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Brief communication: A framework to classify glaciers for water resource evaluation and management in the Southern Andes

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Abstract Numerous drafts of a Glacier Protection Law (GPL) have been proposed in Chile since 2006, but the law has not been approved due to a lack of consensus partially due to inadequate definitions of landform types. Neither the approved Argentinian GPL or Chilean draft explicitly identify or define different glacier types nor are their distinct hydrological roles considered. We propose three glacier categories that group landforms based on their sensitivity to environmental changes, which is strongly associated with their hydrological role, and review both national inventories to facilitate the evaluation and/or management of water resources.

1 Introduction

Glacier protection laws (GPL) that aim to preserve glaciers as strategic water reserves, for their role in sustaining biodiversity, as a source of scientific information, and sustainable tourism were initially drafted in Chile and Argentina in response to the concerns raised during the Pascua-Lama mining project (Herrera Perez and Segovia, 2019). These GPL prohibit activities such as the destruction, movement, dispersion of contaminants, and industrial activity on glaciers. In 2006 the first draft of a GPL was proposed in Chile, which also led to the formal inclusion of glaciers in Environmental Impact Assessments (EIA). Since then, several iterations of the GPL have been proposed, but it has not been approved due to a lack of consensus associated primarily with inadequate definitions of landform types and the use of specific terms (e.g. periglacial areas, permafrost; Sendado de Chile, 2021) and issues associated with competing interests. Neighbouring Argentina implemented the world's first glacier protection law in 2010 (Congreso de Argentina, 2010), but legal issues following its implementation have hindered its application and impacted the Chilean GPL process. Different glacier types are not explicitly defined or mentioned in either GPL nor are their distinct hydrological roles considered. These definitions and which glacier types are covered by the law could be inferred from the associated national inventories, but the lack of clarity potentially leaves these GPL open to diverse interpretations.

One of the main drivers for glacier protection in Chile is the hydrological importance of glaciers, particularly in the water-scarce semiarid region (~27°-35° S). Here, the mean annual glacier contribution to streamflow varies from ~3-44 % for most years and can be > 65 % during dry periods (Ayala et al., 2016; Schaffer et al., 2019). Rock glaciers are well insulated from

https://doi.org/10.5194/tc-2021-167
Preprint. Discussion started: 29 June 2021

the environment by a thick debris cover and while their contribution per unit area to annual streamflow is less than other glacier types, they may provide an important contribution at the end of summer (e.g. > 10 %; Schaffer et al., 2019; Schrott, 1996) and also act as longer-term reservoirs (Jones et al., 2018; Schaffer et al., 2019). Traditionally glaciers have been grouped into three categories: debris-free glaciers, debris-covered glaciers and rock glaciers. However, for practical applications, these categories are often unhelpful and difficult to implement. The distinction between debris-free and debris-covered glaciers is relatively well defined in the literature, however in practice, often a more precise dividing line is needed. Furthermore, the division between a debris-covered glacier and a rock glacier is often ambiguous. Interpretations range from a glacier that has a very thin debris cover and some ice exposed to a thick enough debris cover to insulate the ice below (~> 3 m; Janke et al., 2015). The difference between these interpretations is an important consideration since the former option potentially encompasses landforms that can readily exchange energy with the atmosphere and are therefore sensitive to environmental changes such as temperature, while the latter option only includes landforms that are insensitive to such changes (Bonnaventure and Lamoureux, 2013; Janke et al., 2015). To ensure an appropriate level of protection, monitoring program or management strategy is applied, it is necessary to evaluate where these dividing lines should be and why.

Therefore, the overarching goal of this paper is to propose an ideal dividing line between each glacier category that groups landforms based on their sensitivity to environmental changes, which is strongly associated with their hydrological role. We undertake a thorough evaluation of the Chilean and Argentinian national inventories to determine if they align with the proposed groups and suggestions are provided to modify these to facilitate the evaluation and/or management of water resources associated with the cryosphere in the semiarid Andes in the first instance.

2 Defining debris-covered glaciers and rock glaciers

In general, a glacier is defined as a perennial mass of ice (or perennially frozen ice and debris in the case of rock glaciers) showing evidence of past or present flow detectable in the landscape by the presence of front and lateral margins (Cogley et al., 2011; Delaloye and Echelard, 2020). A debris-covered glacier has a debris layer that varies in thickness with ice exposed at the surface due to the discontinuity of debris cover or thermokarst depressions among other features (Janke et al., 2015; Monnier and Kinnard, 2017). Thermokarst is a terrain-type characterized by irregular surfaces including hollows such as ice collapse features. Some debris-covered glacier definitions require that most of the ablation zone be covered by debris (Barcaza et al., 2017; Cogley et al., 2011). Other definitions specify that the glacier may be fully covered (Delaloye and Echelard, 2020). Rock glaciers are defined as having a debris cover that is thicker than debris-covered glaciers and a discernible frontal slope that is generally convex (Delaloye and Echelard, 2020; Janke et al., 2015; Monnier and Kinnard, 2017). Some definitions specify that the debris cover must be thick and continuous enough so that in general no ice is exposed at the surface (typically several meters thick; Janke et al., 2015; Monnier and Kinnard, 2017; Schaffer et al., 2019). Other definitions specify that debris must cover the entire glacier or differentiate debris-covered glaciers from rock glaciers by the presence of visible ice on the

https://doi.org/10.5194/tc-2021-167
Preprint. Discussion started: 29 June 2021

former, implying that no ice is visible on rock glaciers (Barcaza et al., 2017). These definitions for debris-covered and rock glaciers have been sourced from publications on the Andes, to ensure the definitions are locally relevant.

In summary, debris-covered glaciers are defined in the literature as being partially to fully covered by debris. Rock glaciers are defined as generally having no ice visible at the surface. While these definitions are suitable for scientific investigation, they are not sufficient for water resource management as they do not effectively differentiate between debris-covered landforms that are sensitive to environmental changes compared to those that are not.

3 Glacier classification for water resource management

If the categories of glacier types are to differentiate between landforms that have different sensitivities to changes in the environment (e.g. temperature and precipitation) and different hydrological roles, then debris cover thickness must also be considered, since this has an important influence on glacier melt patterns (Ayala et al., 2016; Burger et al., 2019). Measurements from glaciers in the Himalaya, Canada, and Sweden have shown that a very thin debris cover (<~2 cm) results in higher melt rates than debris-free glaciers due to a reduction in albedo and that under thicker debris cover melt rates progressively decline (Nicholson and Benn, 2006; Östrem, 1959). Heat continues to be transferred through the debris, resulting in surface melt, even when the debris cover is more than a couple of decimetres thick. For example, on Pirámide Glacier (33.57° S, 69.89° W) the debris thickness varies from 0.2 to 1 m and in areas where it is 0.2 to 0.3 m there is sufficient heat transmitted through the debris layer to result in ice melting at the surface throughout the day (Ferrando, 2012). We therefore suggest that a thickness of > ~0.3 m could be used as a threshold between glacier classifications since persistent surface melt appears to be impeded above this threshold at Pirámide Glacier (Ayala et al., 2016; Ferrando, 2012) and the influence of debris cover thickness on the melt rate is reduced considerably if the thickness is more than a couple of decimeters (Nicholson and Benn, 2006). According to Janke et al. (2015) a fully covered glacier (about 95 % of the surface) often has a debris thickness of 0.5 – 3.0 m. Therefore, having > 95 % of the surface covered by debris could be used as a criterion to approximately identify this threshold using satellite imagery.

A thickness ~>3 m is required to thermally insulate the ice within the landform and preserve the ice structure (Janke et al., 2015). For example, at Llano de las Liebres rock glacier (30.25° S, 69.95° W), seasonal variations in temperature affected ground temperatures between 2 to 5 m depth (Janke et al., 2015). When the debris cover is thick enough to preserve the ice structure, the surface is relatively smooth since the degradation of ice leading to the formation of thermokarst depressions is no longer actively occurring (Janke et al., 2015).

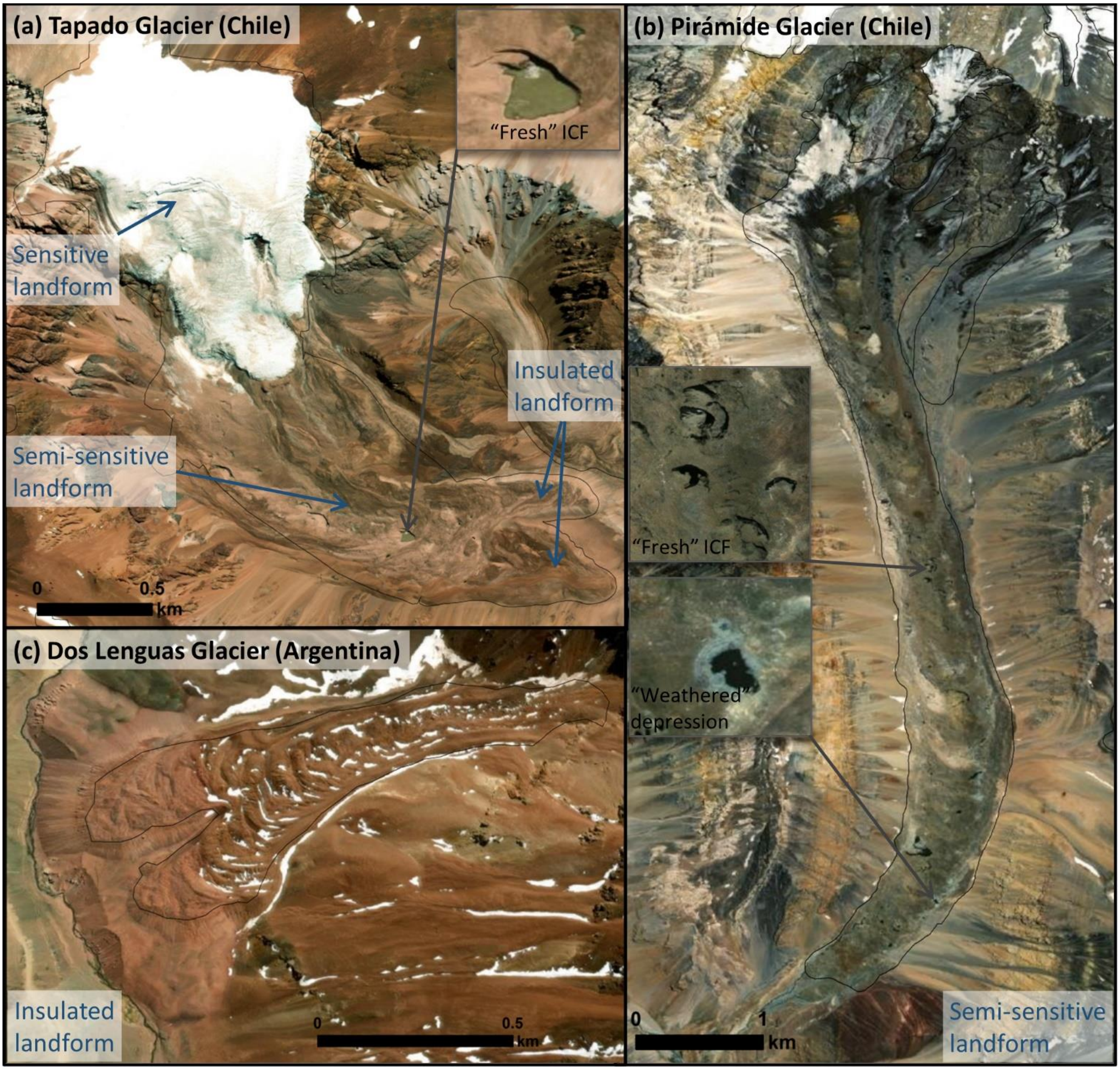
We suggest three categories for glacier classification for the purpose of water resource evaluation and/or management (see Fig. 1 for examples):

https://doi.org/10.5194/tc-2021-167
Preprint. Discussion started: 29 June 2021

1. Landforms that are sensitive to environmental changes. These landforms have exposed ice and include debris-free and some debris-covered glaciers (Fig. 1a).
2. Intermediate landforms that are semi-sensitive to environmental changes defined as having > 95 % debris coverage and a rough surface due to the discontinuity of debris cover, thermokarst depressions including "fresh" ice collapse features, or other features. We define "fresh" ice collapse features as depressions with at least one steep side that creates an abrupt change in topography, usually filled with water, ice or snow (Fig. 1a,b). We assume that the presence of "fresh" collapse features indicates that the landform is somewhat sensitive to climate as such thermokarst features may be a sign of permafrost degradation at depth in the landform (Schrott, 1996).
3. Landforms that are thermally insulated from the environment (Fig. 1c). Based on examples in Janke et al. (2015) and our own observations of more than one hundred glaciers in the semiarid Andes of Chile and Argentina with high resolution satellite imagery (Supplementary material), we conclude that these landforms generally have no exposed ice, convex topography, a discernible frontal slope, and thermokarst depressions are uncommon and generally appear "weathered". "Weathered" depressions have sides that appear eroded and do not form an abrupt change in topography (Fig. 1b). These are definitively rock glaciers.

Insulated landforms (Category 3) may have pronounced ridges and furrows perpendicular to the direction of flow, while semi-sensitive landforms (Category 2) have either no ridges or weakly developed ridges. Insulated landforms should not include rock glaciers that no longer contain ice (relict rock glaciers), however we recognise that such features may still play a significant role in the local catchment by enhancing liquid water storage and delaying spring runoff (Winkler et al., 2016) and should be treated separately in any corresponding legislation. These may be differentiated from other landforms by their collapsed appearance due to subsidence and lack of active flow features, or if necessary, confirmed using geophysical techniques. A frontal slope will likely be visible but may be shallow or eroded. Some glaciers may present individual exceptions to the above guidelines and would need to be evaluated on a case-by-case basis.

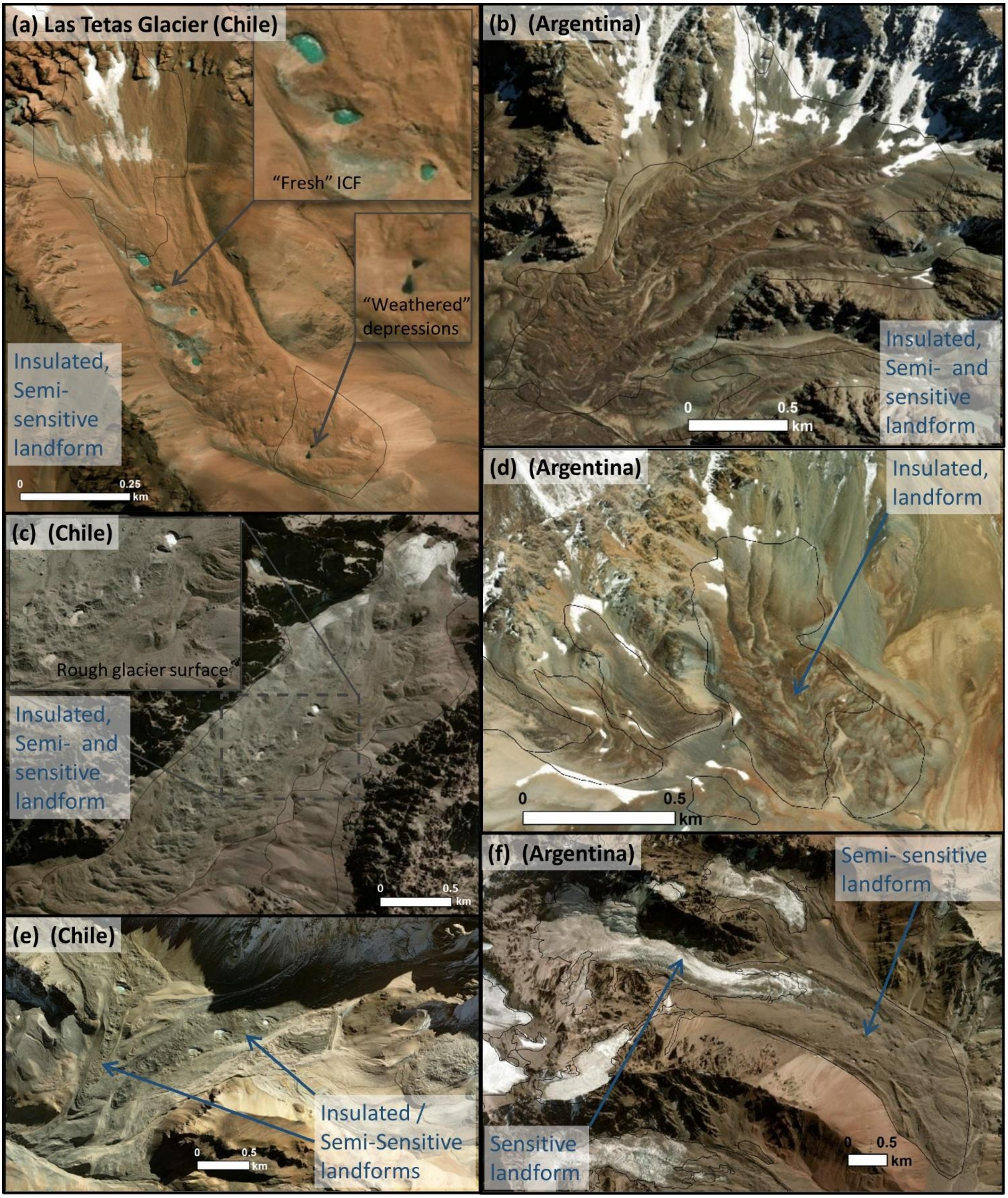
Where a landform is made up of multiple glacier types (Fig. 1a) we expect that these are hydrologically connected and therefore a disturbance of one part will impact the entire system and the water quantity and quality downstream. We therefore suggest the same level of protection be applied to the entire landform. In most cases where multiple landform-types are present, the level of protection associated with the most sensitive category should be applied (e.g. Fig. 1a and 2a, Table 1). However, where this part of the landform is very minor, it may be more appropriate to use the second most sensitive landform classification instead (Fig. 2b,c , Table 1).



125 **Figure 1:** Three landforms in the semiarid Andes for which the landform-type (sensitive, semi-sensitive or insulated) is clearly identifiable based on the geomorophological criterion presented in this paper are shown. Tapado Glacier is made up of the three distinct landform types proposed in this study. Approximately 95 % of surface of Pirámide Glacier is covered by debris and there are numerous thermokarst depression features, so it is classified as a semi-sensitive landform. Dos Lenguas glacier does not have ice exposed at the surface, has convex topography accentuated with ridges and furrows, and an obvious frontal slope so it is classified as an insulated landform. Image source (Esri basemap): (a) 11 March 2019 GeoEye (0.46 m), (b) 18 January 2013 WorldView-2 (0.5 m), (c) 17 September 2017 WorldView-2 (0.5 m).

https://doi.org/10.5194/tc-2021-167
Preprint. Discussion started: 29 June 2021

The Cryosphere
Discussions
Open Access
EGU



https://doi.org/10.5194/tc-2021-167
Preprint. Discussion started: 29 June 2021

Figure 2: Examples from the semiarid Andes of Chile and Argentina are provided to clarify the proposed landform types. All examples provided except for (d) contain multiple landform types. (a) Las Tetas glacier is made up of a semi-sensitive landform in its upper portion, and an insulated landform at lower elevations. (b) This glacier is dominated by the insulated landform type while (c) and (e) are dominated by the semi-sensitive landform type and have a "rough glacier surface". (f) This landform is a sensitive and semi-sensitive landform. (d) This glacier is a typical insulated landform. Examples are provided of "fresh" ice collapse features (ICF) and "weathered" thermokarst depressions. The black outlines are glacier delineations from the national inventories. Image source (Esri basemap): (a) 11 March 2019 GeoEye (0.46 m), (b) 9 April 2018 GeoEye (0.46 m), (c) 1 April 2020 WorldView-2 (0.5 m), (d) 9 January 2018 WorldView-2 (0.5 m), (e) 6 May 2020 WorldView-2 (0.5 m), (f) 1 April 2020 WorldView-2 (0.5 m).

Landforms associated with these three categories likely have distinct hydrological roles, which should be considered in the classification process. Sensitive landforms currently provide a much greater contribution to streamflow than insulated landforms per unit area (Schaffer et al ., 2019) and contain more ice per unit volume (~> 85 % ice content compared to ~<45 % for insulated landforms; Janke et al., 2015). These landforms are more responsive to climatic changes and in the Southern Andes (south of ~25° S) the vast majority of glaciers have already reached or are expected to reach their maximum runoff or "peak water" before 2050 with a decrease in runoff thereafter (Burger et al., 2019; Huss and Hock, 2018). Whilst debris-covered glaciers (including those in the semi-sensitive category) may lose just as much mass as debris-free glaciers due mainly to exposed ice or lakes on the surface and because they are often found at lower elevations (Ayala et al., 2016), debris-covered glaciers are still expected to be less sensitive to longer-term changes in climate than debris-free glaciers (Ayala et al., 2016; Ferguson and Vieli, 2020). In contrast, insulated landforms (rock glaciers) are more resilient to changes in temperature and therefore provide long-term water reservoirs (Bonnaventure and Lamoureux, 2013; Jones et al., 2018). However, this resilience can be diminished with human intervention such as the construction of roads or deposition of waste material on these landforms, potentially leading to slope instability and permafrost degradation (Brenning and Azócar, 2010). As well as contributing water, these landforms likely play a role in storing and delaying runoff by several months (Winkler et al., 2016).

It is likely that some glaciers will evolve over time. In the semiarid Andes of Chile the upward expansion of rock glacier morphology areas at the expense of debris-covered glaciers has been documented for two hybrid landforms in the Colorado Valley (30° S) and Navarro Valley (33° S) that have debris-covered glacier morphology in their upper parts and rock glacier morphology in their lower parts (Monnier and Kinnard, 2017). In the Navarro valley a small debris-covered glacier has evolved into a rock glacier over the last half-century, and such transformations may result in cryospheric landforms being more resilient to changes in climate (Monnier and Kinnard, 2017). Other factors such as precipitation patterns may also change over time which can have an important influence on glacier mass balance (Burger et al., 2019) and water availability in general. These potential changes highlight the need for a glacier protection plan that evolves through time.

https://doi.org/10.5194/tc-2021-167
Preprint. Discussion started: 29 June 2021

Table 1: The category assigned for this article, the national inventories of Chile (DGA) and Argentina (IANIGLA), and in the published literature if available are listed for glaciers illustrated in the figures as well as for named glaciers in the published literature. There are two categories for this article: 1) All landform types present and 2) the landform type that we recommend for assigning a level of protection. The coordinates are provided for each along with the associated figure number or glacier name. The classifications for this study are based on the images displayed in the figures or using the images in the associated publication for glaciers not included in Figures 1 and 2. For classifications by Janke et al. (2015) there are three sub-classes within the class debris-covered glaciers: semicovered, fully covered, and buried glaciers.

Figure ID / name	Latitude	Longitude	All categories present (this article)	Category for protection (this article)	Category DGA	Category IANIGLA	Published literature
1a) Tapado	30°9'15.42" S	69°55'24.88" W	Sensitive/semi-sensitive/insulated landform	Sensitive landform	Mountain glacier	----------	Debris-free, debris-covered and rock glacier (Monnier et al., 2014, Pourrier et al., 2014)
1b) Pirámide	33°33′33.2″ S	69°53′35.1″ W	Semi-sensitive landform	Semi-sensitive landform	Valley glacier	----------	Debris-covered glacier (Ayala et al., 2016, Ferrando 2012), Fully covered (Janke et al., 2015)
1c) Dos Lenguas	30°14'42.26" S	69°46'57.42" W	Insulated landform	Insulated landform	----------	Rock glacier (active)	Rock glacier (Halla et al., 2020; Schrott, 1996)
2a) Las Tetas	30°10'9.00" S	69°55'41.55" W	semi-sensitive/insulated landform	Semi-sensitive landform	Mountain / rock glacier[a]	----------	Debris-covered/rock glacier (Monnier and Kinnard, 2017)
2b)	33°39'25.69"S	69°37'7.59"W	Sensitive/semi-sensitive/insulated landform	Semi-sensitive landform	----------	Debris-covered/ rock glacier	----------
2c)	33°34'51.47" S	70° 4'9.47" W	Sensitive/semi-sensitive/insulated landform	Semi-sensitive landform	Rock glacier	----------	----------
2d)	30°29'26.06"S	70°10'29.90"W	Insulated landform	Insulated landform	----------	Rock glacier (active)	----------
2e)	34°13'7.04"S	70° 6'0.80"W	Semi-sensitive/ insulated landforms	Semi-sensitive landforms	Rock glaciers	----------	----------
2f) - west	33° 9'53.46"S	70° 2'14.97"W	Sensitive landform	Sensitive landform	----------	Debris-free glacier	----------
2f) - east	33°10'17.47"S	70° 1'14.33"W	Semi-sensitive landform	Semi-sensitive landform	----------	Debris-covered glacier	----------
Juncal Norte	32°59′42.8″ S	70°6′13.4″ W	Sensitive landform	Sensitive landform	Valley glacier	----------	Semicovered (Janke et al., 2015)
Llano de las Liebres	30°14'44.49" S	69°57'2.37" W	Insulated landform	Insulated landform	Rock glacier	----------	Rock glacier (Janke et al., 2015)

https://doi.org/10.5194/tc-2021-167
Preprint. Discussion started: 29 June 2021

The Cryosphere
Discussions
Open Access

Navarro	32°53′4.1″ S	70°2′31.1″ W	Semi-sensitive/insulated landform	Semi-sensitive landform	Mountain glacier / rock glacier[b]	----------	Semicovered/ fully covered/buried glacier/rock glacier (Janke et al., 2015; Monnier and Kinnard 2017)
Presenteseracae	32°53'13.48" S	70°1'44.87" W	Semi-sensitive landform[c]	Semi-sensitive landform	Rock glacier	----------	Debris-covered/rock glacier (Monnier and Kinnard, 2017)
Tres Gomelos	32°54′28.0″ S	70°1′36.3″ W	Insulated landform[d]	Insulated landform	Rock glacier	----------	Rock glacier (Janke et al., 2015)
Universidad	34°41′46.0″ S	70°19′55.5″ W	Sensitive landform	Sensitive landform	Valley glacier	----------	Semicovered[e] (Janke et al., 2015)
El Paso	30°13'58.43" S	69°48'52.9" W	Insulated landform	Insulated landform	----------	Rock glacier (active)	Rock glacier (active; Croce and Milana, 2002)

[a]The middle portion of this landform containing many obvious "fresh" ice collapse features not included in the DGA inventory.
[b] Classifications are based on the glacier extent provided in Janke et al. (2015).
[c] While rock glacier morphology is present on the lower reaches of this landform, the debris cover is not thick enough to insulate the landform (>60 cm thick at lower elevations; Monnier and Kinnard 2017).
[d]This classification is based on the 2008 GeoEye-IKONOS imagery within Janke et al. (2015). However, more recent imagery (May 9 2020 World View, and Feb 10 2016 Google Earth) show several "fresh" ice collapse features that appear to have formed after 2008.
[e]Classification is based on our interpretation, not explicitly stated in the publication.

https://doi.org/10.5194/tc-2021-167
Preprint. Discussion started: 29 June 2021

The Cryosphere Discussions

4 Examples from the semiarid Andes

Examples from the semiarid Andes of Chile and Argentina clearly illustrating the three landform types as well as "fresh" ice collapse features and "weathered" depressions are shown in Fig. 1. Additional examples are included in Fig. 2 to help clarify. Details are provided in the figure captions and Table 1 summarizes the classification of each landform in Figs. 1 and 2 according to the landform categories proposed in this study, the categories defined by the Chilean and Argentinian national inventories, and within the published literature where references are available. Glaciers named and classified in the published literature have also been added to Table 1. The sensitive landforms listed in Table 1 (the debris-free section of Tapado Glacier, Juncal Norte, Universidad glacier, and the sensitive landform in Fig. 2f), the semi-sensitive Piramide Glacier and glaciers in Fig. 2e and 2f are included in the Randolph Glacier Inventory (RGI), insulated landforms are excluded, and for all other hybrid landforms only a small area at the highest elevation is included if ice is exposed.

The most recent Chilean national inventory completed by the Dirección General de Aguas (DGA) defines rock glaciers as having no or almost no ice visible at the surface, generally convex topography, and a discernible frontal slope among other characteristics (DGA, personal communication, April 12 2021). It specifies that thermokarst features may be present but does not indicate if these can be numerous or are rare. All other glacier types are categorized based on the Global Land Ice Measurement from Space (GLIMS) classification system (http://www.glims.org/MapsAndDocs/guides.html; DGA, personal communication, April 12 2021) which has two categories of interest for this discussion: 1) valley glaciers and 2) mountain glaciers, both of which include debris-free and debris-covered glaciers. Valley glaciers are generally confined to a valley whereas mountain glaciers are found on mountain slopes and also include glaciers that do not fit into another category. There is no differentiation with respect to the amount of debris cover. The most recent inventory is completed but not yet publicly available, so we have reviewed the preceding inventory which was used as a base for the revised inventory. The vast majority of landforms classified as rock glaciers are insulated landforms as defined in this study (similar to Fig. 1c, 2d). There are some landforms with numerous "fresh" ice collapse features that have been categorized as rock glaciers (Fig. 2c, 2e). We suggest that when using the national inventory to evaluate water resources, that the categories proposed here additionally be applied to the area of interest so that landforms categorized as "rock glaciers" with numerous thermokarst depressions, especially "fresh" ice collapse features, can be differentiated from insulated landforms since considerable mass loss may occur in the vicinity of these features (Ferguson and Vieli, 2020; Miles et al., 2016). Applying the proposed categories would also enable differentiation between sensitive and semi-sensitive landforms which could help facilitate the evaluation process.

Although rock glaciers are not explicitly defined in terms of the debris cover thickness in the Argentinian inventory completed by the Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA), the associated glacier inventory

https://doi.org/10.5194/tc-2021-167
Preprint. Discussion started: 29 June 2021

(https://www.argentina.gob.ar/ambiente/agua/glaciares/inventario-nacional) mostly agrees with the proposed categories. All landforms classified as rock glaciers show no ice exposure, generally have convex topography and a discernible frontal slope (e.g. Fig. 1c). There are many landforms that have an upper portion that has "fresh" ice collapse features and/or is debris-free and a lower portion characteristic of insulated landforms (e.g. Fig. 2b, similar to Fig. 2a). These landforms are characterized as debris-covered glaciers/rock glaciers which matches the classification we would propose here (semi-sensitive/insulated landforms). While far less common, there are some landforms classified as rock glaciers that definitively have the characteristics of insulated landforms except for having very large or numerous ice collapse features. We would like to suggest that these be labelled as semi-sensitive/insulated landforms (corresponds to debris-covered glaciers/rock glaciers in this inventory) for the purpose of water resource evaluation. The category debris-covered glaciers in the Argentinian inventory is generally synonymous with semi-sensitive landforms as defined in this study evidenced by a near perfect match during a thorough review of the Argentinian inventory.

5 Discussion and concluding statements

We propose that landform categories, used for the purpose of water resource evaluation and/or management, should reflect differences in their sensitivity to environmental changes and distinct hydrological roles. We suggest three categories: 1) Landforms that are sensitive to environmental changes, 2) Landforms that are semi-sensitive to environmental changes, and 3) Landforms that are thermally insulated from the environment.

Whilst there is inherent subjectivity in this proposal, we recommend that these categories are more appropriate for the purpose of water resource evaluation and/or management than the available definitions based on glacier type in the scientific literature (Sect. 2) since these definitions can be more ambiguous than those proposed here and do not necessarily reflect the landform's sensitivity. For example, a landform that is almost fully covered with a thin layer of debris could be classified as a debris-covered glacier or as a rock glacier (e.g. Fig. 2e). Considering that such a landform is far more sensitive to changes in climate than an insulated one (e.g. Fig. 2d) and may lose as much mass as a debris-free glacier (Ayala et al., 2016), classifying it as a rock glacier could result in a false assumption that it is not sensitive to environmental changes leading to an inappropriate level of protection.

The manual classification proposed in this study relies on individual interpretation of the geomorphology and is therefore somewhat subjective. A more objective method could be to calculate the probability that glaciers within the study area belong to the sensitive, semi-sensitive or insulated classes using a statistical method such as logistic regression (e.g. Angillieri, 2010). In addition to geomorphological input variables (e.g. debris cover, thermokarst features) quantitative information such as debris cover thickness could potentially be included. A global debris-cover thickness model only requiring input data that can be obtained remotely (geodetic mass balance and velocity fields) has been developed and these outputs could be used to help

https://doi.org/10.5194/tc-2021-167
Preprint. Discussion started: 29 June 2021

differentiate between sensitive and semi-sensitive landforms (Rounce et al., 2021). However, it would be necessary to compare these outputs to measured debris thicknesses on glaciers in the semiarid Andes to evaluate their accuracy since the model was calibrated on a debris-covered glacier in Nepal. At present, methods for modelling thick debris cover (e.g. > 2 m) have not been validated and are therefore not a reliable tool to differentiate between semi-sensitive and insulated landforms. Evaluation of the geomorphology could potentially be completed in an objective way applying methods used to automatically detect rock glaciers (Robson et al., 2020). Utilizing this logistical regression approach for classification would facilitate the application of this scheme at a regional scale. The influence of debris cover on sensitivity could potentially be assessed in a more direct way since a relationship between satellite-derived surface temperatures and mass balance has been observed for debris-covered glaciers with debris thicknesses up to 0.4 m (Moore et al., 2019). Further investigation is needed to determine if this relationship exists for glaciers with thicker debris cover, and how it may vary along the Andean range.

These categories are mostly based on Janke et al. (2015) but have been reduced to three categories that additionally include debris-free glaciers and are distinguished by their sensitivity to changes in the environment which is closely related to their hydrological role and ice content. Sensitive landforms currently provide a much greater contribution to streamflow and have a greater concentration of ice per unit area compared to insulated landforms (Schaffer et al., 2019; Janke et al., 2015), but are also more sensitive to climatic changes (Ferguson and Vieli, 2020). In contrast, insulated landforms (e.g. rock glaciers) are resilient to changes in climate and therefore provide long-term water reservoirs (Jones et al., 2018). It is likely that they also play an important role storing and delaying runoff (Winkler et al., 2016). These glaciers are expected to become increasingly important in a warming climate as the contribution from more sensitive landforms diminishes (Jones et al., 2018). Their value as a water resources is region-specific, with a more significant role in areas that are water-scarce and rock glaciers are the dominant glacier type such as the semiarid Andes (Azócar and Brenning, 2010; Jones et al., 2018; Schaffer et al., 2019). Here, an elevated level of protection may be needed, focusing protection on individual glaciers may not be sufficient and will likely need to be expanded over larger regions to capture the sum of water reserves contained within rock glaciers to meet the needs of society. The Chilean and Argentinean GPL do not identify the distinct role glacier types provide in terms of water resources as described above. We think that this information should be explicitly stated and made easily available so that an informed decision can be made with respect to the protection of glaciers, particularly for regions that are expected to be water-scarce in the coming decades as longer-term water reservoirs may be of critical importance.

The three categories proposed have been designed to facilitate relatively easy and efficient identification of the landform types based on their sensitivity to environmental changes including for non-experts, while retaining the necessary detail to effectively designate an appropriate level of protection and monitoring protocol associated with the GPL and EIA processes. Each category is associated with a distinct hydrological role which we hope will facilitate the evaluation process. Both the Chilean and Argentinian inventories mostly agree with the division between semi-sensitive and insulated landforms. The only exception is for landforms categorized as rock glaciers that also have thermokarst depressions, particularly "fresh" ice collapse features.

https://doi.org/10.5194/tc-2021-167
Preprint. Discussion started: 29 June 2021

The Cryosphere Discussions

We would like to suggest that for the purpose of water resource evaluation these be categorized as semi-sensitive/insulated landforms in general and considered semi-sensitive landforms for evaluating the level of protection since considerable mass loss may occur in the vicinity of these features (Ferguson and Vieli, 2020; Miles et al., 2016). The Argentinian national inventory effectively differentiates between sensitive and semi-sensitive landforms, while the Chilean inventory does not. We would suggest adding this distinction when classifying glaciers for the purpose of water resource evaluation in Chile. We hope that these suggestions and the classification scheme proposed will be useful for public policy, as a complement to the generalized guidelines for glacier protection outlined in the GPL for Argentina and Chile, and an improvement upon the current Chilean EIA which treats all glacier types as one category. We also recommend that in addition to their hydrological value, other values such as ecosystem services provided by glaciers, their scientific importance, potential for sustainable tourism, importance for cultural and natural heritage, presence in a protected area (not limited to national parks), and the rights of indigenous communities be considered within the evaluation process, with the level of protection elevated for glaciers providing these additional benefits to society.

Author contribution and competing interests

Nicole Schaffer prepared the manuscript in collaboration with Shelley MacDonell who contributed content and helped write the manuscript. Whilst the authors declare they have no conflict of interest, we acknowledge that Shelley MacDonell has participated in working groups and panels with respect to the creation of glacier protection legislation in Chile, has conducted training courses for members of the Environmental Impact Assessment system and acted as a reviewer for the Chilean National Glacier Inventory that is currently being finalised.

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The Cryosphere Discussions

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