frontiers | Frontiers in Water

TYPE Original Research
PUBLISHED 09 December 2024
DOI 10.3389/frwa.2024.1367889

Check for updates

OPEN ACCESS

EDITED BY
Nicole Schaffer,
Centro de Estudios Avanzados en Zonas Áridas (CEAZA), Chile

REVIEWED BY
Alfonso Fernandez,
University of Concepcion, Chile
Susanne Schmidt,
Heidelberg University, Germany

*CORRESPONDENCE
Ellie Fox
✉ ef425@exeter.ac.uk

RECEIVED 09 January 2024
ACCEPTED 30 September 2024
PUBLISHED 09 December 2024

CITATION
Fox E, Schwartz-Marin E, Rangecroft S, Palmer S and Harrison S (2024) 'Water resource' framing for the value and governance of glacier water availability in the semi-arid Chilean Andes.
Front. Water 6:1367889.
doi: 10.3389/frwa.2024.1367889

'Water resource' framing for the value and governance of glacier water availability in the semi-arid Chilean Andes

Ellie Fox[1]*, Ernesto Schwartz-Marin[2], Sally Rangecroft[1], Steven Palmer[1] and Stephan Harrison[3]

[1]Faculty of Environment, Science and Economy, University of Exeter, Streatham Campus, Exeter, Exeter, United Kingdom, [2]Faculty of Humanities, Arts and Social Sciences, University of Exeter, Streatham Campus, Exeter, Exeter, United Kingdom, [3]Faculty of Environment, Science and Economy, University of Exeter, Penryn Campus, Penryn, Cornwall, United Kingdom

Water scarcity associated with glacier retreat in mountainous regions is of growing concern worldwide, especially in arid regions, where precipitation is scarce or seasonal. Scientists and decision makers aim to respond to glacier driven water scarcity by improving glacier protection and developing water resource management strategies. Despite the increasingly prominent 'water resource' lens for understanding the changing mountain cryosphere, little research has investigated what this framing means for how different actors value, study, manage, and protect cryospheric water stores. This paper therefore presents a critical analysis of how we conceptualise the importance of glaciers. Specifically, this paper examines how environmental campaigns, scientific research, and policy interact to make glaciers into a water resource, and how this impacts glacier protection. Focusing on a case study of glacier management and protection in the Chilean Andes, the motivations and processes that made glaciers into a water resource in Chile are examined, and the impacts of this for glacier protection in a country where glaciers are exposed to threats from climate change and the mining industry are explored. This paper presents qualitative analysis of interviews conducted with experts in glacier science, policy, and environmental campaigning, and documents associated with managing glaciers as a water resource in Chile. The research shows how, in response to mining threats, glaciers were strategically framed as water resources by environmental campaigners to improve Chilean state protection. This framing was institutionalised within Chile's water resource management system through science and policy, resulting in some successful protection legislation. However, this resource framing has also integrated glaciers into a system which inherently limits their protection, because their protection is conditional on the shifting ways glaciers are valued for storing and releasing water to downstream communities and ecosystems. Here, we highlight processes that make glaciers into a resource, demonstrate that glaciological knowledge is not directly translated into policy, and importantly, show how managing glaciers as a resource may limit, or even undermine glacier protection efforts. As concern globally grows about water scarcity driven by glacial retreat, these findings are vital for the development of glacier protections and effective management of glacial water.

KEYWORDS

glaciers, water resource, semi-arid Andes, qualitative research, glacier protection, water scarcity, water security, water governance

1 Introduction

Climate warming is resulting in glacier loss worldwide (Hugonnet et al., 2021; Rounce et al., 2023), threatening water availability in downstream catchments (Brenning and Azócar, 2010; Kaser et al., 2010; Huss and Hock, 2018; Immerzeel et al., 2020). In some catchments, especially in the South American Andes, glaciers are also threatened by direct and indirect impacts from mining development (Brenning and Azócar, 2010; Cereceda-Balic et al., 2020; Hess et al., 2020; Barandun et al., 2022; Dame et al., 2023). Concerns about water scarcity driven by glacier loss have led to a growing body of research focussed on the water storage capacity of glaciers and contribution to water 'resources' at the global (Immerzeel et al., 2020; Gascoin, 2023), regional (Azócar and Brenning, 2010; Janke et al., 2017; Schaffer et al., 2019; Vishwakarma et al., 2022; Schaffer and MacDonell, 2022), and national (Rangecroft et al., 2015; Barcaza et al., 2017; Gironás and Fernández, 2021) scales.

However, whilst glaciers do store water, this does not mean they are inherently a water resource; a range of interacting processes are required to turn something (whether that is a forest, a mineral, or a glacier) into a useable 'resource', and manage it accordingly (Zimmermann, 1933; Scott, 1998; Bridge, 2009). Firstly, a function or service is identified. In this case, the function is glacier water as a frozen reserve, as a source of water for activities (e.g., domestic consumption, irrigation, or industry) (Bravo, 2017; Li, 2017; Clason et al., 2023), or ecosystem services (Cook et al., 2021). Mapping and quantification are used to estimate glacier extent and the stored water volume (Scott, 1998; Nicholson et al., 2009; Gascoin et al., 2011; Bravo, 2017; Li, 2017; Hess et al., 2020). Values (an indicator of the importance of the function provided) are assigned, such as the price of the water, and the relative importance of this water compared to the total volume of water from other sources in the catchment (Chan et al., 2016; Bravo, 2017; Carey et al., 2017; Li, 2017). Finally, specific policies and legislation are required to govern how the water is extracted, processed and distributed under water management systems (Iza and Rovere, 2006; Bellisario et al., 2013; Bravo, 2017). Understanding something as a resource prioritises its 'instrumental' value, usually meaning the provision of a particular material or service for human or natural systems (Chan et al., 2016). Framing glaciers as a 'resource' thus results in specific consequences for how they are studied, managed, and protected.

It is important to understand these consequences in more detail, given that researchers are increasingly seeking to conduct studies that more directly support the management of glaciers as water resources. For example, Schaffer and MacDonell (2022) classified glaciers in terms of vulnerability to climate change in order to facilitate and integrate their management under environmental impact legislation and glacier protection laws to support water resource management. Similarly, Ruiz-Pereira et al. (2023) examined the degree to which environmental impact legislation can protect the different instrumental and non-instrumental values of the mountain cryosphere, such as water supply and "scenic" landscape qualities, respectively. Brenning and Azócar (2010) classify the types of direct mining impacts on rock glaciers and contextualised this within existing legal frameworks.

Given the growing interest in protecting glaciers and managing them as water resources, this paper assesses how glaciological research and water governance interact to create an understanding of glaciers as a water resource, and how this influences the ways that glaciers are studied, managed, and protected. It examines these issues through a case study of glacier management and protection in the Chilean Dry Andes (Figure 1), a region where water scarcity from glacier loss has been compounded by a 14-year 'megadrought', and where the country's privatised water system has led to highly unequal levels of access to useable water (Budds, 2013; Muñoz et al., 2020; McCarthy et al., 2022). This paper builds upon existing work that explores how conflicts between mining and glaciers has influenced glacial water management in Latin America (Li, 2017; Barandiarán, 2018; Höglund Hellgren, 2022; Dame et al., 2023), to examine the influences of understanding glaciers as a water resource in terms of glacier protection and management in contemporary Chile.

Drawing upon data and contextual understanding developed through analysis of qualitative interviews, observations and document analysis, this paper first traces the emergence of the glacier water resource framing in the case study of Chile through a strategic narrative constructed by environmental campaigners. Second, it demonstrates how this water resource framing was integrated into Chilean legislation and government glacier science, by focusing on glaciers simply as frozen volumes of water. Lastly, the paper explains how this resource framing can be counter-productive for glacier protection in some cases, through making protections for glaciers conditional on the value placed on water provision. Overall, this paper argues that the effectiveness of glacier protection and water management can be restricted when the impacts of a resource framing of glaciers are not considered. This has important implications for how scientific research is used to support glacier protection strategies worldwide.

2 Background

A small body of research has examined the processes through which glaciers are made into a water resource, and how this facilitates and limits certain types of knowledge and management strategies to be used. This literature focuses on Andean glaciers in Chile (Li, 2017; Barandiarán, 2018; Dame et al., 2023), Argentina (Bottaro et al., 2014; Bottaro and Sola Álvarez, 2016; Höglund Hellgren, 2022), and Peru (Carey, 2010). This work (e.g., Bravo, 2017; Höglund Hellgren, 2022), mainly draws upon the understanding of resources outlined by Bridge (2009), who emphasises that, to be made into a resource, the social and technical utility of a material must be identified and assigned value. Making glaciers into a water resource makes them seem valuable (Li, 2017), visible to politicians (Barandiarán, 2018), and facilitates their management by the state (Höglund Hellgren, 2022).

In particular, this body of research emphasises how scientific knowledge and methods are key mechanisms by which glaciers are "made" into a water resource, as it is necessary to know the locations of glaciers in a catchment and how much water each contains (Carey, 2010; Bottaro et al., 2014; Höglund Hellgren, 2022). Glacier inventories are an important tool for this, as they can be used to estimate the equivalent water volume stored in each glacier, supporting state water resource management (Azócar and Brenning, 2010; Carey, 2010; Janke et al., 2017; Barandiarán, 2018). However, large uncertainties remain in these estimates due to the limited availability of ice thickness measurements for mountain glaciers (Farinotti et al., 2009, 2019; Millan et al., 2022) and rock glaciers (Jones et al., 2018, 2019; Schaffer et al., 2019). However, the privileged role of scientific data favours state and corporate (e.g., mining) actors to intervene in the management of glaciers whilst limiting local communities' engagement (Carey et al., 2016, 2017; Li, 2017). This can be, for example, due to favouring technical reports over local communities' knowledge of water quantity and quality; using scientific data to downplay the impact on glaciers of mining operations and their relative importance compared to climate impacts; or facilitating the management of water as a commodity which supports state and corporate interests (Li, 2017). Nonetheless, scientists can also help to support communities' interactions with state and corporate actors, by highlighting the importance of glaciers and the impacts of ice loss for local water availability (Barandiarán, 2018).

Often, these existing studies focus on an aspect of the processes by which glaciers are made into a resource, whether that is through inventories (Carey, 2010; Barandiarán, 2018), environmental impact assessments (Barandiarán, 2019), activist discourses (Bottaro et al., 2014; Bottaro and Sola Álvarez, 2016; Li, 2017), or legislation development (Höglund Hellgren, 2022). The research presented here contributes new insights by building upon this body of work through analysing the combined effect of these various political and material processes. Moreover, we take the research further by considering what the resource framing means for the creation of current and future policies, and consider how in practise this influences how effective they could be for glacier protection. These insights are clearly articulated for a scientific audience, who are often key actors involved in helping develop and implement glacier protection policies. Finally, we draw out wider implications that are relevant for glacier protection beyond Chile and Latin America, and can be useful in other glacierised regions.

To understand the ways glaciers are made into a water resource and the consequences of this for glacier protection, this paper uses a case study of the development of glacier protection and water resource management legislation in Chile, with a focus on threats to glaciers in the Chilean Dry Andes. This case study is of particular interest due to the hydrological importance of glaciers within the region in the face of continued climate warming, threats from mining, increasing demand for water, and developing regulatory changes toward glacier protection and integration within the Water Code in Chile.

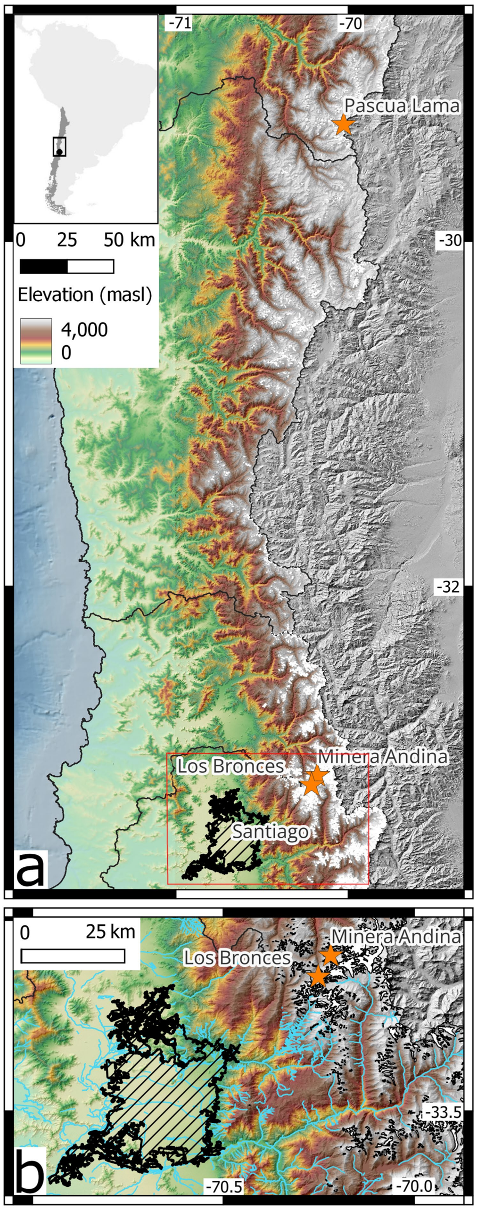

FIGURE 1
Glaciers and key mining areas in the Chilean Dry Andes. **(A)** The locations of mines where there have been key conflicts with glaciers starred: The Pascua Lama mine in the Atacama region (furthest north) and the Los Bronces and Minera Andina mines lie in the catchment above Santiago, the capital city (hatched area). **(B)** Glaciers, mines and waterways in the Región Metropolitana de Santiago (Santiago metropolitan region). The urban extent of Santiago is marked indicated by the hatched area. Elevation shown in colour between 0 and 4000 m a.s.l. with glaciers shown in white. Data sources: NASADEM: https://appeears.earthdatacloud.nasa.gov/, Inventario Público de Glaciares: https://dga.mop.gob.cl/Paginas/InventarioGlaciares.aspx, and the Chilean Waterways shapefile: https://data.humdata.org/dataset/hotosm_chl_waterways was downloaded from the Humanitarian Data Exchange.

2.1 Importance of glaciers and rock glaciers for water storage and provision in the Chilean Dry Andes

In the Chilean Dry Andes, melting glaciers and rock glaciers are important for water provision; only snow-melt contributes more to surface run-off (Favier et al., 2009; Azócar and Brenning, 2010; Ayala et al., 2016; Gironás and Fernández, 2021; Navarro et al., 2023). Glaciers and rock glaciers buffer snow-melt driven variability in river discharge (Masiokas et al., 2020; McCarthy et al., 2022). Glaciers contribute to streamflow over intra-and inter-annual timescales, continuing to store and release water after mountain snow has melted in the dry season (Gascoin et al., 2011; Ayala et al., 2016; Huss and Hock, 2018; Schaffer et al., 2019; Masiokas et al., 2020; Navarro et al., 2023) and over longer periods of reduced precipitation, namely the Chilean 'megadrought' since 2010 (McCarthy et al., 2022).

2.2 Climate and mining impacts on glaciers in the Chilean Dry Andes

Glaciers in the Dry Andes have reduced in thickness and areal extent in the past century (Masiokas et al., 2020), in line with trends in glacier retreat worldwide (Hugonnet et al., 2021). Recent studies estimate generally moderate glacier mass loss rates in the Desert (~17°30'-32° S) and Central (32-36° S) Andes during the past two decades (Braun et al., 2019; Dussaillant et al., 2019), although Braun et al. (2019) indicate mass balance was in fact slightly positive in the Desert Andes over the study period. Mass balance in the region has been more strongly negative since the onset of the Chilean megadrought (Dussaillant et al., 2019), and this pattern is seen in measurements of specific glaciers in the region (Masiokas et al., 2020). River discharge in glacierised catchments is estimated to have decreased by between 28 and 46% after 2009 (Dussaillant et al., 2019).

Glaciers in Chile are also impacted by mining activities, especially copper and gold mining (Brenning, 2008; Brenning and Azócar, 2010; Bellisario et al., 2013; Hess et al., 2020). Mining can directly impact glaciers and rock glaciers by the complete or partial removal of the glacier itself, deposition of mining waste on the glacier surface, and the construction of roads over rock glaciers (Brenning and Azócar, 2010). Mining can also indirectly affect glaciers when mineral dust from nearby mines is transported by wind and deposited on the glacier surface, lowering its albedo (Cereceda-Balic et al., 2020; Barandun et al., 2022). The Pascua-Lama gold mine in Chile's Atacama region at the border with Argentina has been at the heart of multiple social conflicts regarding the impact of mining on glaciers, especially regarding concerns about detrimental impacts on the quantity and quality of water resources after the project proposed to remove and re-locate glaciers in the early 2000s (Brenning, 2008; Pizarro et al., 2010; Taillant, 2015; Zang et al., 2018). Rock glaciers in the Metropolitan Region have been impacted by mining at the Los Bronces and Andina mines, operated by the companies Anglo American and Codelco, respectively (Brenning, 2008). This has taken place by direct removal, mining infrastructure development, and degradation (Brenning, 2008). Glaciers elsewhere have been impacted by mining at the Los Pelambres, Pimentón, División El Teniente, Catedral and Cerro Casale mines (Brenning and Azócar, 2010).

2.3 Regulatory context of glaciers in Chile

The 1981 Water Code (*Código de Aguas*) governs water use in Chile. Whilst water is defined as "national property for public use" under this legislation, the code makes the right to use water private (Bauer, 1998). Water use rights—measured as water volume in a given time period – are granted by the state water agency, the General Water Directorate (Dirección General de Aguas—DGA) and can be bought and sold as private property (Bauer, 1998). The Water Code reform (Law 21.435) modified Article 5 of the Code to include glaciers, which previously were not covered explicitly by the code. It now states that water "in all its states" (i.e., including ice) is national property for public use, and that "exploitation rights cannot be constituted for glaciers" (Law 21.435).

The management of industrial impacts to glaciers in Chile is governed by the General Bases of the Environment Law (Law 19.300), following modification in 2010 under Law 20.417. Industrial or infrastructural projects that may impact glaciers must enter the Environmental Impact Assessment System (SEIA) (Article 11). Decree 40 (2013) provides further specifics regarding the assessment of impacts to glaciers under the SEIA. It states that projects must enter the SEIA if: there may be an adverse effect on renewable resources (Article 6), specifically, the flow volume of a water resource, including the surface or volume of a glacier (Article 6g); or if the activity is located on or near to a glacier, if the glacier is within the area of influence of the project or activity (Article 8). Decree 40 also states that a baseline must be established from which the impacts of a project can be assessed, and it details the characteristics of a glacier which must be evaluated for this baseline, and data which can be used for this evaluation (Article 18e). The glacier characteristics to be considered include its thickness, surface area, and surface characteristics. The evidence to assess these can include ice cores, remote sensing imagery, and calculation of contributions to water flow.

2.4 Neoliberalism and valuing nature

The water and environmental governance context outlined in Section 2.3 is strongly influenced by the dominance of neoliberalism as a political project in Chile, initially during the dictatorship (1973–1990), and following the subsequent transition to democracy (Bauer, 1998; Camus and Hajek, 1998; Budds, 2013, 2020). Neoliberalism is characterised by processes that marketise, commodify, and privatise previously public goods (Harvey, 2005; Apostolopoulou et al., 2021) including water (Bakker, 2014) or glaciers (Carey, 2010). This combination of processes constitutes a popular approach to governing and protecting nature around the world (Bakker, 2010; Büscher et al., 2012; Apostolopoulou et al., 2021). Büscher et al. (2012, p. 4) describe neoliberal nature and neoliberal conservation, as "how nature is used in and through the expansion of capitalism [and] how nature is conserved in and through the expansion of capitalism," and is rooted more widely in rational environmental governance approaches developed in the late 20th century (Camus and Hajek, 1998; Dryzek, 2013). In other words, neoliberal approaches to environmental protection can be summarised as 'selling nature to save it' (McAfee, 1999, p. 133).

Neoliberal governance engenders a strongly instrumental or transactional way of valuing nature, where it is valued for the goods and services it can provide humans. Examples of neoliberal ways of valuing nature include seeing nature as a 'resource' or 'ecosystem service', both of which value what nature provides to humans. This understanding of value in turn brings about specific governance practises, such as the creation of markets to govern resources (Bakker, 2014), or payment for ecosystem services programmes (Cook et al., 2021; Dextre et al., 2022). Whilst not all instrumental approaches to valuing and governing nature are neoliberal (Kull et al., 2015), neoliberalism is the dominant contemporary influence on how water, and by extension – as we argue in this paper – glaciers, are valued and governed in Chile.

2.5 Manuscript aims

The Chilean Dry Andes are an important site to examine the opportunities and limitations of a 'water resource' framing for the study, valuation, and management of glacier water for the following four reasons: (i) glaciers in the region form a crucial element of the hydrological system; (ii) the ongoing threats to glaciers from climate change and mining; (iii) the developing regulatory changes toward glacier protection and integration within the Water Code (1981); and (iv) Chile's ongoing neoliberal environmental and water governance approach. The aim of this paper is thus to examine the processes by which glaciers were turned into a resource in Chile and the impacts of doing so for the effectiveness of glacier protection and water management. Given the wider concerns about glacier retreat and water scarcity worldwide, important insights can be gained from the complex Chilean case.

3 Methods

To analyse the emergence of the water resource framing of glaciers in Chile and its impacts for glacier protection and resource management, we conducted qualitative research, analysing complementary primary and secondary datasets. The primary data were interviews and field observations conducted during a period of fieldwork in Chile between March and April 2022 (Table 1). The secondary data are relevant legislative and scientific documents accessed online (Table 2).

3.1 Data collection

In total, twenty semi-structured interviews were conducted with glaciologists, environmental organisation members (activists and NGOs), and members of the Chilean government office the General Water Directorate (DGA), within the Ministry of Public Works (Table 1). The interviews were conducted in Spanish. Interviewees were identified by consulting scientific and grey literature, media resources (online news and social media), and existing academic networks. Further interviewees were identified via snowballing from contacts provided by initial interviewees and attending events organised by key stakeholders. Stakeholders were predominantly scientists, policymakers, and members of socio-environmental organisations (NGOs and citizen groups). Within these networks, interviewees were selected due to their expertise related to glaciers, water resources, and environmental activism around glaciers, water and mining in the region.

Some of the interviews conducted were 'elite-expert' interviews. Interviewees were both elites, that is, they occupy powerful positions within their organisations or wider society, and experts, that is, they hold a high level of specialised knowledge and/or experience (Van Audenhove and Donders, 2019). The elite-expert status has important methodological implications. 'Elite-experts' are naturally a smaller population, due to, for example, being the head of their organisation, or the leader in their knowledge field. Insights are developed through an interview process that engages with their privileged knowledge, experience, and access to powerful actors and spaces in society. Due to this unavoidable small population size, the aim is not to generate a sample representative of a wider population as this does not often exist. Instead, sampling is informed by appropriateness rather than quantity, and the reliability comes from critical and reflexive engagement with their highly specialised accounts (Higgins, 2019).

Informal interviews and observations were conducted during the fieldwork period in central and northern Chile. This included conversations with various actors, but also attendance at five scientific and activist events or workshops. These observations were recorded as fieldnotes over the course of fieldwork and used as rich qualitative data for analysis.

To complement the interview data, documents were collected and analysed from a range of sources, totalling 13 documents (Table 2). Two key strands of documents were collected: (1) legislation (Laws, Codes, and Resolutions passed by state organisations), and (2) NGO publications focused on the threats to and the protection of glacial water resources in Chile and the southern Andes. Additionally,

TABLE 1 Table of interviews conducted.

Sector	Role description	Interview code
Tourism	Hostel owner; mountaineer	A1
Environmental activism	Environmental activist (local area protection)	A2
Citizen Science	Citizen science professional	A3
Citizen Science	Citizen science professional	A4
Glaciology; Citizen science	Glaciologist	A5
Agricultural community	Community land managers	A6
Environmental activism	Citizen Science volunteer; environmental activist	A7
Environmental activism	Environmental activists (local area protection); Indigenous Diaguitas	A8
Environmental activism	Environmental organisation (local area protection); members	A9
Municipality environment workers	Municipality within the Limarí Province	A10
Environmental NGO	Glacier NGO spokesperson	A11
Environmental activism	Environmental organisation (local river basin protection) spokesperson	A12
Environmental activism	Environmental organisation (local river basin protection) founder	A13
United Nations Economic Commission for Latin America and the Caribbean	Management Level (Environmental Division)	A14
Science	Glaciologist	A15
Science	Glaciologist who has supported work within the Ministry of Public Works	A16
Environmental NGO	Chile Sustentable (Management level)	A17
Science	Glaciologist who has contributed to work within the Ministry of Public Works	A18
Science	Glaciologist (University)	A19
Science	Ministry of Public Works	A20

TABLE 2 Table of documents analysed.

Type	Name (English)	Organisation	Year
Legislation	Water Code	Ministry of Justice	1981
	Law 19.300/1994 General Bases of the Environment	General Secretariat of the Presidency	1994
	DGA Resolution 1851	General Water Directorate	2009
	Law 20.417/2010 Create the Environment Ministry, Evaluation Service and Superintendence.	Environment Ministry	2010
	Decree 40/2013 Regulation of the Environmental Impact Assessment System.	Environment Ministry	2013
	Law 21.435/2022 Reform of the Water Code	Ministry of Public Works	2022
	Legislation of Glaciers in Chile	Parliamentary Technical Advisory	2022
	DGA (Exempt) Resolution 3,824	Parliamentary Technical Advisory	2022
NGO Literature	Chilean Glaciers: Strategic Freshwater Reserves for Society, Ecosystems and the Economy	Chile Sustentable	2006
	Andean Glaciers – Water Resources and Climate Change: Challenges for Climate Justice in the Southern Cone	Chile Sustentable	2011
	Chile's Glaciers: The Mining Lobby and the Torturous Road to Protect them	Chile Sustentable	2020
Other	Legal Aspects of Glacier Conservation	Unión Mundial Para la Naturaleza	2006
	National Glacier Strategy	Ministry of Public Works; Centro de Estudios Científicos	2009
	Methodology of the Public Glacier Inventory	Glacier and Snow Unit: General Water Directorate	2022

documents related to measuring and protecting glaciers were also analysed. Document review is particularly important to support triangulation and critical interrogation of elite and expert accounts (Natow, 2020).

3.2 Data analysis

Interview transcripts and documents were analysed using qualitative research methodologies and software. Firstly, data from interviews and documents were incorporated into the qualitative analysis software NVivo, which allows holistic analysis of the full body of data (Tables 1, 2), an established approach in qualitative research (Silverman, 2022). The data analysis was guided by principles in thematic analysis and qualitative coding (Saldaña, 2021). This means that a 'set of analytical categories' was devised through analysing the content, narratives and underlying assumptions in the textual interview and document data (Hammersley and Atkinson, 2019, p. 172). The categories and themes were developed inductively, meaning that they were not determined prior to beginning the analysis of interview and documentary data. This enabled the most relevant themes to emerge through analysis (rather than reproducing preconceived ideas of what is important) and centred the voices of those who gave interviews, rather than the preconceived ideas of the researchers, in line with the widely used method of inductive code development (Boyatzis, 1998).

Qualitative data reported in this paper (e.g., quotes from interviews documented in Section 4) have been translated from Spanish into English by the authors (see Supplementary material for all original versions). The interview quotes presented here are selected as they are illustrative of key findings of the analysis, however, the full body of interviews presented in Table 1 were analysed as part of this research.

Fieldnotes provided rich contextual information that supported and was incorporated into the analysis, providing valuable understandings of the motivations that underpinned the actions and insights of the interviewees, as well as providing insight into what interviewees excluded from their narratives (Madden, 2017). Additionally, fieldnotes supported the document analysis, providing insight into the sociopolitical conditions under which the documents were produced. Taken together, this supported further 'situational analysis' (Clarke, 2011) into the complex relations between science, activism and legislation that are vital to understanding the themes of glacier water resource management and protection in this paper.

4 Results

4.1 A strategic narrative of glaciers as a water resource in Chile

The narrative of glaciers as a water resource originated from Chilean environmental campaigners in the early 2000s. The Canadian company Barrick Gold began development of the Pascua Lama mine on the Chile-Argentina border, following initial explorations during the 1990s. The proposed site of the mine overlapped with three glaciers, Toro 1, Toro 2 and Esperanza in Chile's Huasco Valley (Dame et al., 2023). Barrick proposed to 'move' the glaciers by removing the ice in order to develop the mine, which would destroy them. On both sides of the border, many local communities were concerned about the impact this would have on water availability and quality, and on culturally important glaciers (French et al., 2015; Taillant, 2015; Dame et al., 2023). National and international NGOs including Greenpeace and Chile Sustentable, also campaigned against the mine's impact on glaciers.

Framing glaciers as a water resource was an important strategy for campaigners in aiming to develop state-led protections for glaciers in Chile, as the conflict revealed the lack of legal protection for glaciers. For an NGO involved in the conflict, the motivation for framing glaciers as a strategic resource were twofold: (1) to create a "*common sense*" understanding about the importance of glaciers for the general public, and (2) to bring about greater legal protection and regulation of mining activities in glacierised areas, by framing glaciers scientifically, in a way which mattered to government and the house of deputies (A17). A17 Explained:

> "*We were already with the issue of less water, etc, etc, with La Niña for various years without the El Niño phenomenon […] there was La Niña and climate change, so a decline in water … these are* strategic freshwater reserves, *so you need to find* vehicles to incorporate this into the consciousness of society, *and so, for this we created this concept." [emphasis added]*
>
> *"[We needed] scientists who know the theme exactly. And well*, to package it in a way that the political sector can understand it, *or digest it, or assimilate it*, and right away transform and defend [glaciers]." *[emphasis added]*

A17's account explains that the framing and popularisation of the concept glaciers as a freshwater resource in Chile was a strategic choice from environmental campaigners who engaged with politicians, rather than a framing which simply emerged unplanned. Firstly, the logic was that highlighting glaciers' water provision function would resonate with concerns held in wider Chilean society about water scarcity in the context of climate change and the El Niño and La Niña cycles. Campaigners recognised that framing glaciers in terms of provision would provide a compelling and easy to understand way of understanding their importance, and so prioritised this framing in public-facing campaign messaging. Secondly, the logic was to take a scientifically described function (glaciers storing volumes of water), and then communicate this to politicians so they would understand that glaciers were important and therefore needed to be protected. Campaigners were therefore using science to help leverage regulatory change to protect glaciers. This approach is in line with the 'deficit' model of science communication, which assumes that, when a problem is described scientifically and in an effective way, this science can be translated directly and linearly into policy, thus ensuring logical policymaking (Wynne, 1992; Bucchi and Trench, 2014). However, this is rarely the case, and widespread critiques of this deficit model are discussed further in section 5.2 in the case of Chilean glaciers.

4.2 Institutionalising glaciers as water and as a resource in Chile

The strategic framing of glaciers as a water resource by environmental NGOs succeeded in bringing about greater regulation of glaciers by the Chilean state in the late 2000s. Figure 2 shows a chronology of the state-led changes and attempted changes that institutionalised glaciers in environmental and water legislations, and within state organisations. Crucially, it was glaciers' water provision function which was addressed directly in these regulations, strategies, and by state agencies, to a far greater extent than other values and functions glaciers provide. This is in line with the narrative outlined in section 4.1, where glaciers were seen as important specifically due to their water storage and provision function.

That glaciers were understood by the Chilean state as water resources is evident in many of the changes outlined in Figure 2. For example, Decree 40 (2013, p. 21–22) and Law 19.300 (1994, p. 11) both categorise glaciers as "natural renewable resources," and Decree 40 also labels them "hydric resources for intervention or exploitation." Resolution 1851 (p1, emphasis added) even directly uses the same language as Chile Sustentable's reports, stating "glaciers constitute *strategic reserves of fresh water*, have scenic value and are part of humanity's environmental heritage." Whilst this text also acknowledges glaciers' cultural values, it still places water resources first, and mirrors the clear focus on them as a resource in other legislation. The Glacier and Snow Unit itself was housed within the DGA, which is the government body charged with managing Chile's water resources. This reflects how glaciers were understood as water resources by the Chilean state. As one employee at the DGA (A16) explained:

> "*We're housed in the Water Directorate, so, the principal objective of the Directorate, the General Water Directorate, is to evaluate water resources. So, when we talk about glaciers, what they're most interested in knowing is as a freshwater reserve. Not about environmental themes, or very little, and if not - more about how much water is available for use lower in the basin."*

This quote demonstrates that the activities of the Glacier and Snow Unit were primarily concerned with studying and managing glaciers as a water resource, i.e., mapping and monitoring of glaciers in order to study changes in the availability of water downstream. Once glaciers were understood by the state as a resource, not only were they viewed as important, but they had to be integrated into the water rights system outlined in the Water Code (1981), where the state must calculate the water available in the basin so it can create sellable water extraction 'rights'. Whilst the updated Law 21.435 clarifies "*exploitation rights cannot be constituted for glaciers*" (p. 1) themselves, calculating the amount of water equivalent that glaciers store and contribute to the downstream catchment nonetheless incorporates them into the neoliberal system of water rights in place in Chile. Thus, whilst certain laws state the importance of other "*environmental themes*" (A16) such as their "*scenic value and are part of humanity's environmental heritage*" (Resolution 1851), these in practice are overlooked within the state's glacier monitoring activities which centre on quantifying glacial water stores with the aim of integrating them into Chile's current water resource management system. Crucially, the system is focused on managing the continued extractive use of Chile's water resources, rather than *protecting* glaciers, as was the initial aim of institutionalising glaciers as a water resource.

The main implication of the framing and legislating of glaciers as a water resource was that glaciers were studied, monitored, and legislated as if they were simply "*a block of ice, of freshwater*" (A16). This means that glaciers were understood and managed by the state as

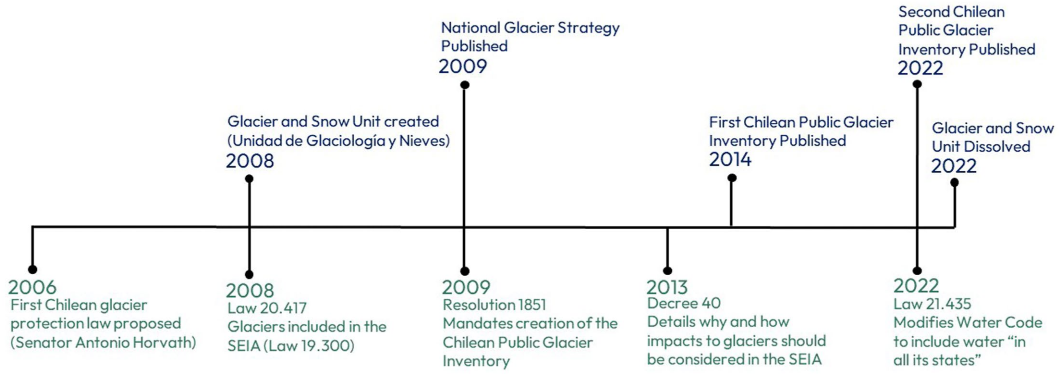

FIGURE 2
Development of state glacier protections in Chile (2006-2022). Legal protections are shown in green, and key developments from the Glacier and Snow Unit (UGN) are shown in blue.

water that is held in a particular location only by virtue of it being in a frozen state, rather than as a glacier, which is a complex and dynamic system with internal ice flow that loses and gains mass and shapes the landscape. This is evident through three processes: the use of scientific inventories to calculate glacier contribution to water sources in each basin, the use of hydrological concepts in proposed glacier legislation, and the dissolution of the Glacier and Snow unit.

A glacier inventory is a spatial database and map that records the characteristics of each glacier in an area, providing a synoptic view at (in the Chilean case) the national scale. Chile's first Public Glacier Inventory was published in 2014 and updated in 2022 (DGA, 2022). The inventory details the basins and sub-basin each glacier is located in. It records several glacier hypsometry variables including surface area, altitude (minimum, maximum, and average), and average thickness (Resolution 1851). These are all inventory variables which support the quantification of glaciers as water resources (Carey, 2010). The updated Public Glacier Inventory (2022) addresses this more explicitly, including a variable for *"estimated water equivalent of the glacier"* (DGA, 2022, p. 8). This supports the DGA's obligation as a government body:

> *"To calculate how much water there is available in the river, to whom it can be sold, and how much can be used." (A16)*

Glaciology within the Chilean state was therefore conducted in a way to create knowledge about glaciers as frozen volumes of water, and support the calculation of the total water volume available in a catchment, supporting the creation and selling of water rights.

Glaciers were also treated scientifically as water through the use of concepts from hydrology in legislation. A glaciologist (A18) involved in developing a recent version of the proposed Glacier Protection Law explained that to scientifically determine the area around a glacier that needed to be protected under the proposed law, they used a concept from hydrology (rather than glaciology):

> *"so we made a definition of basin, that basically - if you have a glacier here, take the edge, the divide - from the head above the glacier, and in the lower part, up to where a possible water droplet […] is going to end up in front of the glacier, and this is the glacial basin, you have to use a hydrological concept, while a glacier is solid, but that doesn't matter"*

The protection discussed here referred to delimiting zones around a glacier where different degrees of human activity (such as mining) would be permitted or limited. This quote clearly demonstrates where hydrology and hydrological concepts were used to determine the extent of legal protection in glacierised regions: the zone receiving water from a glacier was deemed worthy of protection. Hydrology was used as the scientific basis for management and protection of glaciers, rather than glaciology, emphasising the treatment of glaciers as water.

Finally, the dissolution of the Glacier and Snow Unit in 2022 (Resolution 3,824) shows that glaciers were understood as almost indistinguishable from water. The DGA's management practices were guided by the view that since glaciers and water were similar and interchangeable, there was no longer a need for an independent glaciology unit, because the hydrology division was capable of carrying out the functions and science to manage glacier water resources. This was confirmed by interviewees from both inside and outside the DGA, who explained how since glaciers were water reserves, the state considered that they could be managed more effectively by the DGA directly, rather than the need for a special glaciology unit. For example, A17 explained:

> *"And now this government has just dissolved the Glaciology and Snow Unit. And merged it with water resources. Well, of course we wrote a letter saying how can they even think instead of moving forward to go backwards. [They said] "no, it's that we have few resources, and water is the same truthfully" but it's that hydrology is not the same as glaciology, it's not the same monitoring, it's not the same logic, the same work, do you follow? But well, there you have it."*

So, whilst framing glaciers as synonymous with water was what initially enabled the Unit to be created, by conveying glaciers' importance to policymakers "*in a way that the political sector can understand*" (A17), it also established grounds for its dissolution too, as glacier protection and management became streamlined into water resource management. It did this by creating the scientific and regulatory structures that facilitate the DGA focusing its glacier-related activities in terms of *"how much water is available for use lower in the basin" (A16).*

Overall, the strategic narrative of glaciers successfully brought about regulatory changes for their protection and management. But, regulation was oriented specifically to protecting glaciers' water provision function rather than their other characteristics. In order to achieve this, and as a result of the legislation in place, glaciers were increasingly understood by the state simply as volumes of frozen water, rather than glaciers. This facilitated the integration of glaciers into Chile's water rights system, where water use rights can be privately bought and sold. The strategic framing of glaciers as water resources thus influenced both the scientific study of glaciers and the associated legislative management and treatment of them. This overall represents a shift from glacier protection-oriented legislation and science, to water resource management. Section 4.3 will show that the extent to which the water resource framing was ingrained may have impeded state-led protections for glaciers in Chile.

4.3 Limits to glacier protection

Despite the integration of glaciers into environmental management regulations, and the wider recognition of the importance of glaciers for water storage, the effectiveness of these outcomes for glacier protection is limited. Valuing glaciers for their water provision function (Section 4.1) and understanding them as volumes of frozen water (Section 4.2) limits the effectiveness of glacier protection because protection consequently became *conditional* on the extent to which their water provision function is valued.

The conditional nature of glacier protection in Chilean legislation is evident in the text of Resolution 1851 (p. 1), which states that one of the conditions that "*explains and justifies [glaciers'] preservation and/or conservation*" is that they are "*a strategic freshwater reserve*." The justification for glacier protection is conditional on their storage and release of water. Not only this, but it is conditional on the extent to which this function is valuable, or "*strategic*." Protecting glaciers because they are strategic freshwater reserves therefore can limit protection to only *some* glaciers, but not those seen as less strategically important. This is exemplified by A17's description of how, during the development of initial glacier protection regulations, (then-)President Michelle Bachelet's response to requests to protect glaciers because they were strategic water resources was:

> *"To use a twisted form, they wanted it to be that only the glaciers that were located in some areas, with a certain size to constitute water reserves, were protected."*

This shows the limitations of justifying glacier protection based on the logic of them being "*strategic*" water resources. The value of glacial water resources is lower if a glacier is small so stores only limited water. The value is also lower if it is located in a catchment where water supply from other sources such as precipitation is greater, or water demand from agriculture or industry is lower. Creating the conditions where glaciers were seen as worthy of protection due to a specific resource value (water provision) necessarily limits the glaciers to which protection is extended.

In summary, seeing glaciers as a resource of frozen water, and valuing them instrumentally for their water storage and provision functions, weakens justifications for glacier protection by making their protection conditional on the value assigned to that resource, which is constantly shifting, in line with changing water supplies and demands.

5 Discussion

This paper has investigated the motivations and processes by which glaciers were made into a water resource in Chile and demonstrated how this influences glacier protection. Through analysis of elite interviews and public documents produced by regulators, scientists, and NGOs, it has assessed the relationship between activism, science, and policy for the protection and management of glaciers in Chile. It has demonstrated that, whilst turning glaciers into a resource conveyed their importance to the public and decisionmakers, and integrated glaciers into Chile's environmental protection and water management policies, the protections created are limited in their efficacy. The insights this case study provides into how glaciology is used to inform glacier protection and water resource management, have wider relevance for the ongoing development of glacier policies internationally, and the use of scientific methods and knowledge to support these efforts.

5.1 Glaciers are not inherently a water resource, they become a resource through a specific set of processes

This paper has shown that the narrative of glaciers as a water resource in Chile emerged in response to a specific conflict between mining, glaciers, and communities in the early 2000s. They were not widely considered to be a resource in the country prior to this. Glaciers became a resource by being valued for their water storage and provision, were mapped to quantify their water storage, and integrated into state water resource management regulations. Taken together, this meant that glaciers were understood by the Chilean state as frozen volumes of water. This is supported by existing research which shows that glaciers and ice are *made into* a resource (Bravo, 2017; Höglund Hellgren, 2022) and that tools such as inventories and legislation are vital to achieving this, especially through making glaciers visible to states as water bodies (Carey, 2010; Li, 2017; Barandiarán, 2018). This challenges the often taken for granted idea that glaciers are inherently a resource, and is important because understanding glaciers as a resource commonly entails an 'instrumental' approach to valuing them (Chan et al., 2016). Valuing glaciers instrumentally has important implications for how science is translated into policy (Section 5.2) and the effectiveness of glacier protection (Section 5.3). This is an important insight given the growing body of research and policy aimed at managing of glaciers as a water resource and protecting glaciers (United Nations General Assembly, 2022; Schoolmeester et al., 2018; Schaffer et al., 2019; Immerzeel et al., 2020; ICIMOD, 2023).

5.2 Glaciology is not directly translated into policy

This paper has shown that the initial motivation for making glaciers into a water resource in Chile was to make them valued more by the wider public and the state, with the aim of bringing about policy change for glacier protection (Section 4.1). Underlying this motivation is the expectation that the relationship between science and policy is linear, rational, and neutral, in line with the deficit model of the relationship between science and policy (Wynne, 1992). In other words, the expectation is that once decision makers understand glaciers' importance for water storage and release—as identified and monitored by glaciologists and hydrologists—and once the issue becomes salient to decision makers through the public also being aware of glaciers' importance, then legislation will be made that directly and effectively responds to the importance of protecting glaciers.

However, this paper has shown that in practice the relationship between science and policy is more complex, and that glaciology does not directly translate into policy. Instead, scientists and policymakers make a series of decisions about which characteristics of a glacier are deemed as important and which variables should be measured to make this importance clear to decision makers. Policies are then made that reflect this *selective, value-laden, and context specific* view of glaciers. The Chilean case examined here, for example, shows that integration of glaciers into existing legislation, as well as the work of the Glacier and Snow Unit, was influenced by the neoliberal water rights system in Chile and the role of science in supporting this (Bauer, 1998; Budds, 2009). The relationship between glaciology and policymaking is all the more complex for rock glaciers, where greater uncertainties remain regarding their extent and water storage capacity than compared with bare-ice or debris-covered glaciers (Jones et al., 2018, 2019; Schaffer et al., 2019; Schaffer and MacDonell, 2022), and rock glaciers themselves can be a mountain hazard (Marcer et al., 2021; Vivero et al., 2021). Moreover, work by Carey (2010) and Anacona et al. (2018) highlights that the focus on glaciers as a water resource limits scientific understanding and policy capacity to manage other important aspects of glaciers, such as their influence on mountain hazards. This understanding about the selective and non-linear way that science is made into policy is in line with existing literature that critiques the deficit model of science and policymaking (Wynne, 1992; Jasanoff, 2004).

5.3 Instrumental values are insufficient for glacier protection

Finally, this paper has shown that valuing glaciers instrumentally (Chan et al., 2016), which is inherent in understanding them as a resource (Bravo, 2017; Barandiarán, 2018), weakens glacier protections. This is because glacier protection justified instrumentally means protection is *conditional* on the extent to which the function(s) glaciers carry out are valued. This offers weak protection because values can change over time and between different places (Höglund Hellgren, 2022). In the Chilean case, where glacier protection legislation was justified based on their water resource function (Resolution 1851, 2009), protection is conditional on the extent to which this water provision function is valued. For glacier protection to be effective and longstanding, it must therefore be justified by more than instrumental values.

Making glaciers into a water resource also weakens their protection because they could potentially be substituted for water from other sources. This is because the understanding of glaciers as a resource is underpinned by the view that the water that glaciers contain, and functions that they provide are fungible: they can be replaced by other sources and resources. For example, water could be provided from desalination, which is growing in prominence in Chile (Fieldnotes – 29th March 2023), or water could be stored in and released by a reservoir. Whilst neither a desalination plant nor a reservoir would provide the same range of ecosystem services as a glacier (Cook et al., 2021; Clason et al., 2023), the transactional principle that each function or material is exchangeable remains. The processes and tools outlined in Section 4.2., especially the Public Glacier Inventory, are particularly important to making glaciers into fungible resources. This is because they enable the water content of glaciers to be measured, integrated into the state's understanding of basin-scale water availability, and integrated into Chile's system of creating and selling private water extraction rights. If glaciers are simply frozen water, this water can be obtained from other sources, then valuing and protecting glaciers solely for the water they provide represents weak protection.

Thus, the findings presented here imply that recognising a wider range of the services glaciers provide—such as 'cultural, 'regulating', and 'supporting' services (Clason et al., 2023, p. 2)—may be insufficient to justify and guarantee glacier protection. This is because this perspective still values a specific 'service' or function that a glacier offers, any of which could be substituted for a function provided from elsewhere (Chan et al., 2016). This is not to say that these functions are not valuable. Moreover, such research is a crucial step in recognising the plurality of ways glaciers are important, which are often overlooked in scientific research (Carey et al., 2016, 2020). Rather, this paper calls for caution in research and policies that, by taking a resource - or service-based approach, could inadvertently build weaknesses into the protection they hope to create, and instead call for more politically engaged and justice-oriented research to develop how glaciers are valued and protected. For example, emphasising that a glacier is 'incommensurable', meaning it cannot be replaced (Li, 2017; Section 5.4) challenges this view.

5.4 Beyond a resource framing?

What could alternative ways to knowing, valuing, and protecting glaciers look like? One option could be to use existing management strategies such as an ecosystem services approaches (Cook et al., 2021) in a way that is underpinned by value systems *other than* neoliberal governance (Kull et al., 2015). Another could be to use other protection strategies such as the creation of protected areas, which are focused more on protection and *less on management* compared to the Water Code (1981) and General Bases of the Environment Law (Law 19.300). This has been trialled for example with the recent creation of the Parque Nacional de Glaciares de Santiago (Santiago Glacier National Park, Chile) (CONAF, 2023) in response to the citizen-led Queremos Parque campaign.

Beyond different management strategies, it is also essential to engage with other ways of *valuing* glaciers. Li (2017, p. 116), for example, details where environmental campaigners draw attention to the "incommensurability" of glaciers, arguing that they cannot be replaced or compensated for by the benefits a mine would bring. This therefore directly challenges the fungibility (Section 5.3) that is inherent in an instrumental, resource-centric view of glaciers that weakens their protection. Valuing glaciers relationally, for example, would mean they become valuable through being part of a web of interrelationships between multiple human and non-human actors (Chan et al., 2016); therefore, they cannot be as easily substituted, as their value hinges not through a singular function, but is a product of the complex relations between many actors and objects.

In turn, valuing glaciers in non-instrumental ways could go some way to decentre scientific knowledge as the only, or most authoritative, way of deciding glacier management and protection, and the preference for market based-solutions for glacier protection (Section 2). This could thus create space for a wider range of actors, especially from local communities to become involved in developing alternative ways of valuing and protecting glaciers, beyond a resource framing.

Alternative ways of valuing and protecting glaciers could be integrated into legislation, by including glaciers in legislation other than the Water Code (1981), as glaciers are important for more than just water. Furthermore, if glaciers are considered to be non-fungible, and relationally important, then the protection offered by the General Bases of the Environment Law (Law 19.300)—where some impacts to glaciers are permissible provided that they are not "significant"—is likely insufficient to protect something so valuable.

It is beyond the scope of this paper to offer an in-depth examination of these alternatives, but these are initial suggestions of both protection strategies and approaches to value that we hope will open up further debate and discussion, and we suggest that exploration of these is an important direction for research in the future.

6 Conclusion

This study represented a novel contribution to academic literature through its consideration of the implications of the water resource framing for glacier protection, and examining how the glacier protection strategies that emerged in response to the Pascua Lama conflict continue to affect glacier protection in Chile in light of contemporary conflicts (e.g., the Los Bronces Integrado mining expansion project). The key findings from this research are as follows: glaciers are not inherently a water resource, they become a resource through a specific set of processes (Section 5.1); findings from glaciological research are not directly translated into policy, instead, the uptake of scientific knowledge into glacier management and protection policies is the product of specific values and social, cultural, and economic context (Section 5.2); and instrumental ways of valuing glaciers are insufficient to guarantee their protection (Section 5.3). In light of this, the study has also suggested ways to protect glaciers and the water they provide beyond resource-and service-based approaches (Section 5.4). This research is especially important given increasing interest in glaciers' water resource value, in Chile, the Andes, and in other key glacierised 'water tower' mountain ranges (Huss and Hock, 2018; Immerzeel et al., 2020; Drenkhan et al., 2022; ICIMOD, 2023). Indeed, the UN has announced an International year of Glaciers' Preservation in 2025, which focuses on glaciers as a water resource and developing glacier protection.

This study was limited in two key ways which future research should address. First, through the study's focus on the relationship between science and state glacier protection instruments, the paper focused on national elites, overlooking the role of local activists in the Pascua Lama conflict, although local activist perspectives from the Metropolitan and Coquimbo Regions are included here. The perspectives of mining companies were also not represented in this paper as they did not wish to partake in an interview. Local and mining perspectives have however previously been examined by Dame et al. (2023), Li (2017), Barandiarán (2019), and Höglund Hellgren (2022), and should be the focus of future research in this area in order to incorporate all voices and communities. Second, this study's in-depth analysis has focused on Chile specifically. Previous research has demonstrated how glaciers were made into water resources to facilitate their incorporation into environmental regulations in Peru (Carey, 2010) and to develop a national glacier protection law in Argentina (Bottaro and Sola Álvarez, 2016; Carey et al., 2022; Höglund Hellgren, 2022). So, future research should take a comparative approach to study the relationship between resource framing of glaciers and the protection of them in different countries.

Focus on glaciers' utility as water reserves is rapidly expanding, as concerns for climate-driven water scarcity grow, glacier melt accelerates, and calls increase for research that is of direct relevance to issues that societies are facing. The results of this paper thus have important implications for the growing field of scientific research that supports the development and implementation of regulations for glacier water resource management and glacier protection. As this research has demonstrated, scientists should recognise the non-neutral ways in which their research can be used, and that its uptake into policy and water management is a complex process. The most effective way to protect glaciers may not be through facilitating their incorporation into existing state environmental regulation. Despite the positive intentions behind this approach of using scientific research to inform glacier policy and protection, if conducted uncritically, it risks reinforcing processes that threaten glaciers by supporting instrumental views of glaciers' value and integrating them into environmental management systems that ultimately are not focused on glacier protection. Scientists, governments, and civil society must instead consider how to address the vital issue of glacier water provision in a way that embraces the plurality of ways glaciers are known and valued, and in a way that recognises the complex and unequal processes through which science is deployed in glacier protection and resource management. Such an approach is essential to respond more effectively to the range of threats glaciers face.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Faculty of Environment, Science and Economy (FESE) Geography Ethics Committee—University of Exeter. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

EF: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Visualization, Writing – original draft, Writing – review & editing. ES-M: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – review & editing. SR: Conceptualization, Supervision, Writing – review & editing. SP: Supervision, Conceptualization, Writing – review & editing. SH: Supervision, Conceptualization, Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This research was funded via a doctoral training grant awarded as part of the UKRI AI Centre for Doctoral Training in Environmental Intelligence (UKRI grant number EP/S022074/1). The fieldwork was supported by a Royal Geographical Society Postgraduate Research Award, supported by the HR Mill Trust Fund (grant reference number PRA 38.23). For the purpose of open access, the author has applied a 'Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising.

Acknowledgments

First and foremost, we would like to thank all who took part in this research through formal and informal interviews, as well as those who allowed us to accompany them for ethnographic observations in their places of work and homes. Sharing your experiences, expertise, and time, was invaluable. We would like to thank partners in Chile for supporting our communication and work with research participants, in particular, CEAZA. An earlier version of this paper was presented at the Resources, Consumption and Global Crises XXI Summer School (University of Leipzig), and we are grateful to the organisers and participants for their feedback and discussions of the research in this stage. Thank you to the reviewers and editors at Frontiers in Water for their timely reviews, their very helpful feedback, and their support in the article publication process. Thank you to Dr. Sylvia Hayes (University of Exeter) for providing feedback on the manuscript drafts. We are grateful to the University of Exeter and Frontiers for their agreement that covers the article processing fees. This research has been supported by a generous EPSRC environmental Intelligence Studentship, and the HR Mill Postgraduate research grant from the Royal Geographical Society.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2024.1367889/full#supplementary-material

References

Anacona, P. I., Kinney, J., Schaefer, M., Harrison, S., Wilson, R., Segovia, A., et al. (2018). Glacier protection laws: potential conflicts in managing glacial hazards and adapting to climate change. *Ambio* 47, 835–845. doi: 10.1007/S13280-018-1043-X/FIGURES/4

Apostolopoulou, E., Chatzimentor, A., Maestre-Andrés, S., Requena-i-Mora, M., Pizarro, A., and Bormpoudakis, D. (2021). Reviewing 15 years of research on neoliberal conservation: towards a decolonial, interdisciplinary, intersectional and community-engaged research agenda. *Geoforum* 124, 236–256. doi: 10.1016/j.geoforum.2021.05.006

Ayala, A., Pellicciotti, F., Mac Donell, S., McPhee, J., Vivero, S., Campos, C., et al. (2016). Modelling the hydrological response of debris-free and debris-covered glaciers to present climatic conditions in the semiarid Andes of Central Chile. *Hydrol. Process.* 30, 4036–4058. doi: 10.1002/hyp.10971

Azócar, G. F., and Brenning, A. (2010). Hydrological and geomorphological significance of rock glaciers in the dry Andes, Chile (27°–33°S). *Permafr. Periglac. Process.* 21, 42–53. doi: 10.1002/PPP.669

Bakker, K. (2010). The limits of 'neoliberal natures': debating green neoliberalism. *Prog. Hum. Geogr.* 34, 715–735. doi: 10.1177/0309132510376849

Bakker, K. (2014). The business of water: market environmentalism in the water sector. *Annu. Rev. Environ. Resour.* 39, 469–494. doi: 10.1146/annurev-environ-070312-132730

Barandiarán, J. (2018). "Conflict at the Pascua Lama gold mine" in Science and environment in Chile (Cambridge, Massachusetts: MIT Press), 127–155.

Barandiarán, J. (2019). Documenting rubble to shift baselines: environmental assessments and damaged glaciers in Chile: environment and planning E. *Nat. Space* 3, 58–75. doi: 10.1177/2514848619873317

Barandun, M., Bravo, C., Grobety, B., Jenk, T., Fang, L., Naegeli, K., et al. (2022). Anthropogenic influence on surface changes at the Olivares glaciers; Central Chile. *Sci. Total Environ.* 833:155068. doi: 10.1016/j.scitotenv.2022.155068

Barcaza, G., Nussbaumer, S. U., Tapia, G., Valdés, J., García, J. L., Videla, Y., et al. (2017). Glacier inventory and recent glacier variations in the Andes of Chile, South America. *Ann. Glaciol.* 58, 166–180. doi: 10.1017/AOG.2017.28

Bauer, C. J. (1998). Against the current: Privatization, water markers, and the state in Chile. London: Kluwer Academic Publishers.

Bellisario, A., Ferrando, F., and Janke, J. (2013). Recursos hídricos en Chile: La relación crítica entre los glaciares y la minería para el manejo sustentable del agua. *Investigaciones Geográficas* 46, 3–24. doi: 10.5354/0719-5370.2013.30288

Bottaro, L., Latta, A., and Sola, M. (2014). La politización del agua en los conflictos por la megaminería: Discursos y resistencias en Chile y Argentina. *Euro. Rev. Latin Amer. Carib. Stud.* 97, 97–115. doi: 10.18352/erlacs.9798

Bottaro, L., and Sola Álvarez, M. (2016). La politisation des glaciers en Argentine: une analyse de l'application de la loi nationale sur les glaciers (2010). *Cahiers des Amériques latines* 82, 113–128. doi: 10.4000/cal.4353

Boyatzis, R.E. (1998). Transforming qualitative information: Thematic analysis and code development. California: SAGE Publications, Inc.

Braun, M. H., Malz, P., Sommer, C., Farías-Barahona, D., Sauter, T., Casassa, G., et al. (2019). Constraining glacier elevation and mass changes in South America. *Nat. Clim. Chang.* 9, 130–136. doi: 10.1038/s41558-018-0375-7

Bravo, M. (2017). "A Cryopolitics to reclaim our frozen material states" in Cryopolitics: Frozen life in a melting world. eds. J. Radin and E. Kowal (Cambridge: MIT Press), 27–57.

Brenning, A. (2008). "The impact of mining on rock glaciers and glaciers. Examples from Central Chile" in Darkening peaks: Glacier retreat, science, and society. eds. B. Orlove, E. Wiegandt and B. H. Luckman (London: University of California Press), 196–205.

Brenning, A., and Azócar, G. F. (2010). Minería y glaciares rocosos: impactos ambientales, antecedentes políticos y legales, y perspectivas futuras. *Revista de Geografía Norte Grande* 47, 143–158. doi: 10.4067/S0718-34022010000300008

Bridge, G. (2009). Material worlds: natural resources, resource geography and the material economy. *Geogr. Compass*. Environment and planning D: Society and Space. 3, 1217–1244. doi: 10.1111/J.1749-8198.2009.00233.X

Bucchi, M., and Trench, B. (2014). Routledge handbook of public communication of science and technology. *2nd* Edn. Oxford: Routledge.

Budds, J. (2009). Contested H2O: science, policy and politics in water resources management in Chile. *Geoforum* 40, 418–430. doi: 10.1016/J.GEOFORUM.2008.12.008

Budds, J. (2013). Water, power, and the production of neoliberalism in Chile, 31. 301–318.

Budds, J. (2020). Securing the market: water security and the internal contradictions of Chile's water code. *Geoforum* 113, 165–175. doi: 10.1016/J.GEOFORUM.2018.09.027

Büscher, B., Sullivan, S., Neves, K., Igoe, J., and Brockington, D. (2012). Towards a synthesized critique of neoliberal biodiversity conservation. *Capital. Nat. Social.* 23, 4–30. doi: 10.1080/10455752.2012.674149

Camus, P., and Hajek, E. R. (1998). Historia ambiental de Chile. Andros Impresores. Santiago: Departamento de Ecología, Facultad de Ciencias Biológicas, Pontificia Universidad Católica de Chile.

Carey, M. (2010). In the shadow of melting glaciers: Climate change and Andean society: Oxford, Oxford University Press.

Carey, M., Barton, J., and Flanzer, S. (2022). "Glacier protection campaigns" in Ice humanities. eds. K. Dodds and S. Sörlin (Manchester: Manchester university press), 89–109.

Carey, M., Jackson, M., Antonello, A., and Rushing, J. (2016). Glaciers, gender, and science: a feminist glaciology framework for global environmental change research. *Prog. Hum. Geogr.* 40, 770–793. doi: 10.1177/0309132515623368

Carey, M., Molden, O. C., Rasmussen, M. B., Jackson, M., Nolin, A. W., and Mark, B. G. (2017). Impacts of glacier recession and declining meltwater on mountain societies. *Ann. Am. Assoc. Geogr.* 107, 350–359. doi: 10.1080/24694452.2016.1243039

Carey, M., Moulton, H., Barton, J., Craig, D., Provant, Z., Shoop, C., et al. (2020). Justicia glaciar en Los Andes y más allá. *Ambiente, Comportamiento y Sociedad* 3, 28–38. doi: 10.51343/racs.v3i2.584

Cereceda-Balic, F., Ruggeri, M.F., and Vidal, V. (2020). Glacier retreat differences in Chilean Central Andes and their relation with anthropogenic black carbon pollution. IEEE Latin American GRSS & ISPRS Remote Sensing Conference (LAGIRS), 434–440.

Chan, K. M. A., Balvanera, P., Benessaiah, K., Chapman, M., Díaz, S., Gómez-Baggethun, E., et al. (2016). Why protect nature? Rethinking values and the environment. *Proc. Natl. Acad. Sci. USA* 113, 1462–1465. doi: 10.1073/pnas.1525002113

Clarke, A. (2011). "Doing situational maps and analysis" in Situational analysis (Thousand Oaks, CA: SAGE Publications, Inc.) doi: 10.4135/9781412985833

Clason, C., Rangecroft, S., Owens, P. N., Łokas, E., Baccolo, G., Selmes, N., et al. (2023). Contribution of glaciers to water, energy and food security in mountain regions: current perspectives and future priorities. *Ann. Glaciol.* 63, 73–78. doi: 10.1017/AOG.2023.14

CONAF, (2023). Available at: [https://www.conaf.cl/parque_nacionales/parque-nacional-glaciares-de-santiago/#:~:text=El Parque Nacional Glaciares de,Cordillera%2C en la Región Metropolitana](https://www.conaf.cl/parque_nacionales/parque-nacional-glaciares-de-santiago/#:~:text=El%20Parque%20Nacional%20Glaciares%20de,Cordillera%2C%20en%20la%20Regi%C3%B3n%20Metropolitana).

Cook, D., Malinauskaite, L., Davíðsdóttir, B., and Ögmundardóttir, H. (2021). Co-production processes underpinning the ecosystem services of glaciers and adaptive management in the era of climate change. *Ecosyst. Serv.* 50:101342. doi: 10.1016/J.ECOSER.2021.101342

Dame, J., Nüsser, M., Schmidt, S., and Zang, C. (2023). Socio-hydrological dynamics and water conflicts in the upper Huasco valley, Chile. *Front. Water* 5:1100977. doi: 10.3389/frwa.2023.1100977

Dextre, R. M., Eschenhagen, M. L., Camacho Hernández, M., Rangecroft, S., Clason, C., Couldrick, L., et al. (2022). Payment for ecosystem services in Peru: assessing the socio-ecological dimension of water services in the upper Santa River basin. *Ecosyst. Serv.* 56:101454. doi: 10.1016/J.ECOSER.2022.101454

DGA (2022). Metodología del Inventario Público de Glaciares, SDT n°447. Chile: Santiago.

Drenkhan, F., Buytaert, W., Mackay, J. D., Barrand, N. E., Hannah, D. M., and Huggel, C. (2022). Looking beyond glaciers to understand mountain water security. *Nat. Sustain.* 6, 130–138. doi: 10.1038/s41893-022-00996-4

Dryzek, J. (2013). The politics of the earth environmental discourses. *3rd* Edn. Oxford: Oxford University Press.

Dussaillant, I., Berthier, E., Brun, F., Masiokas, M., Hugonnet, R., Favier, V., et al. (2019). Two decades of glacier mass loss along the Andes. *Nat. Geosci.* 12, 802–808. doi: 10.1038/s41561-019-0432-5

Farinotti, D., Huss, M., Bauder, A., Funk, M., and Truffer, M. (2009). A method to estimate the ice volume and ice-thickness distribution of alpine glaciers. *J. Glaciol.* 55, 422–430. doi: 10.3189/002214309788816759

Farinotti, D., Huss, M., Fürst, J. J., Landmann, J., Machguth, H., Maussion, F., et al. (2019). A consensus estimate for the ice thickness distribution of all glaciers on earth. *Nat. Geosci.* 12, 168–173. doi: 10.1038/s41561-019-0300-3

Favier, V., Falvey, M., Rabatel, A., Praderio, E., and López, D. (2009). Interpreting discrepancies between discharge and precipitation in high-altitude area of Chile's Norte Chico region (26–32°S). *Water Resour. Res.* 45:2424. doi: 10.1029/2008WR006802

French, A., Barandiarán, J., and Rampini, C. (2015). "Contextualizing conflict: vital waters and competing values in glaciated environments" in The High-Mountain cryosphere: Environmental changes and human risks. eds. C. Huggel, M. Carey, J. Clague and A. Kääb (Cambridge: Cambridge University Press), 315–336.

Gascoin, S. (2023). A call for an accurate presentation of glaciers as water resources. *Wiley Interdiscip. Rev.* 11:e1705. doi: 10.1002/WAT2.1705

Gascoin, S., Kinnard, C., Ponce, R., Lhermitte, S., Macdonell, S., and Rabatel, A. (2011). Glacier contribution to streamflow in two headwaters of the Huasco River, dry Andes of Chile. *Cryosphere* 5, 1099–1113. doi: 10.5194/tc-5-1099-2011

Gironás, J., and Fernández, B. (2021). Water resources of Chile. Tokyo: Springer.

Hammersley, M., and Atkinson, P. (2019). Ethnography: Principles in practice. *4th* Edn. London: Taylor and Francis Group.

Harvey, D. (2005). A brief history of neoliberalism. Oxford: Oxford University Press.

Hess, K., Schmidt, S., Nüsser, M., Zang, C., and Dame, J. (2020). Glacier changes in the semi-arid Huasco valley, Chile, between 1986 and 2016. *Geosciences* 10, 1–19. doi: 10.3390/geosciences10110429

Higgins, K. (2019). "Qualitative interviewing of elites" in SAGE research methods: Foundations. eds. P. Atkinson, A. Cernat, J. Sakshaug and R. Williams (London: SAGE publishers).

Höglund Hellgren, J. (2022). "Negotiating governable objects: glaciers in Argentina" in Ice humanities (Manchester: Manchester University Press), 228–249.

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., et al. (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature* 592, 726–731. doi: 10.1038/s41586-021-03436-z

Huss, M., and Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nat. Clim. Chang.* 8, 135–140. doi: 10.1038/s41558-017-0049-x

ICIMOD (2023). Water, ice, society, and ecosystems in the Hindu Kush Himalaya: An outlook. Kathmandu, Nepal: International Centre for Integrated Mountain Development (ICIMOD).

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., et al. (2020). Importance and vulnerability of the world's water towers. *Nature* 577, 364–369. doi: 10.1038/s41586-019-1822-y

Iza, A., and Rovere, M.B. (2006). Aspectos jurídicos de la conservación de los glaciares. Available at: <https://portals.iucn.org/library/sites/library/files/documents/EPLP-061.pdf>. (Accessed May 23, 2023).

Janke, J. R., Ng, S., and Bellisario, A. (2017). An inventory and estimate of water stored in firn fields, glaciers, debris-covered glaciers, and rock glaciers in the Aconcagua River basin, Chile. *Geomorphology* 296, 142–152. doi: 10.1016/J.GEOMORPH.2017.09.002

Jasanoff, S. (2004) in states of knowledge: The co-production of science and the social order. ed. S. Jasanoff (New York: Routledge).

Jones, D. B., Harrison, S., Anderson, K., and Betts, R. A. (2018). Mountain rock glaciers contain globally significant water stores. *Sci. Rep.* 8:2834. doi: 10.1038/s41598-018-21244-w

Jones, D. B., Harrison, S., Anderson, K., and Whalley, W. B. (2019). Rock glaciers and mountain hydrology: a review. *Earth Sci. Rev.* 193, 66–90. doi: 10.1016/J.EARSCIREV.2019.04.001

Kaser, G., Großhauser, M., and Marzeion, B. (2010). Contribution potential of glaciers to water availability in different climate regimes. *Proc. Natl. Acad. Sci. USA* 107, 20223–20227. doi: 10.1073/pnas.1008162107

Kull, C. A., Arnauld de Sartre, X., and Castro-Larrañaga, M. (2015). The political ecology of ecosystem services. *Geoforum* 61, 122–134. doi: 10.1016/j.geoforum.2015.03.004

Li, F. (2017). Moving glaciers: remaking nature and mineral extraction in Chile. *Lat. Am. Perspect.* 45, 102–119. doi: 10.1177/0094582X17713757

Madden, R. (2017). Being ethnographic: a guide to the theory and practice of ethnography. *SAGE Publications Ltd.* doi: 10.4135/9781529716689

Marcer, M., Cicoira, A., Cusicanqui, D., Bodin, X., Echelard, T., Obregon, R., et al. (2021). Rock glaciers throughout the French Alps accelerated and destabilised since 1990 as air temperatures increased. *Commun. Earth Enviro.* 2, 1–11. doi: 10.1038/s43247-021-00150-6

Masiokas, M. H., Rabatel, A., Rivera, A., Ruiz, L., Pitte, P., Ceballos, J. L., et al. (2020). A review of the current state and recent changes of the Andean cryosphere. *Front. Earth Sci.* 8:99. doi: 10.3389/feart.2020.00099

McAfee, K. (1999). Selling nature to save it? Biodiver. Green Develop.. 17:, 133–154. doi:10.1068/D170133.

McCarthy, M., Meier, F., Fatichi, S., Stocker, B. D., Shaw, T. E., and Miles, E. (2022). Glacier contributions to river discharge during the current Chilean megadrought. *Earth's Future* 10, 1–15. doi: 10.1029/2022EF002852

Millan, R., Mouginot, J., Rabatel, A., and Morlighem, M. (2022). Ice velocity and thickness of the world's glaciers. *Nat. Geosci.* 15, 124–129. doi: 10.1038/s41561-021-00885-z

Muñoz, A. A., Klock-Barría, K., Alvarez-Garreton, C., Aguilera-Betti, I., González-Reyes, Á., and Lastra, J. A. (2020). Water crisis in Petorca Basin, Chile: the combined effects of a mega-drought and water management. *Water* 12:648. doi: 10.3390/W12030648

Natow, R. S. (2020). The use of triangulation in qualitative studies employing elite interviews. *Qual. Res.* 20, 160–173. doi: 10.1177/1468794119830077

Navarro, G., MacDonell, S., and Valois, R. (2023). A conceptual hydrological model of semiarid Andean headwater systems in Chile. *Prog. Phys. Geogr.* 47, 668–686. doi: 10.1177/03091333221147649

Nicholson, L., Marín, J., Lopez, D., Rabatel, A., Bown, F., and Rivera, A. (2009). Glacier inventory of the upper Huasco valley, Norte Chico, Chile: glacier characteristics, glacier change and comparison with Central Chile. *Ann. Glaciol.*, [online] 50: 50, 111–118. doi: 10.3189/172756410790595787

Pizarro, J., Vergara, P. M., Rodríguez, J. A., and Valenzuela, A. M. (2010). Heavy metals in northern Chilean rivers: spatial variation and temporal trends. *J. Hazard. Mater.* 181, 747–754. doi: 10.1016/J.JHAZMAT.2010.05.076

Rangecroft, S., Harrison, S., and Anderson, K. (2015). Rock glaciers as water Stores in the Bolivian Andes: an assessment of their hydrological importance. *Arct. Antarct. Alp. Res.* 47, 89–98. doi: 10.1657/AAAR0014-029

Rounce, D. R., Hock, R., Maussion, F., Hugonnet, R., Kochtitzky, W., Huss, M., et al. (2023). Global glacier change in the 21st century: every increase in temperature matters. *Science* 379, 78–83. doi: 10.1126/science.abo1324

Ruiz-Pereira, S., Peterson, V. A., and Liaudat, D. T. (2023). Mountain cryosphere landscapes in South America: value and protection. *Conservation* 3, 232–246. doi: 10.3390/CONSERVATION3010017

Saldaña, J. (2021). The coding manual for qualitative researchers. Sage. London: Sage.

Schaffer, N., and MacDonell, S. (2022). Brief communication: a framework to classify glaciers for water resource evaluation and management in the southern Andes. *Cryosphere* 16, 1779–1791. doi: 10.5194/tc-16-1779-2022

Schaffer, N., MacDonell, S., Réveillet, M., Yáñez, E., and Valois, R. (2019). Rock glaciers as a water resource in a changing climate in the semiarid Chilean Andes. *Reg. Environ. Chang.* 19, 1263–1279. doi: 10.1007/S10113-018-01459-3

Schoolmeester, T., Johansen, K.S., Alfthan, B., Baker, E., Hesping, M., and Verbist, K. (2018). The Andean glacier and water atlas - the impact of glacier retreat on water resources. Paris: United Nations Educational, Scientific and Cultural Organization (UNESCO).

Scott, J. (1998). Seeing like a state: How certain schemes to improve the human condition have failed. New Haven and London: Yale University Press.

Silverman, D. (2022). Doing qualitative research. *6th* Edn. London: Sage.

Taillant, J. D. (2015). Glaciers: The politics of ice. USA: Oxford University Press.

United Nations General Assembly. (2022) International Year of Glaciers' Preservation, 2025. Seventy-seventh session. Second Committee. Agenda item 18. A/C.2/77/L.17/Rev.1. Available at: https://digitallibrary.un.org/record/3994297?ln=en&v=pdf

Van Audenhove, L., and Donders, K. (2019). Talking to people III: Expert interviews and elite interviews. In: M Puppis, BulckH Van den, K Donders and AudenhoveL Van, The Palgrave Handbook of Methods for Media Policy Research. Palgrave Macmillan. Cham

Vishwakarma, B. D., Ramsankaran, R., Azam, M. F., Bolch, T., Mandal, A., Srivastava, S., et al. (2022). Challenges in understanding the variability of the cryosphere in the Himalaya and its impact on regional water resources. *Front. Water* 4:909246. doi: 10.3389/frwa.2022.909246

Vivero, S., Bodin, X., Farías-Barahona, D., MacDonell, S., Schaffer, N., Robson, B. A., et al. (2021). Combination of aerial, satellite, and UAV photogrammetry for quantifying rock glacier kinematics in the dry Andes of Chile (30°S) since the 1950s. *Front. Remote Sens.* 2:784015. doi: 10.3389/frsen.2021.784015

Wynne, B. (1992). Misunderstood misunderstanding: social identities and public uptake of science. *Public Underst. Sci.* 1, 281–304. doi: 10.1088/0963-6625/1/3/004

Zang, C., Dame, J., and Nüsser, M. (2018). Hydrochemical and environmental isotope analysis of groundwater and surface water in a dry mountain region in northern Chile. *Environ. Monit. Assess.* 190, 1–19. doi: 10.1007/s10661-018-6664-9

Zimmermann, E. (1933). World resources and industries. New Yorkn: Harper.