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Environmental changes in Boeckella Lake, Antarctica Peninsula, between 1958 and 2023

Cambios ambientales en el lago Böeckella entre 1958 y 2023, península Antártica

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Keywords
Permafrost, remote sensing, thermokarst

ABSTRACT
The Antarctic Peninsula (AP) has experienced rapid warming in recent years, which has caused permafrost degradation. In the north of AP, in Hope Bay, Boeckella Lake has experienced rapid and sudden drainage events in recent decades driven by thermokarst processes. The study aims to characterize environmental changes in Hope Bay, especially in Boeckella Lake between 1958 and 2023. Data generated in this research and from bibliographic sources on limnological and sedimentological characteristics; thaw water supply data; photographs; Remote Sensing; and bathymetry of Boeckella Lake were used. Remote Sensing data shows that on February 29, 1988, the lake had an area of 40,236 m². Since 2010, Boeckella Lake has been divided into small lakes, recording an area of 20,408 m² in 2023, a decrease of approximately 50%. Bathymetric data show that between 1993 and 2013 the lake increased in depth, due to the ground collapse. In addition, the high level of surface runoff in the area from the Buenos Aires glacier may contribute to an increase in organic and inorganic matter entering Boeckella Lake and other limnological changes. The Boeckella Lake has undergone significant changes over the years due to permafrost thaw and intensified thermokarst erosion, driven by the rising air temperatures observed in recent years. However, anthropogenic interferences strongly affect the lake dynamics.

Palabras clave
Permafrost, sensores remotos, thermokarst

RESUMEN
La Península Antártica (PA) ha experimentado un rápido calentamiento en los últimos años, lo que ha provocado la degradación del permafrost. En el norte de la PA, en Bahía Esperanza, el lago Böeckella ha experimentado eventos de drenaje rápidos y repentinos en las últimas décadas impulsados por procesos de termokarstía. Este estudio tiene como objetivo caracterizar los cambios ambientales en la Bahía Esperanza, en especial en el lago Böeckella entre 1958 y 2023. Se han utilizado datos limnológicos y sedimentológicos; datos de suministro de agua de deshielo; fotografías; teledetección; y datos de batimetría del lago Böeckella. El 29 de febrero de 1988, el lago tenía un área de 40236 m² pero desde el 2010, el lago Böeckella se ha dividido en pequeños lagos, registrando un área total de 20408 m² en 2023. Una disminución de aproximadamente el 50%. Los datos batimétricos muestran que entre 1993 y 2013 el lago aumentó en profundidad, debido al colapso del terreno. Además, el alto nivel de escorrentía superficial en el área proveniente del glaciar Buenos Aires puede estar contribuyendo a un aumento de materia orgánica e inorgánica que ingresa al lago Böeckella, así como a otros cambios limnológicos. El lago Böeckella ha sufrido cambios a lo largo de los años debido al deshielo del permafrost y a la intensidad de la erosión termokarstica provocada por el aumento de la temperatura del aire registrado en los últimos años. Sin embargo, las interferencias antropogénicas afectan fuertemente la dinámica del lago.

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Introduction

The Cryosphere has a high sensitivity in a changing global climate, leading to changes in energy balance and runoff (Levy et al., 2018; Liu et al., 2020; Qin & Ding, 2010; Turner et al., 2014). The degradation of permafrost is one of the impacts of climate change (Biskaborn et al., 2019; Grosse et al., 2011; Jin & Ma, 2021; Murton, 2021; Revich et al., 2022), resulting in topography perturbations in frozen landscapes due to changes in glacial and ground ice stability and soil hydrology (Levy et al., 2018; Schaefer et al., 2014; Smith et al., 2022). Although it is not certain the magnitude and timing that it will occur, it is estimated that the thaw of permafrost will continue to occur (Smith et al., 2022).

The process of thawing of ice-rich permafrost ground causing land subsidence and disruption, is called thermokarst, resulting in the development of distinctive landforms (Murton, 2009; Olefeldt et al., 2016). The characteristic landforms are thermokarst lakes, thermokarst depressions (alasses), thermokarst mounds, alas basins, and thaw sinks (Kokelj & Jorgenson, 2013; Morgenstern et al., 2021; Olefeldt et al., 2016). The melting of ground ice caused subsidence over several study areas containing continuous permafrost (Heslop et al., 2020; Levy et al., 2018).

This research will emphasize thermokarst lakes, which are open-water areas of thermokarst landscapes (Olefeldt et al., 2016). The thermokarst lakes form when ice-rich permafrost thaws and has water accumulation at areas with low relief, topographic depressions, thick unconsolidated sediments, and high ground ice contents (Bouchard et al., 2017; Jones et al., 2011; Kokelj & Jorgenson, 2013). The expansion of lakes occurs due to rapid heat conduction through water bodies leading to the thawing of ice-rich permafrost (Heslop et al., 2020; Walter et al., 2007; Zandt et al., 2020).

Permafrost soils contain approximately 1,700 gigatons of carbon in frozen organic matter, roughly twice as much carbon as is currently in the atmosphere (Tarnocai et al., 2009). Thermokarst lakes are effective in inducing rapid permafrost thaw, triggering the release of substantial amounts of CH4 in recent years (Anthony et al., 2014; Brosius et al., 2012; Grosse et al. 2013; Heslop et al., 2015; Heslop et al., 2020; Jin and Ma, 2021; Walter et al 2007). In this way, most researchers are from the Arctic and are focused on the potential release of carbon from thermokarst lakes, because it is a major driver of landscape change in those regions, while Antarctica research recently began to recognize and study these processes (Sudman et al., 2017).

In recent decades, continued warming has occurred in the Antarctic Peninsula - AP - (Cape et al., 2015; Siegert et al., 2019; Vaughan et al., 2003). In February 2020, the AP and surrounding islands faced one of the highest temperature extremes since observations became available (Gonzalez-Herrero et al., 2022). Like the warming of the continuous permafrost zone in the Arctic, Antarctic permafrost warmed by 0.37 ± 0.10 °C between 2007 and 2016, although there are inconsistencies, and more data is needed (Biskaborn et al., 2019). Therefore, the PA has witnessed several environmental changes in recent years such as permafrost degradation (Bockheim et al., 2013; Guglielmin, 2012; Guglielmin & Vieira, 2014; Hrbáček et al., 2023; López-Martínez, 2012; Oliva & Ruiz-Fernández, 2015).

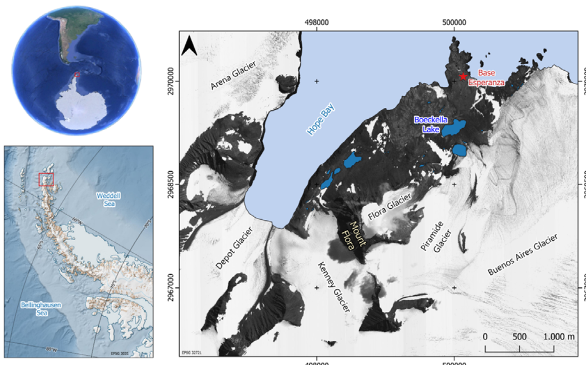
Thermokarst process has been previously studied in Antarctica (Fountain et al., 2014; Levy et al., 2013; Levy et al., 2018; López-Martínez, 2012; Oliva & Ruiz-Fernández, 2015; Sudman et al., 2017; Swanger e Marchant, 2007). The Hope Bay area, north of the AP, the Boeckella Lake (63°24'S; 57°00'W) have been characterized by thermokarst processes in the last decades (Ermolin, 2009; Ermolin & Silva Busso, 2007; Moreno et al., 2014; Pereira et al., 2013; Rosa et al., 2022; Schaefer et al., 2015; Schaefer et al., 2017; Vieira et al., 2024). Settlements of up to 8 meters thick caused by thermo-erosion processes have been measured in the Hope Bay area (Moreno et al., 2014). Therefore, this study aims to characterize environmental changes in Hope Bay, especially in Boeckella Lake, between 1958 and 2023, using data from limnological and sedimentological features; meltwater supply data; photographs; Remote Sensing; and bathymetry.

Study Area

Hope Bay (63°24' S; 57°W) is located at the northern end of the AP (Figure 1). Its ice-free area is 3.5 km², limited to the south by Mount Flora and the east by the Buenos Aires Glacier (Izaguirre et al., 2012; Pereira et al., 2013; Serrano et al., 2005; Sotille et al., 2020). The Argentine Esperanza Base, opened in 1952, is in the northern portion of Hope Bay.

The geology is associated with rocks from the Trinity Peninsula and Botany Bay Groups and volcanosedimentary detrital rocks from the Antarctic Peninsula Group (Montes et al., 2019). The area presents relict glacial forms such as erratic blocks, moraine, and periglacial forms and processes (Serrano et al., 2005).

Figure 1. Location of Hope Bay and Boeckella Lake, at the northern end of the AP



Fuente:

The vegetation in Hope Bay is concentrated in units with crustose lichens, green algae (Prasiola crispa), and few mosses (Pereira et al., 2013; Sotille et al., 2022). Poeiras (2010) identified one species of terrestrial algae, 19 species of lichens, and eight species of mosses.

Between 1952 and 2010, the average air temperature at Esperanza Station was -5.1°C, with annual precipitation of approximately 250 mm (Pereira, 2013). Hope Bay is located in a climate transition zone between the maritime and continental polar zones, presenting rapid changes in glacier fronts and air temperatures over recent years (Sotille et al., 2020).

The soils are shallow and cryoturbic, however, in some parts, the nesting activity of penguins on stable surfaces can increase weathering and soil formation (Pereira et al., 2013; Schaefer et al., 2015). Lithic Haploturbels occur chiefly on shallow rocky terrains whereas Typic Haploturbels are localized on patterned ground (Schaefer et al., 2015). Geomorphic processes in the area are related to summer snowmelt, increased periglacial erosion, and local thermokarst (Pereira et al., 2013).

Ermolin (2003) estimated a permafrost thickness of 80–100 m in this area, and that the permafrost active layer below Boeckella Lake was 2.5–3.5 m thick. The structure of the upper zone of permafrost, developed in the surrounding glacial deposits, is characterized by the presence of large masses of buried ice related to the last stages of Quaternary glaciation (Ermolin, 2009; Ermolin & Silva Busso, 2007). Consequently, Lake Boeckella was directly impacted by an increase in mean annual permafrost temperature, and the deepening of the active layer, with rapid and sudden drainage events (Ermolin, 2005; Izaguirre & Almada, 2001; Izaguirre et al., 2012; Izaguirre et al., 2021; Nozal et al., 2019; Pizarro et al., 2004; Rosa et al., 2022; Vieira et al., 2024).

Materials and Methods

This study used data from other research and data generated by the authors (Table 1). The research includes data obtained between 1956 and 2023, for the Hope Bay area and Boeckella Lake.

We used multispectral satellite imagery, 6 Landsat images from sensor TM, ETM+, and OLI (1988-2023) derived from Google Earth Engine (GEE) data collections (Table 2). Collection 2 Tier 2 of Landsat is calibrated

Table 1
Data used for integrated analysis at the thermokarst landscape of Hope Bay

Data	Date from the source	Source	Purpose
Historical photographs	1959	Koerner et al (1961)	Verifying the affected areas by thermokarst processes
	2005 and 2008	Nozal, Martín-Serrano and Montes, (2019)	
Field photographs	2008/2009, 2013 and 2017	Obtained in the field and by the Instituto Antártico Argentino	
Aerial photographs	1956 and 1974	Instituto Antártico Argentino	Verify the glacial lake area
Remote sensing imagery (Landsat and Quickbird images)	1988-2023 (Landsat)	Google Earth Engine	
	2005 (QuickBird)	Instituto Antártico Argentino	
Limnological and sedimentological features	1991-2021	Izaguire et al. (2012) Scravagluieri (2021) Fieldwork	Verify changes in various features
Meltwater supply	2005	Ermolin and Silva Busso (2007)	Calculate the flow of melting water entering Boeckella Lake
Bathymetric data	1987	Drago y Paira (1987)	Verify lake depth changes
	2013	Fieldwork	

top-of-atmosphere (TOA) reflectance. For the Landsat 4 image, it was necessary to coregister the image using QGIS 3.0. The QuickBird image is from January 8, 2005. Satellite images were chosen on cloud-free dates and to represent drainage events at Boeckella Lake. Unfortunately, the spatial resolution of Landsat satellite images is not the most suitable for calculating the area of small lakes in Antarctica, but it is the sensor available to show the changes in Boeckella Lake.

The normalized difference water index (NDWI) has been applied to Landsat and Quickbird to identify water bodies. NDWI has been successfully applied in other glacial lake studies (Lesi et al., 2022; Sarwar and Mahmood, 2024; Vieira et al., 2024; Wang et al., 2022). The McFeeters (1996) equation used was:

$$\mathbf{NDWI = (G - NIR)/(G + NIR)} \qquad \textbf{Eq.1}$$

For Landsat 4 and 7 the bands 2 and 4 correspond to G (Green) and NIR (Near infrared). For Landsat 8, G and NIR correspond to bands 3 and 5 respectively. For QuickBird, the bands 3 and 5 are G and NIR, respectively.

NDWI values range from -1 to +1 (McFeeters, 1996) and was established as the zero limit value for water bodies. The same limit was adopted in studies to identify glacial lakes (Sarp & Ozcelik, 2017; Zhang et al., 2018).

Results

Glacial lake area changes between 1956-2023: data obtained with Remote Sensing and photographs (aerial and from the field)

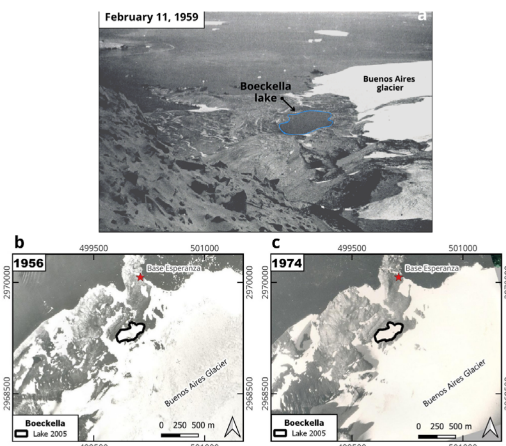
This period includes the beginning of human intervention in Hope Bay, through the Esperanza Base construction in 1952. Despite the large amount of snow cover in the aerial photographs, it can be seen that Boeckella Lake, between 1956 and 1974, was just a few meters from the front of the Buenos Aires glacier (Figure 2a; 2b; 2c).

Boeckella Lake showed variation in area during the monitoring period with Landsat images, due to thermokarst processes. On February 29, 1988, the lake had an area of 40,236 m² and on February 21, 2000, the area was 36,794 m², constituting one the first sudden drainage event. At the beginning of January 2001, there was a sudden water level drop, around 3 m, due to the discharge of water into the sea (Ermolin, 2005; Izaguirre & Almada, 2001; Izaguirre et al., 2012; Izaguirre et al., 2021; Pizarro et al., 2004). The remaining Boeckella Lake volume was about 22,923 m³, about 19% of its original volume (Izaguirre et al., 2012).

Table 2
Remote sensing imagery used to verify the thermokarst lake extent

Data	Date from the source	Source
February 29, 1988	4	Thematic Mapper (TM)
February 21, 2000	7	Enhanced Thematic Mapper Plus (ETM+)
February 22, 2003		
January 18, 2014	8	Operational Land Imager (OLI)
February 13, 2020		
February 4, 2023		

Figure 2. Boeckella Lake historical records: a) Photograph by Koerner et al. (1961) and aerial photographs from Argentine Antarctic Institute



On February 22, 2003, Boeckella Lake had an area of 37,510 m². After successive attempts to dam the lake's water and several sudden drainage events (which will be explained in the following items), in 2010, the containment dam broke again due to thermokarst processes and was not rebuilt. From this, Boeckella Lake is divided into small lakes, recording in 2014, 2020, and 2023 respectively the areas of 15,687 m², 22,306 m², and 20,408 m² (Figure 3). Currently, Boeckella Lake has underground drainage caused by thermokarst that can quickly empty the lake in summer (Vieira et al., 2024).

Other authors have observed the formation of new lakes in the Boeckella area. After 2010, five ponds were formed that behave differently from each other (Moreno et al., 2014). The number of lakes observed may differ depending on the spatial resolution from satellite images, however, the role of these data in understanding the mechanism of variation in Boeckella Lake is undeniable. Numerous remote sensing studies have recently examined changes in the area extent of thermokarst lakes (Arp et al., 2012; Jones et al., 2011; Lantz et al., 2015; Smith et al., 2005). Mapping and monitoring lakes associated with thermokarst processes is essential to document these changes and provide information about their underlying processes (Olthof et al., 2015).

Anthropogenic interference: construction of the containment dike at the Boeckella Lake

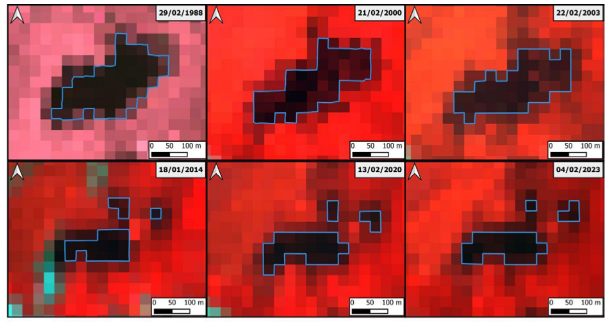
For decades, Boeckella Lake was the primary drinking water supply for the Argentine Antarctic Base (Izaguire et al., 2012). Given the lack of a sufficient supply guarantee, various actions were carried out to increase the volume of stored water (Moreno et al., 2014). The most significant of these actions has been the construction, in different stages, of a containment dam at Boeckella Lake. This construction is characterized as the first direct anthropogenic intervention, in the 1980s.

The artificial containment dam of Boeckella Lake was initially made of concrete and was around 2 meters high and 35 meters wide. As the volume of water in the reservoir increased, it reached beyond its crest. Therefore, over the first 15 years, the height was increased, filled with local materials extracted from the adjacent moraine.

A concrete wall was built in the summer of 2000/2001, which recovered the lake level but did not stop water infiltration (Ermolin, 2005). Given the frequent problems of instability of the damming during the summer of 2001, the design and construction of the Boeckella dam were improved (Izaguirre et al., 2012). The proposed solution was the construction in 2002 of a complementary dam (Figure 4a) with a system of artificial soil freezing using liquid convection thermosyphons (Ermolin, 2005). The intention is to keep the area below 0°C in such a way as to increase cohesion and the angle of internal friction, minimizing damage and improving closure (Ermolin 2003, 2005).

Between 2002 and 2004, the thermosyphon liquid convection mechanism proved to be effective, with the recovery of uniform geocryogenic conditions and the formation of an impermeable ice core beneath the dam (Ermolin, 2005). This solution provided a relative degree of stability for almost ten years, at least from the point of view of the quantities of water for supply. However, these actions, and the dam in particular, have produced a notable modification of the lake morphology and even its local hydrogeological and geocryological functioning.

Figure 3. Changes in the Boeckella Lake area between 1988 and 2023



Between December 2004 and January 2005, several days of high air temperatures combined with liquid precipitation, led to an increase in glacial meltwater flowing into Boeckella Lake, causing the dam to overflow (Nozal et al., 2019). According to the same authors, there was a reduction in the level of around 2 m, causing the appearance of beaches inside Boeckella Lake (Figure 4b). In the field, in 2005, the development of a cavity was observed near Boeckella Lake, approximately 2-3m below the permafrost active layer, indicating that melting occurred through thermally eroded tunnels (Nozal et al., 2019).

On February 2, 2005, Boeckella Lake had already recovered considerably its volume (Figure 4c). High average air temperatures caused the continuation of solifluction processes and small surface subsidence in the area adjacent to the SW sector of the dam, consequently, the dam began to collapse again in 2007 and 2008 (Figure 4d).

By modifying the volume of water stored in the lake, the talik associated was modified (Nozal et al., 2019), increasing its spatial extension. Furthermore, erosion processes begin to act. Thermal and mechanical erosion by water plays an essential role in the formation of thermokarst environments (Harris et al., 2018).

Thermoerosion processes accelerated at the base of the flanks (Ermolin & Silva Busso, 2007), leading to the collapse of the northern flank of the dam along an approximate extension of 700 meters (Montes & Nozal, 2007). According to Ermolin & Silva Busso (2007), the processes described were notably aggravated due to the extraction of rocks and sediments in some immediate areas, facilitating the thermoerosion produced by groundwater circulating at the ground ice exposed.

These processes increased the dike's structural weakness, adding to the thermokarst processes, and causing its rupture in a warm summer period with intense ablation. Overall, in 2010, the dike broke after the lake flank's destruction (Figure 4e). From the point of view of supply management to the base, it has also had negative consequences since it dries completely in summer and freezes at all depths in winter, it can no longer be used as a water source.

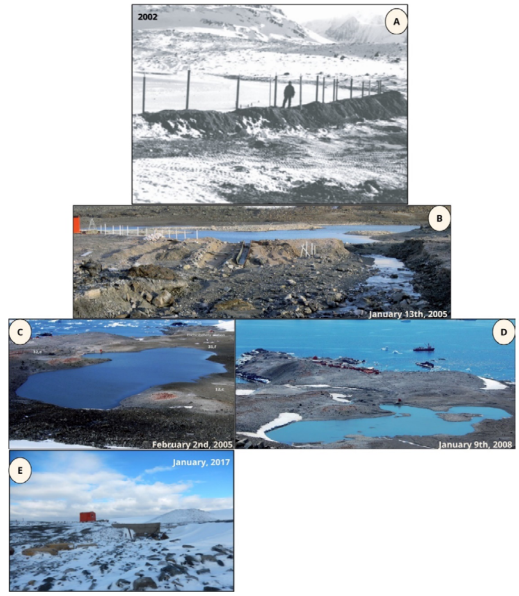
Lake morphology of Boeckella: changes in depth

The first study of Boeckella Lake was carried out by Drago & Paira (1987) to describe the morphometry and geomorphology of the area. This data contained in Izaguirre et al. (1993) demonstrate an area of 67,454 m², an estimated volume of 124,097 m³, a maximum depth of 4 m, and a mean depth of 1.84 m for Boeckella Lake. There is a very diffuse glacier-fed stream system from the Buenos Aires Glacier to the lake. Is a body of water with poorly defined depocenters and maximum depths barely more significant than 4 m (Figure 5a).

With the reduction of lake volume, a new bathymetry measurement was performed. In bathymetry carried out in 2013, the development of 4 depocenters identified as A, B, C, and D, respectively, is observed (Figure 5b). Depocenter B is the deepest, approximately 8m deep. A and C have a maximum depth of 5 m and D reaches the class between 6.5 m.

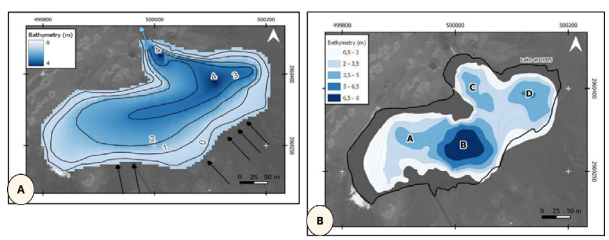
The morphometric parameters of Izaguirre et al. (1993) are compared to those of 2013 (Table 3). Negative values indicate a reduction in the previous value and positive values indicate an increase in them. In general, a reduction in linear and areal parameters is observed, however, there is a significant deepening (more than 90%) and a consequent increase in the volume of the lake. The thermal capacity of the lake water promotes permafrost thaw, therefore causing thermokarst subsidence (Hinkel et al., 2012). Thus, causing more subsidence of the ground surface, and deepening and expansion of thermokarst depressions at Boeckella Lake

Figure 4. A) Dam built in 2002 on Boeckella Lake with the thermosyphon liquid convection mechanism. Source: Ermolin (2005); B) Break of the dam in 2005, it is possible to see beaches in the central part of the lake, due to the decrease in volume; C) shows volume recovery on February 2, 2005; D) Shows another moment of decrease in the lake's volume, in 2008.



Source (B, C and D): Nozal et al., (2019); E) Material remaining after the Boeckella Lake dike breached. Source: Petsch & Silva Busso (2017).

Figure 5. A) Boeckella Lake during the summer of 1987. Adapted from Drago in Izaguirre et al. (1993); B) Bathymetry of Boeckella Lake, in 2013.



Limnological and sedimentological variables changes at the Boeckella Lake

Izaguirre et al. (2012) made a 16-year comparative analysis (from 1992 to 2007), and Boeckella Lake underwent important changes in its physical and chemical variables. As for Phytoplankton chlorophyll, Water conductivity, dissolved reactive phosphorus (DRP), nitrates, and ammonium, the authors demonstrate changes in the values of these parameters because of the draining event in 2001. Izaguirre et al. (2012) highlight that Dissolved oxygen, and pH did not show inter-annual variability.

These changes in the Boeckella Lake system have consequences for the entire environment. After the 2001 event, for example, there were restrictions to the development of epilithic communities since the rocks sampled in Boeckella Lake were submerged (Pizarro, Allende e Bonaventura, 2004). The morphometric and depth changes observed in the previous item may explain changes in the limnology of Boeckella Lake. Lake morphometry,

Table 3
Quantitative geomorphic change detection results of Boeckella Lake between 1993-2013.

Parameters	1993	2013	% change
Area (m2)	67,454	55,902	-17
Volume (m3)	124,097	132,659	7
Maximum depth (m)	4	7.8	95
Mean depth (m)	1.84	3.66	99
Length (m)	445	429	-3.5
Maximum width (m)	230	202	-12
Mean width (m)	151.6	130.3	-14
Shoreline length (m)	1190	1176	-1
Shoreline development (m)	1.28	1.41	10

Source: Izaguirre et al. (1993) and Silva Busso (2013).

Figure 6. Decrease in water transparency of Boeckella Lake, between 1992-2007. Source: adapted from Izaguirre et al. (2012).

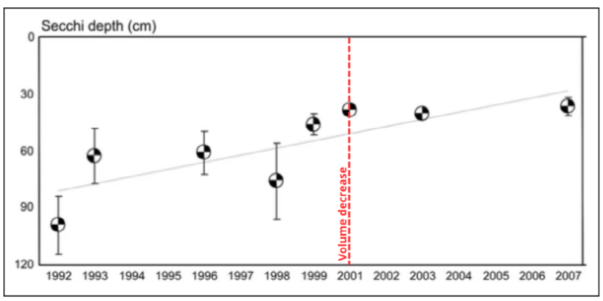
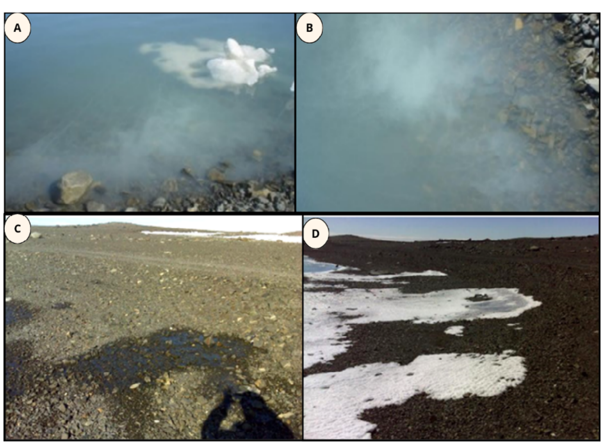


Figure 7. Fine material enters Boeckella Lake due to groundwater flow. A e B) Photograph from Summer 2008-09; C e D) The icing of the Boeckella Lake, Summer of 2012-13.



precisely depth, can change temperature regulation and biogeochemistry (Coulombe et al., 2022).

Izaguirre et al. (2012) indicate that the increase in phosphorus between 1991 and 2007 is linked to the past and present activity of penguins, the permafrost thaw, and the increase in glacial meltwater flowing into the lake. This runoff rate may be influencing water transparency over the years. Furthermore, there was a significant decrease in water transparency (Figure 6), which may be linked to the more significant development of phytoplankton (Izaguirre et al., 2012). However, the authors also indicate that the high runoff in the area may be contributing to the increased input of inorganic and organic matter into Boeckella Lake.

Scravagluieri (2021) carried out a geochemical study after the emptying of Boeckella Lake and concluded that it is related to the weathering of limestone rocks, sediments, or carbonatic cement. It also includes plagioclase alteration associated with the alteration of volcanic rocks. It is interpreted that there is evidence of cation exchange. In addition, it detects a chemical link that may be associated with the influence of sea spray and the effect of organic matter.

The hydrochemical classification of the waters shows a disparity in the input in Boeckella Lake (Scravagluieri, 2021). They result in sodium-calcium bicarbonate, in the Boeckella Lake system and the contribution of the icing, and subway contribution from the Buenos Aires Glacier. It detects another group of calcic and/or magnesic sulfate and/or chloride deposits in other parts of the Boeckella Lake, probably fed by surface water in contact with penguin guano.

Photographs taken on the southeast coast of Boeckella Lake show the entry of fine glacier material carried by the flow processes of supra permafrost groundwater (Figure 7a). In the other record, it is possible to distinguish the flow lines marked by the trajectory of fine material entering the lake waters (Figure 7b). Sudman et al. (2017) analyzing thermokarst erosion activity on streams of Taylor Valley (Antarctica) also point to the entry of fine material into the stream channel, and that this can cause changes to the biota of the channel and the lake.

The contribution of supra permafrost groundwater from the southeast coast from the front of the Buenos Aires Glacier has also been verified on the field. The austral summertime of 2012-13 shows the development of icing processes characteristic of groundwater discharge (Figure 7c; e; d).

In the Quickbird image from 2005, the penguin guano (Figure 8a) is dark red in the immediate area of Boeckella Lake. The blue tones in the NDWI of the Quickbird image indicate the presence of liquid water (Figure 8b). The lake is actively recharged by glacier meltwater and local snowmelt. In Scravaglieri (2021) a Landsat 7 satellite image is presented with the combination of bands: 7, 4, and 2. It allows highlighting and delineating bodies of water and identifying areas with high moisture content. Differences in hue were observed between the Boeckella basin and the Buenos Aires glacier. It was identified as glacial deposits with significant moisture, potentially indicating groundwater circulation through the basin's sediments, sourced from the glacial front.

It has been calculated by the authors that of the total meltwater supply from the Buenos Aires Glacier, 74% is superficial and 26% is underground supra permafrost. Of the total water inflow to Boeckella Lake, 43.5% is lost through the spillway and 12.2% through infiltration into the dam foundation. The flow value measured in a profile before crossing the bottom moraine includes a small additional contribution from lateral ablation or talik contributions (not exceeding 10%). However, it is observed that the flow value measured downstream at the outlet of the moraine is lower, leaving a negative balance of around 38% of the water (Table 4). The water enters the eroded base of the moraine. This factor is mentioned because it is the key that demonstrates the input of water that acts as an activator of the thermoerosion process of the moraine and the destruction of the penguin colony (Ermolin & Silva Busso, 2007).

Data have also been obtained from the study of the bottom sediments in the different depocenters that allow us to understand their functioning. A mean vertical hydraulic conductivity of 0.28m/d for the bottom sediments has been determined by carrying out a monitoring study of the lake's water levels. Based on this measurement and being fundamentally a bed that as a whole consists of thick sediments with abundant very poorly selected sandy silt matrix, a specific porosity close to 6% can be estimated using reference tables (Custodio & Llamas, 1983), a total porosity of 40%. These are common characteristics of an aquifer with little or low permeability. However, it is evident the loss of water through the lake depocenters collapses and their feeding into the talik.

From an environmental point of view, the main impact and landscape have been the destruction of part of the penguin colony located on the left part of Boeckella Lake. The penguin colony is undergoing an intense process

Figure 8. Boeckella Lake during the summer of January 8, 2005 (A) and NDWI image showing in light blue the transfer of melting water from the Buenos Aires Glacier to the proglacial zone (B).

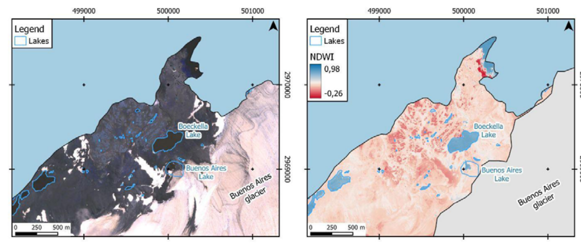


Table 4
Results of water flow along the Reservoir-Morena section of the Boeckella Stream

Input	Flow (m^3/s)
Contribution from Buenos Aires Glacier (superficial)	0.405
Contribution from Buenos Aires Glacier (suprapermafrost)	0.143
Landfill losses (crowning)	0.238
Foundation drainage losses	0.067
Runoff A Boeckella (Pre-moraine)	0.378
Infiltration in the moraine	0.144
Runoff A' Boeckella (Post-moraine)	0.233

Source: Ermolin & Silva Busso (2007).

of active thermoerosion, increasing the already notable retreat (Ermolin & Silva Busso, 2007). In addition, the appearance and intense development of cracks and surface subsidence have been observed in the field, which will result in a greater decline in the penguin nesting area in the next few years. On the other hand, Schaefer et al. (2017), suggest that guano deposition was associated with the trampling of birds contributing to increasing Thawing Degree Days and modifying active layer thermal regime and depth. This is a subject that requires further scientific research.

Conclusions

This study was dedicated to demonstrating environmental changes in Hope Bay, mainly in Boeckella Lake, over 67 years. The process of permafrost degradation caused by factors associated with the increase in average air temperature in the region and anthropogenic interference has accelerated thermoerosion processes. As a result, data from photographs and Remote Sensing show that the lake has suffered several episodes of sudden drainage since the 2000s. For a decade, attempts were made to solve these problems by building dams to ensure the maintenance of drinking water for the Argentine Esperanza station.

After 2010, when the dam broke, Boeckella Lake began to form small lakes in its interior. Bathymetric data confirms that Boeckella Lake has deepened in some depocenters, allowing the formation of small lakes. From the point of view of the consequences, the alteration of the lake's morphometric data implies changes in the sedimentological and limnological data, for example, a decrease in transparency due to the greater entry of fine sediments into the lake, which is detrimental to the lake's biota. Given this, it is recommended that environmental monitoring of Hope Bay, especially Boeckella Lake, continue to generate data to compare with that already presented and compiled in this research.

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Conflict of interest

The authors have no conflicts of interest to declare.

Declaration of Authorship

Carina Petsch: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing
Adrián Angel Silva Busso: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing.

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