decades (Johansen et al., 2018) (pp. 12–16), not only causing water scarcity, but also an increase in natural phenomena such as landslides and alluviums due to the increase in the surface area of glacial lakes (Guardamino and Drenkhan, 2016). In this sense, it is urgent to pay attention to this problem and implement appropriate adaptation responses. The task lies not only with the solutions provided by scientists and glaciological experts, but also with the general public (CARE Perú Una).

2.2. Implementation of ICTs for the benefit of the environment

In recent years, the implementation of ICT in contributing to environmental improvement has become more involved; in Guo and Shi (2022), 3D image processing technology was used for urban planning and protection of mountain landscape resources, serving as a technological tool for the exploration of sustainable development methods aimed at the real estate development of mountain water cultural tourism, in order not to damage local landscape resources. Hoping to be able to optimally manage these bodies of water in the tourist area in search of improving the efficiency of the forests that supply water, improving the aquatic ecosystem which favors the retention of dust from rivers, as well as the dissipation of some sources of pollution.

Likewise, en Benyezza et al. (2023)., developed an interactive and intelligent bottle that provides information and communicates with the water refill station using IoT technology, to contribute to the reduction of plastic, motivating and directing the users of a higher institute towards approaches that do not harm the environment, in addition, consequently promoting sustainability and ecological awareness in the academic environment. On the other hand, in search of drastic changes for the care and sustainability of our ecosystems as well as improvements in education to generate public awareness, in Keaveney et al. (2016). the potential of Virtual Reality (VR) was exploited through 3D scanning and modeling, hoping that these models can be complemented later in future applications that interact with AR and Mixed Reality (MR), managing to improve educational techniques in biological sciences topics such as zoology areas, avoiding damaging the sustainability of ecosystems.

Ali et al. (2021). After several comparisons of applications with VR already made for the teaching of the water cycle, it was shown that in younger students it was possible to expand the concepts learned in class, while in younger students it was possible to understand easily and interactively the general concept of the water cycle. A study (Angarita López, 2018) showed that teachers consider that the support of ICT in the teaching-learning process of students decreases comprehension difficulties and strengthens constructive communication, as well as awakening scientific thinking. Especially VR and AR technologies that allow a better interaction, complementing inverted classroom activities (Tsai et al., 2020).

The efficient use of water makes the saving of this resource itself become a water source, therefore, taking methods that facilitate the implementation of conservation techniques, directly intervenes with social education. The aim is to create an informative mobile application with AR, which shows the current situation of some of the snow-capped mountains of the Peruvian Andes that have had the greatest impact, how they were approximately 40 years ago and how they are today, as well as providing information on good practices that promote the care of our water resources, teaching how pollution and global warming affects our glaciers and therefore us.

2.3. Augmented reality and open innovation

AR and open innovation are two concepts that are increasingly being applied in the environmental field to generate innovative solutions and promote environmental awareness and action. In this context, AR is used to create immersive experiences that help to better visualize and understand environmental challenges (Lee and Yoon, 2020). It can also be used as an interactive tool to raise awareness about the importance of the Andean snow capped mountains and the challenges they face due to climate change and human activity. Through AR applications, images and data about the snowfields can be displayed, such as their current extent, historical changes, and the consequences of their disappearance. This can help people understand the magnitude of the problem and motivate action for its protection and environmental monitoring (Rizzato et al., 2020).

Open innovation also plays a crucial role in environmental conservation (Lee et al., 2022; Bigliardi and Filippelli, 2022). By opening up the solution-generation process, two different actors, such as scientists, local communities, non-governmental organizations, and businesses, a wide range of knowledge, skills, and resources can be tapped (Salim et al., 2021; Dupont et al., 2016). This can lead to the identification of innovative and sustainable strategies for the conservation of snow-capped mountains.

Collaboration between scientists, local communities, and other stakeholders can generate creative ideas and solutions to address specific challenges facing mountain glaciers, such as reducing the impacts of climate change, protecting surrounding ecosystems, and promoting sustainable water resource use practices (Pan et al., 2022). By working together, solutions can be found that combine scientific knowledge with the traditional knowledge of local communities, thus achieving more effective, equitable, and sustainable management of fragile ecosystems (Beck et al., 2023).

Both are promising approaches to promote environmental awareness and action by providing interactive tools and fostering collaboration among different actors (Lee et al., 2022; Kim and Lee, 2022), as well as raising awareness about the importance of ecosystems such as the Andean snow-capped mountains and motivating the actions for their protection. These technologies have the potential to generate innovative and sustainable solutions to address current and future environmental challenges (Beck et al., 2023; Ramirez-Montoya, 2020).

3. Materials and methods

3.1. Type and design of research

The research article is of a non-experimental type with a quantitative approach, according to Hernández et al (Hernández et al., 2014)., it refers to research that is carried out without intentionally manipulating variables and in which phenomena are simply observed in their natural environment and then analyzed. Within this, there are types that can be classified into transactional design and longitudinal design. In this case, the longitudinal design was chosen because it allows us to analyze the changes that occurred in the variables over a given period, to reach conclusions about the consequences of the changes (INTEP, 2018). According to Hernández et al (Hernández et al., 2014)., longitudinal designs collect data from different moments and periods to make inferences about change, seeking to analyze the evolution of variables.

3.2. Methodology

Innovation in educational processes is crucial for today's children, who are born and grew up surrounded by technology, and this goes hand in hand with the need to seek new and innovative methodologies that not only allow understanding but also optimize the teaching-learning process. For the development of the project, the Design Thinking methodology was chosen to address the subject of work in a simple, efficient, and above all highly productive ways; this methodology allows us to explore the problem approached from small parts in search of innovative solutions focused on the user (Jerónimo Yedra and Almeida Aguilar, 2021). Different researchers have preferred to develop VR, AR, or MR applications making use of the Design Thinking process (Kudale and Buktar, 2021; Jerónimo Yedra and Almeida Aguilar, 2021) serving as a methodological strategy for the realization of educational applications aimed at children from an early age to older. This is because it allows us to focus on the research problem itself, looking for the best approaches that allow us to understand the task rather than the methods (Marful et al., 2022). According to Jerónimo Yedra (Jerónimo Yedra and Almeida Aguilar, 2021), Design Thinking is oriented to the development of creative products, spaces, and services, based on the understanding of needs, combining empathy with creativity and rationality. This methodology comprises 5 stages that lead to innovation in an orderly fashion, the first being understanding and empathizing, defining the problem, developing solutions, prototyping, and finally evaluating or testing (Kudale and Buktar, 2021).

3.3. Population and sample

The Peruvian Andes have the highest percentage of tropical glaciers in South America, distributed in 19 snow-capped mountain ranges, which have suffered the consequences of climate change and are causing negative changes worldwide. The Cusco region has some of the highest glaciers, 117 in total, including the snow-capped Chicon and Pumahuanca located in the Urubamba Mountain range belonging to the Sacred Valley of the Incas, which supply water to the Urubamba district (Tecsi Conza and Tupa Ramos, 2017). Chicon is the highest peak of the Urubamba Mountain range, with an altitude of 5800 masl, and Pumahuanca has an altitude of 5330 masl; both peaks are in southern Peru (Carlotto et al., 2010). As a first prototype, both snow-capped mountains were chosen because this is where the greatest glacial retreat has been evidenced, and it has been reported that in recent years there have been alluviums derived from this unfortunate event (Vuille et al., 2008; CARE Perú Una; Tecsi Conza and Tupa Ramos, 2017; Carlotto et al., 2010). For correct information and evaluation of the current situation of the snow-capped mountains, a previous analysis of images of the last 40 years was carried out, taking 12 satellite images as a sample. Considering the area obtained from the snowfields around the period from 1985 to 2021.

It was also considered that the target user population for the use of the proposed application includes primary and secondary school students, since the awakening of scientific thinking occurs more frequently at that age.

3.4. Materials

3.4.1. Snowfall retreat data collection techniques and instruments

To obtain results on the variables, it was necessary to collect the data by performing detailed procedures. The technique used in this research was observed or visual exploration, analysis of the data supported by the satellite, allowing the data to be obtained based on snow cover. The materials that were necessary for data collection and analysis of the retreat of the Peruvian Andean snow-capped mountains considered are shown in Table 1.

3.4.2. Materials required for the elaboration of the 3D models

For the realization of the 3D models of the snow-capped mountains, the interaction of three tools was necessary:

Google Maps: Location search tool, allows geolocation of places as well as satellite images of the world.

RenderDoc (0.26 or higher): This is a graphical debugger based on 3D frame capture, allowing us to download the source files of the preferred location on Google Maps and export it to Blender (RenderDoc, 2022; Schumann).

Blender: It is a 3D material creation suite that includes modeling, rendering, animation and rigging, compositing, and texturing, among others (Blender, 2022). The capture of Google Maps in ".rdc" format is imported into Blender, to be later textured and rendered in a file with ".fbx" extension, so that the 3D model created is compatible with Unity.

3.4.3. Materials needed for the elaboration of the Application

Some of the most important tools used for the development of the proposed RA application were:

Unity 3D (2019 or higher): Platform for the creation of video games and real-time content, this is a cross-platform software that enables the creation of interactive 2D and 3D environments combining tools and a unified workflow across multiple devices for VR, AR, and MR developers (Unity Technologies Unity, 2022; Unity Technologies, 2022).

Vuforia Development Kit: Leading platform for the development of AR and MR applications. This kit allows the use of computer vision technology for the recognition of plan images and 3D objects in real-time and allows the programming of applications in different languages through an extension of the Unity game engine (Unity Vuforia, 2021). Its operation is through image registration, allowing 3D objects to be positioned and displayed after tracking the location of the image using a camera phone.

Language C#: General and complete object-oriented programming language used for the programming and interaction of the interfaces developed in Unity.

Table 1
List of materials needed for the collection of data on the current glacier situation.

Materials	Equipment	Software
Google Earth imagery (image dataset: Lansat/ Copernicus, ©2022 Maxar Technologies, and ©2022 CNES/Airbus) from the period 1985, 2005, 2012, 2015, 2018, 2019, and 2021.	Asus Laptop with Windows 11 OS, intel core i5 tenth generation, NVIDIA graphics card, Ram 16 GB, 1 TB hard drive.	Google Earth Pro, Google Colab Python, HTML, Google Drive

4. Development of the solution under the Design Thinking methodology

This stage details the development of the proposed solution based on the phases of Design Thinking.

4.1. Empathize

This phase involves understanding and observing, identifying needs, taking into account the context and environmental factors, as well as the inclusion of research through the analysis of findings in different scientific references (Zemp et al., 2019; María Paz Aedo and Montecinos, 2011; Bernex and Tejada, 2022; Bulege, 2016; Schauwecker et al., 2014; Mayo, 2022; Instituto Nacional, 2022; Johansen et al., 2018; Tecsi Conza and Tupa Ramos, 2017) that warn of the current situation in which we find ourselves concerning glacial loss and retreat in the Peruvian Andean snow-capped mountains. Likewise, a study was carried out using satellite observation or remote sensing techniques to monitor the surface mass balance of the glacial mantle (Pan et al., 2022). Satellite images from 1985 to 2021 were used to identify the glacial retreat of the Chicon and Pumahuanca snow-capped mountains in a graphic and easily understandable way.

4.1.1. Identification of the study area

The delimitation of the study area that includes the Chicon and Pumahuanca snow-capped mountains, which have been considered for this study, is shown in Fig. 1. Both snow-capped mountains are located in the Province of Urubamba, department of Cusco, Peru. For this delimitation, we made use of Google Earth Pro satellite images edited with HTML language.

4.1.2. Study of the glacier coverage of the Chicon snow-capped mountain

The loss of glacier cover of the Chicon snow-capped mountain in the period 1985–2021 is shown in Fig. 2.

It was identified that for the year 1985 (Fig. 2a) the ice coverage area was 9,63 km^2 delimited in blue and for the year 2005 (Fig. 2b) delimited in light blue the coverage was 3,44 km^2 showing a reduction of 6,19 km^2in a span of 20 years. On the contrary, for the year 2012 (Fig. 2c) delimited in red the coverage area was 2,52 $km^2$and for the year 2015 (Fig. 2d) the coverage area demarcated in yellow was 3,79 km^2 evidencing an increase of 1,27 km^2 in a period of 3 years. On the other hand, for the year 2019 (Fig. 2e) shows a new reduction with a coverage area of 2,84 km^2, the same that has a slight increase of 2021 (Fig. 2f) since the coverage area for that year was 3,13 km^2. Therefore, as can be observed over the years, coverage has suffered reductions and slight increases, which could be related to the planet's climate variability and the reduction of greenhouse gas emissions.

4.1.3. Study of the glacier coverage of the Pumahuanca snow-capped mountain

The loss of glacier coverage of the Pumahuanca snow-capped mountain in the period 1985–2021 is shown in Fig. 3.

It was identified that for the year 1985 (Fig. 3a) the ice coverage area was 2,88 km^2 delimited in blue and for the year 2005 (Fig. 3b) delimited in light blue the coverage was 0,37 km^2, showing a reduction of 2,51 km^2 in a span of 20 years. Similarly, for the year 2012 (Fig. 3c) delimited in red the coverage area was 0,34 km^2 and for the year 2015 (Fig. 3d) delimited in yellow the coverage 0,17 km^2, showing a reduction of 0,17 km^2 in a span of 3 years. On the contrary, for the year 2018 (Fig. 3e) delimited in green the coverage of 0,48 km^2, and for the year 2021 (Fig. 3f) delimited in orange the coverage of 1,64 km^2, showing an increase of 1,16 km^2 in a span of 3 years. In that order of facts, we can see that in the period of less than 40 years, the coverage has shown reductions, except for the last 3 years, in which it suffered a slight increase, which could be related to the planet's climate variability.

4.2. Definition

After identifying the patterns of the problem, the next step was to define the problem. In this research, it was found that after the analysis of satellite images between 1985 and 2021 there has been a drastic change in glacier coverage as a result of climate change, and it was also identified that although in the most recent years, the level of coverage has increased slightly, this was due more to climatic anomalies and the increase and decrease in humidity, but not to the density of glacier coverage itself (Arroyo et al., 2015). It can also be inferred that in the period 2020–2021, due to the social isolation and quarantine brought about by the COVID-19 pandemic, the gases emitted to the atmosphere were lower than in previous years (UN environment programme, 2022); however, the reported increase in the glacial mantle was minimal, superficial, and temporary.

It was also identified that one of the most relevant reasons that are not considered is the lack of social education on global warming and efficient use of water in the localities; the inhabitants have little interest in the care and quality of the water they are receiving from the snow-capped mountains under study (Tecnología y Sociedad, 2009).

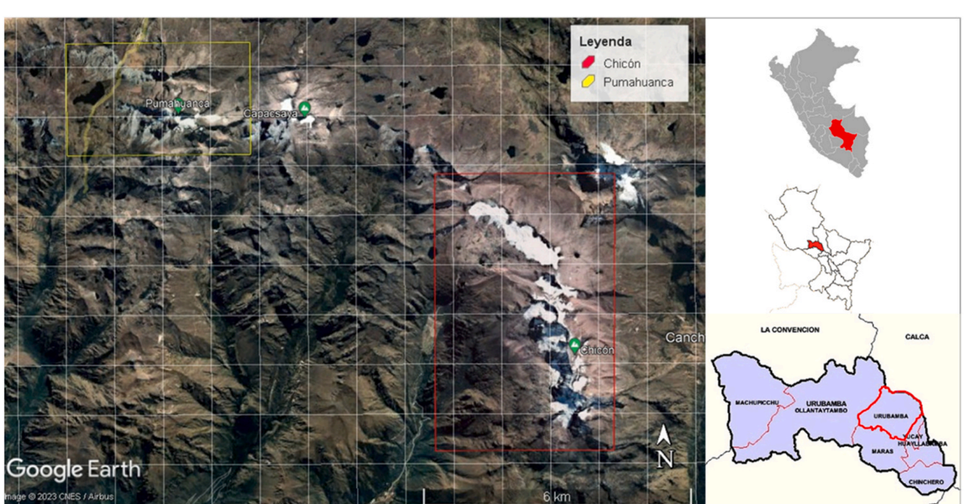

Fig. 1. Identification map of the study area, Chicon and Pumahuanca snow-capped mountains.

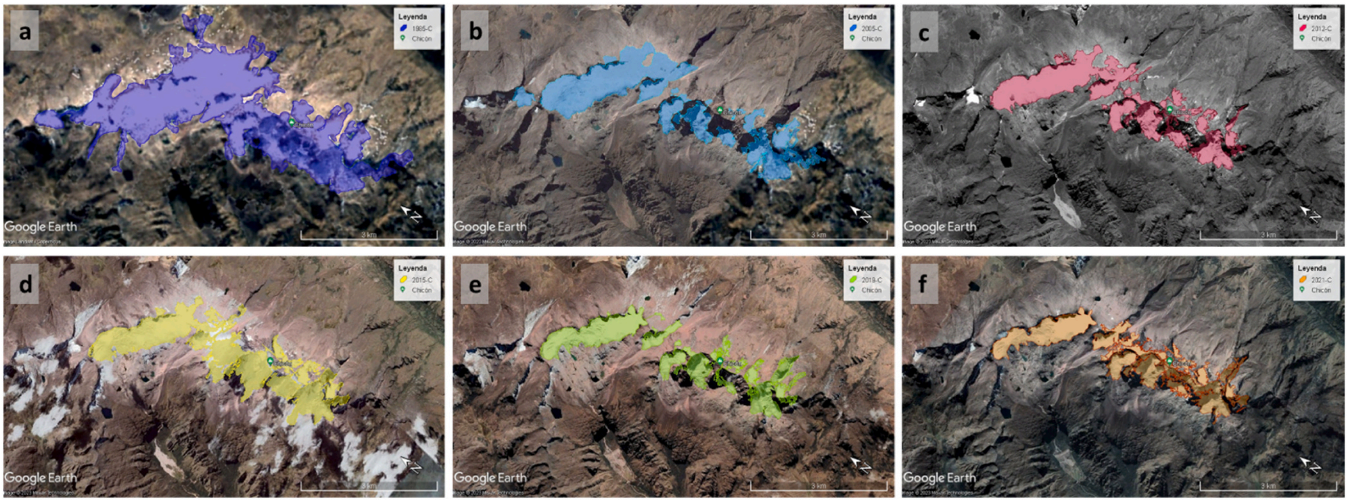

Fig. 2. Satellite image of the coverage of Chicon snow-capped mountain, 1985–2021.

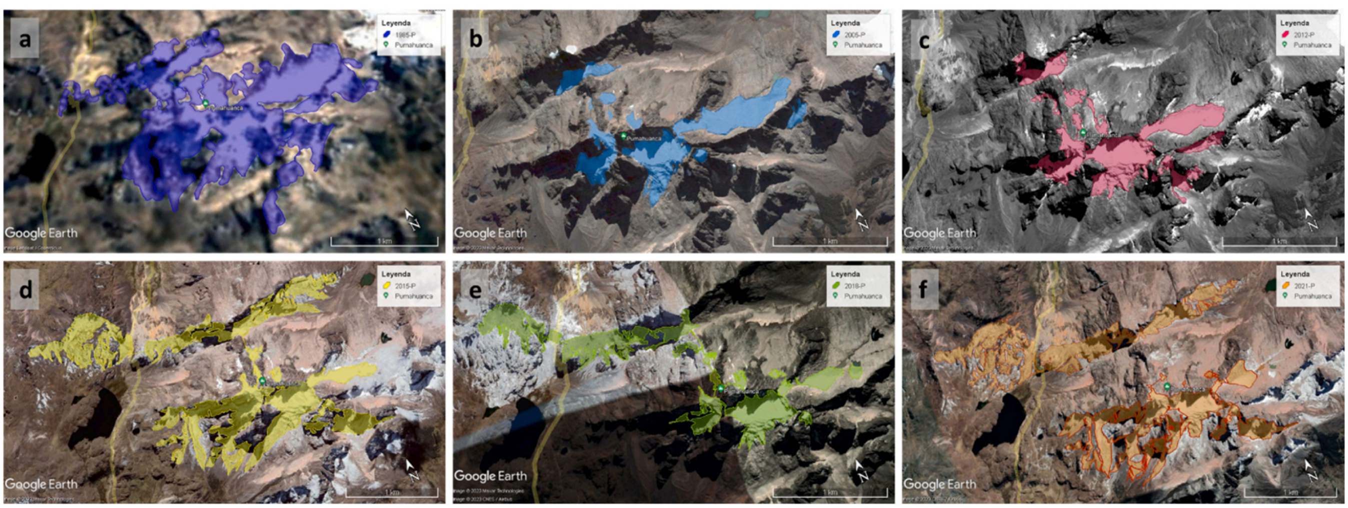

Fig. 3. Satellite image of Pumahuanca snow-capped mountain coverage 1985 – 2021.

4.3. Idea

After a complete analysis of the problem, possible solutions and the first designs were created. The idea was to create an AR application to raise awareness among the population, starting with the school-age population, to contribute to the saving and care of water, as well as to

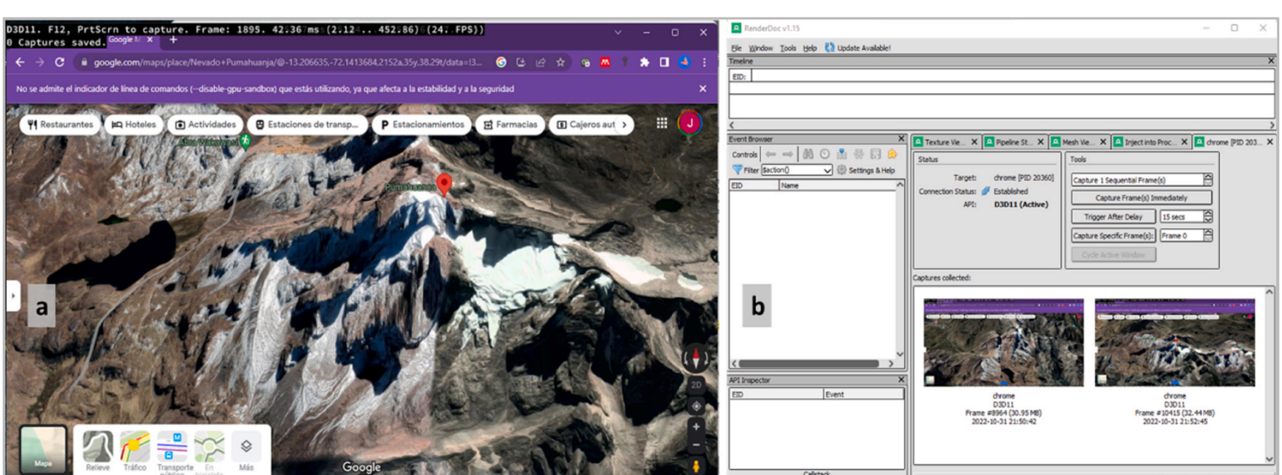

Fig. 4. Frame capture, the interaction between Google Maps and RenderDoc.

the reduction of practices that contribute to global warming, seeking to capture the current situation of the snow-capped mountains of the Peruvian Andes and the impact they have had in less than 40 years.

4.4. *Prototype*

In this phase, the prototype was developed in Unity, as well as the creation of the 3D models of the snow-capped mountains.

4.4.1. *Elaboration of 3D models*

The interaction between Google Maps and RenderDoc is shown in Fig. 4. Once the connection between the two is established, we search in Google Maps for the location of the place where we want to extract a 3D model (Fig. 4a), then when we capture the models, the captured frames are shown in RenderDoc (Fig. 4b), when we save them, they are created as ".rdc" files.

Then we proceed to import the ".rdc" file to Blender using the Google Maps Capture option (Fig. 5a), where we can visualize the captured model without texture (Fig. 5b), to continue we add the textures by pressing the shading option of the view and eliminate the unnecessary parts so that finally the model is exported as a ".fbx" file together with its texture folder to be read by Unity (Fig. 5c).

4.4.2. *Application development*

The development of the AR application called "Hatun Chullunku" which means "glacier" in Cusco Quechua, was divided into 3 main interfaces, "current situation" where it details how the snow-capped mountains are and how they were before, "Consequences" derived from deglaciation and finally "Conservation" where it details the conservation techniques to practice, shown in Fig. 6 where the main interface of the application is located.

After the development of the 3D models, the interfaces of the application were created within the Unity environment. Fig. 7 shows the interfaces that interact with the AR technology by clicking on the

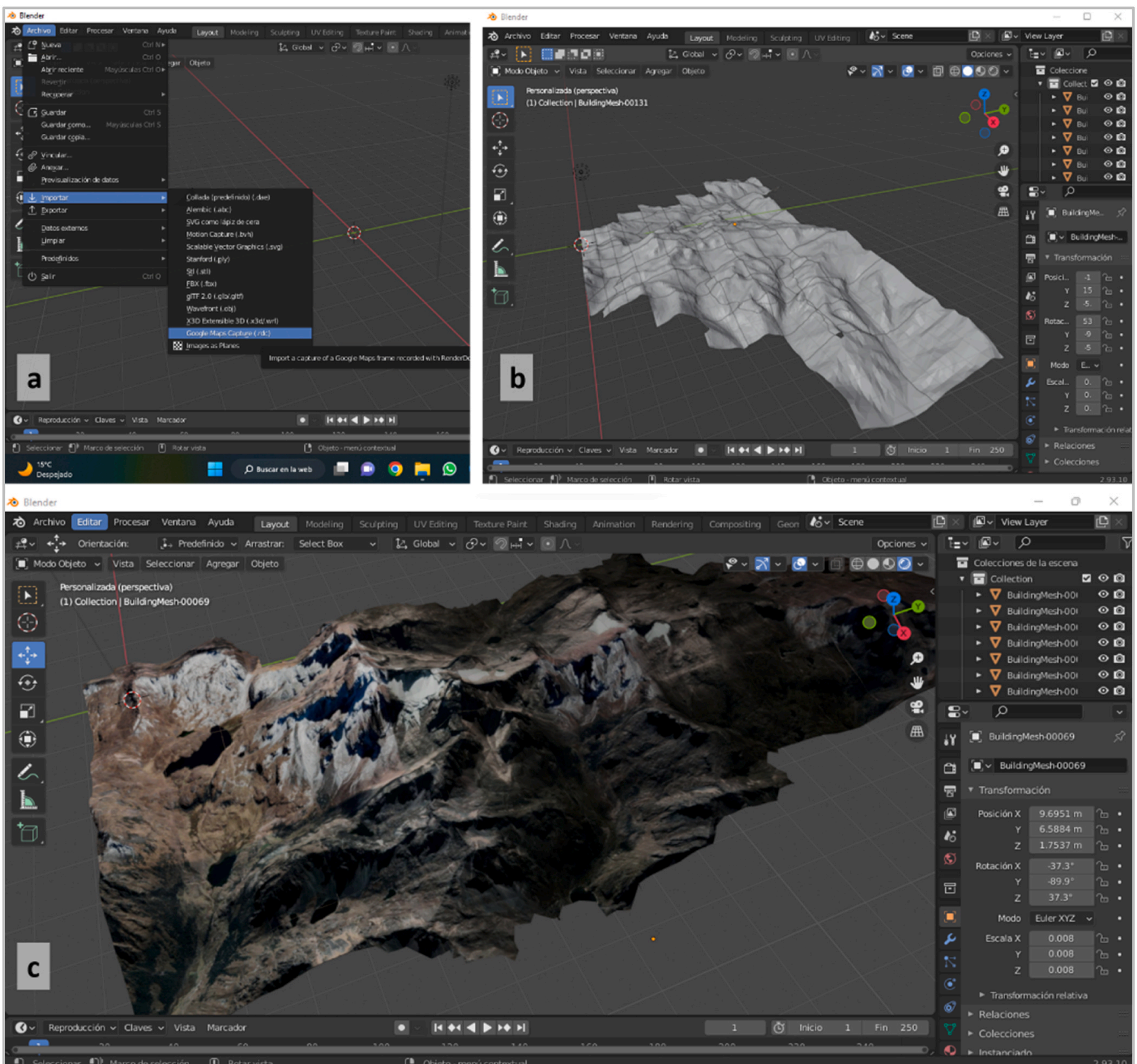

Fig. 5. Texturing of 3D models in Blender.

Fig. 6. The main interface of the mobile application "Hatun Chullunku".

Fig. 7. AR interfaces: (a) AR Chicon snow-capped mountain; (b) AR Pumahuanca snow-capped mountain.

"Current situation" option of the main interface.

Within each AR interface of the application, two options are shown "What was it like before?" which refers to how the snowfields looked before and how they look now with the poor glacier coverage illustrated in Fig. 8; and "How much have we lost?" illustrated in Fig. 9.

After clicking on the "How much have we lost?" button, the informative interface is displayed (Fig. 9) where, with more in-depth and illustrative data, it is shown how much glacier cover has been lost in both snowfields, bordered with blue to show how far the snowfield expanded before and bordered with orange to show how much of the snowfield remains today. Also, for the student's better understanding, the explanation of the illustration is shown on the right side.

When returning to the main interface and clicking on the "Consequences" option, Fig. 10a is displayed. This interface provides brief but important information about the consequences of glacier retreats and how this affects our way of life. Likewise, after clicking on the "Conservation" option, Fig. 10b is shown. This interface shows some of the most relevant conservation techniques that students can practice at home according to the educational material of the Ministry of the Environment (Ministerio del Ambiente, 2013). In the end, students are given the option "Learn more", which leads to an informative web page where more details will be provided.

4.5. Testing

In this phase we proceeded to evaluate and test the developed application, as well as the interaction of its interfaces which gave favorable results (Figs. 7–10), also the interaction of the AR with the camera of the mobile device, and the fast response to display the models when detecting the object (Image targets) specified in Vuforia (Fig. 7).

5. Discussion

After the previous study of the glaciers, it was found that ice coverage during the 1985–2021 period decreased by 32.5% for the Chicon glacier and 56.94% of the Pumahuanca glacier. Between 1985 and 2005, there was a drastic decrease in the extent of Pumahuanca glacier (Fig. 3b); this decrease was more gradual in the following years

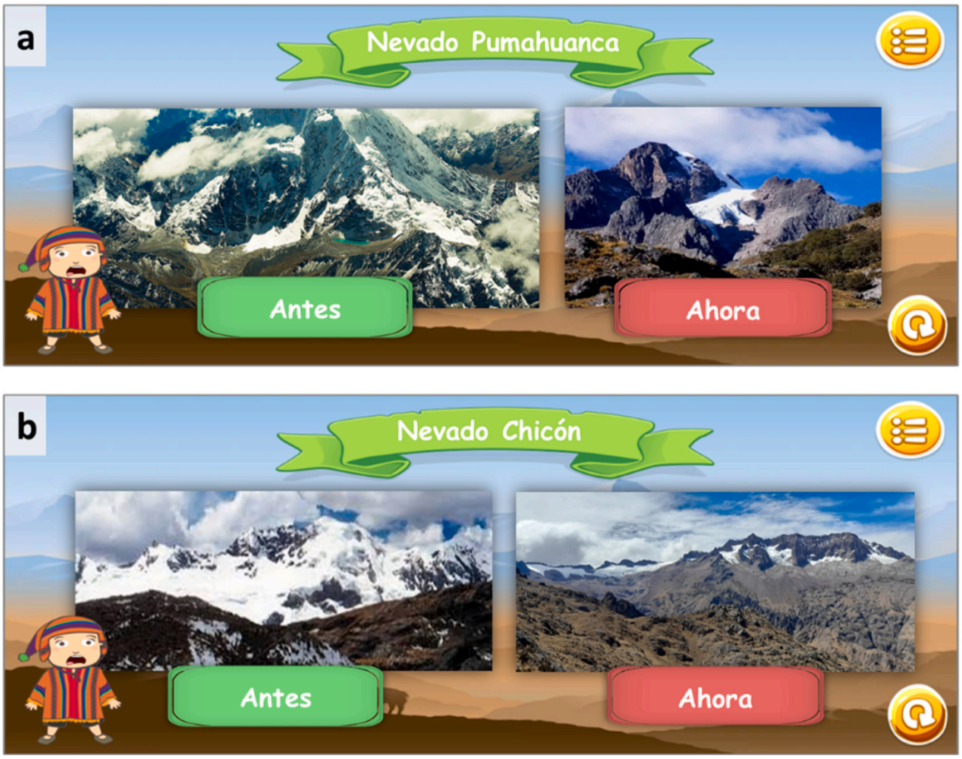

Fig. 8. Before-now informative interfaces. (a) Before and now photographic comparison of the Pumahuanca snow-capped mountain. (b) Before and now photographic comparison of the Chicon snow-capped mountain.

Fig. 9. Informative interfaces: (a) Loss of Chicon glacier cover; (b) Loss of Pumahuanca glacier cover.

up to 2015 (Fig. 3c, d, and e). Although there is an increase in the extent for the years 2018 and 2021 (Fig. 3f) according to the images presented, the density of this snow cover is minimal, superficial, and temporary.

In the case of Chicon, a drastic change was also observed between 1985 and 2005 (Fig. 2b). In the following years, the reduction of the snow-capped area is observed more gradually (Fig. 2c, d, and e), in addition to its low density.

The effect of natural climate variability as well as the action on

Fig. 10. Interfaces Consequences and Conservation.

climate change represents significant disturbances and threats, mainly to societies that depend on the use of natural resources (Tecnología y Sociedad, 2009). According to Vuille et al (Vuille et al., 2015)., from the different investigations carried out in the Tropical Andes, it was determined that the temperature increase of 0.13 °C/decade that was registered between 1950 and 2010 is the cause of the deglaciation that occurs. There are other factors such as changes in precipitation patterns, cloud cover, humidity, the occurrence of natural events, and even unique factors such as the aftermath of the COVID-19 pandemic, which also influence the increase or decrease of glaciers.

It is important to highlight the importance of having a record of glaciers in Peru, as it is often difficult to obtain sufficient satellite images during a specific period of the year or period of years that meet ideal cartographic conditions, i.e., without snow or seasonal clouds hiding the glaciers. Therefore, glacier inventories are often constructed from images collected over several years. This information on glacier extent is crucial for many investigations and calculations related to glaciology and hydrology. These studies range from surface mass balance and future projection of glaciers to runoff analysis, and hydroelectric power generation, among others (Paul et al., 2020).

6. Conclusions

The retreat of glaciers/snow-capped mountains is a consequence of the increase in global temperature that ends up affecting our ecological environment and way of life. Peru has the highest percentage of South American snow-capped Andes, of which we know that many of them have alarmingly lost their glacier cover; Although actions are being taken to mitigate this process, it is still necessary to emphasize the education of citizens regarding global warming and water culture. In this sense, environmental education from an early age plays a fundamental role, since it has important advantages, such as sensitizing and committing children to their environment and the reality in which they develop. This motivates them to actively participate in the protection of the environment, acquiring new knowledge and skills that will allow them to offer optimal solutions to environmental problems in the future.

The use and implementation of ICT have a positive impact on the teaching-learning process, both inside and outside the classroom. Therefore, the proposal of a mobile application with AR will allow teaching students in a didactic and interactive way about the current situation of the main snow-capped mountains in the Peruvian Andes. This first prototype is based on the analysis of two of the Peruvian Andean snow-capped mountains, demonstrating the decrease of their glacier coverage in a specific period, as well as providing information on the measures that citizens can take to counteract this change. The study carried out is easy to understand and reflects the problem addressed, being aimed mainly at educational institutions to promote public awareness of climate change and its consequences, thus complying with SDG 13.

The study identified the trend of decreasing ice cover of the glaciers studied throughout the period analyzed. The drastic retreat and subsequent gradual retreat in the extent of the Pumahuanca glacier also highlight the vulnerability of these ecosystems to climate change. The low density of ice found in the most recent years reinforces concerns about the loss of glacier mass and its implications for the water supply in the region.

The scientific contribution of this research work is considered important because it serves as a precedent for future projects involving the care of the environment and the use of ICT.

7. Limitations and future recommendations

This study was limited to a narrow perspective rather than adopting a broader approach, focusing on showing the current situation of two of the main snow-capped mountains in the Cusco region of Peru. Likewise, the sample used consisted of 12 satellite images manually collected using Google Earth Pro for a period of 40 years. Therefore, it is considered that its limitations lie in not including a larger number of snow-capped mountains, especially those considered the largest and most important in Peru, as well as not having a larger number of images due to the lack of availability of a database of digitized Peruvian glaciers. This implies that future research should focus on exploring the implications of the diversity of Peruvian Andean snow-capped mountains, performing a more complete analysis of them, and creating the corresponding 3D models that complement the application with AR.

It is also recommended the incorporation of technologies such as MR, to achieve a more immersive user experience with the application. Also, future research is recommended to use image analysis using Python, which will allow for a more accurate collection and analysis of the data obtained.

Ethics statement

I, Joselyn Zapata Paulini, as the person in charge of the research entitled "Augmented reality for innovation: education and analysis of the glacial retreat of the Peruvian Andean snow-capped mountains", submit the following ethical statement to affirm that no studies on human subjects were conducted in the development of this research.

The present research has been carried out with the objective of developing an interactive pedagogical resource aimed at raising awareness in educational institutions about the glacial retreat of the Peruvian Andean snow-capped mountains, with the intention of being used in the future. Throughout the process of design, data collection, analysis and conclusions, fundamental ethical principles have been followed, prioritizing respect for the rights, integrity and dignity of the human beings involved.

The absence of studies in human subjects is based on the nature of this research, which is based on showing the current situation of some of the snow-capped mountains of the Andes that have suffered a greater impact, implementing augmented reality technology to obtain an interactive link. To understand the current situation in greater detail, a study was conducted using satellite remote sensing techniques to monitor the balance of the surface mass of the glacier mantle in a specific period of time.

We reiterate our commitment to ethics in scientific research by declaring under oath that the following oath that the following research ethics principles have been respected:

- No experiments, clinical trials, surveys or other studies directly involving human subjects were conducted at any stage of the research. Likewise, no individual was subjected to medical, psychological, social or any other type of procedures for research purposes.
- The rights and dignity of individuals and groups have been respected.
- The participation of all those involved has been voluntary and adequately informed.
- The investigation has been conducted with integrity and transparency.
- The hierarchy of responsibilities and accountability has been clearly defined.
- The independence of the research has been maintained, avoiding conflicts of interest.
- The ecosystem has been respected, which is the basic functional unit of ecology that includes the following components: all living beings (plants, animals, microorganisms) and the balance between them.

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The authors of this research paper entitled "Augmented reality for innovation: education and analysis of the glacial retreat of the Peruvian Andean snow-capped mountains" declare that we have conducted the entire study with our own funds without receiving external funding for the execution of the research project. However, we would like to acknowledge and thank the Universidad Continental for their financial support provided specifically to cover the expenses associated with the publication of this work.

During the development of the research, we personally assumed the costs related to:

- Acquisition of material and equipment necessary for data collection.
- Travel and logistics expenses to carry out the collection of information.
- Access to databases, scientific journals and other relevant sources of information.

- In this regard, we reiterate that no other body or entity has participated in the design, execution or interpretation of the results of the investigation.

Universidad Continental provided financial support only to cover the publication costs of this work, as part of its commitment to the dissemination and promotion of scientific research.

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Declaration of Competing Interest

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

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