

### Reviewer 3

Schaffer and MacDonell present a new classification of glaciers in terms of their hydrological importance. The new classification is proposed in the context of the ongoing discussion of the Glacier Protection Law (GPL) in Chile and how this classification could be useful in defining the level of protection. The classification is determined in terms of its sensitivity to environmental changes based on the percentage of debris-cover area and surface characteristics. Based on this, the authors mention that this classification could allow different degrees of protection depending on their sensitivity which, is closely related to the hydrological role. The classification includes debris-free glaciers (highly sensitive and greater contribution to streamflow), debris-cover glaciers, including thermokarst features and zones of exposed ice in the surface (semi-sensitive) and rock glaciers, classified as insulated from the environment and hence with a lower hydrological role. Some examples are given for the semiarid environment in Chile and Argentina. The manuscript is well written and could be an important contribution to the discussion of GPL but also to understand the hydrological role of glaciers and its differences.

My main concern, however, is related to the classification and the criteria used and how useful could be to GPL discussion. I understand this as a highly complex topic and probably there could be several classifications criteria depending on the researchers. So please, take my comments on this topic as recommendations. Having said this, I recommend clarifying some points in the manuscript in order to understand the proposed classification.

#### **General comments:**

##### *Classification*

My general view is that the classification is simple and do not captures the diverse nature of glaciers in the Andes. In L115-116 it is mentioned that the guidelines need to be evaluated on a case-by-case basis. If this is the case, and I agree with previous reviewers, things seems to be more complicate following this classification. The hydrological role of a glacier, it is probably a concept that most of non-experts understand as a key role of the glaciers. In this sense, an explanation of the differences in time responses it is more adequate to introduce in a context of a GPL discussion in order to fully protect all glaciers. However, I agree that this classification can be useful to water resource management (L66-68).

RESPONSE: We agree that the qualitative approach proposed here is simplistic compared to the heterogeneity and variability that exist among glaciers. We envision the methodology outlined in this paper as an initial classification that could be efficiently completed at a national scale using data already available (e.g. high resolution satellite imagery). In the paper we now suggest that a more sophisticated and quantitative approach that could consider topography, climate, anthropogenic factors such as black carbon be applied as the data, advancements in methodology required, and qualified personnel become available. However, this approach would require much more time, expert professionals and in situ data, so it may be challenging given that there are no trained glacier professionals in the EIA system or local government departments in Chile and there is very limited in situ data available to complete a more sophisticated and quantitative modelling approach at a regional scale. We have modified the discussion paragraph starting on

line 227 to suggest this two-tiered approach (an initial classification as outlined in this paper, followed by a more quantitative and sophisticated approach). We have also modified and expanded upon the quantitative approaches suggested. Finally, we have explicitly identified the limitations of the quantitative approach presented in this paper at the beginning of this paragraph (line 228).

We have added a paragraph at line 49 discussing the large variation in climate, topography, and glacier characteristics that exists from north to south in the Andes and recognize that the dividing line (debris thickness threshold between categories) will vary from north to south. We clarify here and, in the discussion, that the study area chosen is meant to function as an example upon which classification schemes for other regions could be based. We have added a new paragraph starting on line 243 that details how the dividing line might vary from north to south and why with an emphasis on the difference between the semiarid Andes and Patagonia..

A simple modeling approach could be applied such as a temperature-index model that includes solar radiation. However, above 4000 m a.s.l. the performance of temperature-index models is poor within the study area (Ayala et al., 2017). Additionally, this type of model would not be able to incorporate debris thickness and would therefore not provide realistic results for sensitivity. A debris-cover model would need to be used to calculate the thickness, then this would need to be incorporated into a mass balance model capable of accounting for debris-cover. 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 differentiate between sensitive and semi-sensitive landforms (Rounce et al., 2021). The outputs from an earlier version of this model compare well to measurements of debris thickness on Pirámide Glacier (Ayala et al., 2016), but comparison with other glaciers in the semiarid Andes is necessary to evaluate the 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.

While strictly speaking if the hydrological role is defined as a particular function within an ecosystem, differences in timescales of water contribution (short-term versus long-term) represent the same hydrological role. However, we would like to continue to use the term “hydrological role” since this term has been used to describe differences in timescales in previously published papers on the subject of rock glaciers and water resources (e.g. Jones et al. 2018; De Pasquale et al., submitted; Schaffer et al., 2019). If the reviewer feels strongly about not using this term please suggest an alternate term. We would be open to using it.

We have modified the first paragraph in the introduction to highlight the usefulness of the classification scheme proposed with respect to legislation in general, including the GPL. We have also added a few sentences to the discussion starting on line 257 to highlight how incorporating the classification scheme in combination with water-scarcity could improve the GPL by making it possible to match the level of protection to the water resource need resulting in protection that would be region-specific, meet the needs of society without over- or under-protecting, and could evolve through time as the climate and water availability changes. We agree that introducing the proposed classification would likely complicate the proposed GPL and

make it more difficult to pass this law. However, the currently proposed GPL is limited in its ability to effectively protect glaciers as a single classification for all glaciers makes it rigid in both space and time. We have also added a couple sentences to the first paragraph of the introduction to highlight the usefulness of the proposed classification for glacier management (EIA).

### *Concepts*

The concept of hydrological role is not well defined in the manuscript. Following the explanation in L144-157, it seems that it is related mainly to the contribution of each type of glacier to streamflow at an annual scale. I suggest a clearer definition of what the authors mean by “hydrological role” including temporal and spatial scales and also the potential contribution to groundwater. The authors mentioned (L30-33 and L155-157) that insulated glaciers (rock glaciers) storage and delay the runoff. This is an important point as the hydrological role and importance of these glaciers have a different time scale in comparison to debris-free glaciers and must be included to define the hydrological role.

RESPONSE: We have explicitly defined the hydrological role in the first paragraph of the introduction.

“Here we define hydrological role as including contributions to the catchment as well as the impact on storage and drainage of water. For example, glaciers that are more sensitive to changes in climate (e.g. debris-free glaciers) provide a relatively large annual contribution to streamflow now, while rock glaciers are less sensitive and provide a longer-term reservoir (Jones et al., 2018), in some cases even acting as perched aquifers (De Pasquale et al., submitted).”

“Sensitivity to environmental changes” I understand that probably the use of “environmental changes” is used to include the atmospheric drivers of the melt as well as the feedback (positive or negative) that the debris-cover and glaciers surface characteristics exert on melt rates. However, the concept of “environmental changes” is wide and includes several other factors. I suggest clarifying what exactly means “sensitivity to environmental changes”. Maybe, constrain this concept will allow a clearer link between the classification and the hydrological role. I think in a concept like “sensitivity to melt drivers” or probably something better.

RESPONSE: In the introduction we now define sensitivity to environmental changes as including temperature, precipitation, and black carbon.

### *Clarification on the level of protection*

In order to avoid confusion, I suggest including, explicit, the order of the level of protection for each type of the classification i.e. the type that needs more protection according to your classification.

RESPONSE: We are proposing a type-dependant level of protection. We have added a paragraph to the discussion starting on line 260 that addresses the level of protection. We think that the specific decisions with regards to the level of protection for each region and assigned to each

glacier category proposed are public policy decisions that require balancing many factors such as water resources and the economy and are beyond the capacity of authors of this paper to decide. However, we do provide some general recommendations.

**Specific comments:**

L20 “Sendado” to “Senado” (also in the reference list).

RESPONSE: This change has been made.

L274-278: Although is not the focus of the paper, I think that the other values of glaciers mentioned here must be included in the Introduction. This manuscript is concentrated on the meltwater contribution to runoff, which of course is important, but as mentioned, glaciers also play other key roles.

RESPONSE: The majority of the additional roles are already mentioned in the introduction when defining what glacier protection laws aim to preserve (glaciers as strategic water reserves, for their role in sustaining biodiversity, in sustainable tourism, and their scientific importance). The other roles mentioned on lines 274-278 are very important, and we have incorporated these into the introduction.

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