Reviewer 1

Review of "Brief communication: A framework to classify glaciers for water resource evaluation and management in the Southern Andes" by Shaffer & MacDonnell

Summary

This brief communication proposes a new classification of the glacier landforms present in the Andes. The classification focuses on the sensitivity of the landforms to climate change and their hydrological impacts rather than purely on their geomorphological traits. The proposed classification is suggested to contribute to the discussion on the development of glacier protection legislation in both Chile and Argentina, which up to now have been relatively unsuccessful.

General comments

In general, the manuscript is well written and the message the authors intend to convey is clear. However, I have to say I am slightly confused about the intention of this communication. On the one hand, I do see the benefit of publishing this work in The Cryosphere, as this discussion may also exist in other parts of the world and a consensus in identifying glacier sensitivity from a policy standpoint could be beneficial. To serve this purpose, I do think the manuscript in its present form is (too) much focused on the Andean case. On the other hand, I wonder whether (the message of) this manuscript wouldn't be a better fit for a journal or other medium that allows direct targeting of the intended audience, i.e. policy makers, nature conservatists and water resource managers in the respective countries. I am not saying I do not see the benefit for TC and a "general" audience, but a more general focus would better support that.

RESPONSE: We decided to submit this article to The Cryosphere because we thought it would be very valuable to receive feedback from other glaciologists around the world to help build a consensus within the scientific community on identifying glaciers based on sensitivity for the purpose of water resource policy and management. To meet this objective, it was necessary to include technical details and information very specific to glaciology. Once this initial objective is met, a secondary document could be written that is less technical aimed specifically at policy makers, water resource managers and the general public.

We focus the paper on the semiarid Andes as a case study since this area is particularly relevant for water resource evaluation, legislation and management given that it is water-scarce, a large portion of glaciers are found outside of national parks, and it has a relatively high population density. Such high mountain areas are expected to see the largest temperature increases by the end of the twenty-first century. Areas of particular concern are in Ecuador, Peru, Bolivia, and northern Chile (Bradley et al. 2006; Souvignet et al. 2010; MRI Working Group 2015). Therefore, we think that a case study on the semiarid Andes is highly relevant within a global context. We decided to narrow our focus to a relatively small region so that we could provide very specific and concrete guidelines for defining the glacier categories. Given the large variability along the Andes in climate, topography and glacier characteristics, the appropriate debris thickness threshold among other criteria differentiating the categories will vary from north

to south so broadening the paper scope to encompass all of Chile and Argentina or a larger area would have required very general guidelines which we think would be less useful. Our aim is that the classification proposed for the semiarid Andes can serve as an example upon which classification schemes for other regions in Chile or other high mountain areas could be based.

I am also wondering how relevant it really is to identify the different landform types from a legislation perspective. Apparently, the political discourse has not yet been fruitful with respect to the GPL, even when just considering them as a single entity. Wouldn't introducing a system of sensitivities complicate things even further? In my opinion, the current manuscript does not express clearly enough how the introduction of the proposed classification would benefit the discourse around glacier protection, how it would benefit drafting related legislation, and how water resource management will be improved as a result.

RESPONSE: After careful consideration, 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.

The proposed classification would benefit the discourse around glacier protection by initiating a discussion on the distinct contribution different glacier types can make toward helping to meet water-resource needs, particularly over decadal or longer time scales. 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). Sensitive glaciers 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). Therefore, in the coming decades insulated landforms will become increasingly important.

Classifying different glacier types in a way that reflects their distinct hydrological roles opens the possibility for more flexible legislation that can match the level of protection to the 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. The current law is likely to under-protect in water-scarce regions such as from Santiago (Chile) to the north, assuming it only includes active rock glaciers, and may over-protect in areas with abundant water reserves (e.g. Patagonia) potentially limiting economic activity that could reasonably be carried out with precautions given that water from rock glaciers here is not likely critical. If the level of protection was linked to water-scarcity levels by region, the level of protection could be modified as water-scarcity levels change through time.

Water resource management would be improved with these classifications. Currently, many of the requirements in the EIA process are the same regardless of glacier type, and variable impacts are not given adequate consideration. For example, a debris-free glacier would be more sensitive to air particles such as black carbon from a nearby road than a debris-covered glacier, but this difference cannot be adequately addressed within the current EIA. Monitoring requirements would be more relevant if they were glacier-type specific. For example, obtaining an ice core

from a debris-free or debris-covered glacier is relatively straight forward and requires equipment that can be carried on foot, while obtaining one from a rock glacier is difficult and requires a much more robust setup that is difficult to transport. The most effective method to measure mass balance also differs between glacier types.

We have modified the first paragraph of the introduction to focus less on GPL and more on the general benefit of these classifications for legislation and the EIA as outlined above. We have also added some additional text on line 257 of the discussion suggesting that the level of protection could be matched to water needs.

I agree that the (quite minor) redefinition in classes defined by the authors with respect to traditional geomorphological categories of clean-ice, debris-covered and rock glaciers could improve assessment in terms of sensitivity and hydrological impacts up to a certain extent. However, in essence, the classification is still just based on a simple interpretation of the surface morphology, which is an oversimplification. This results in the straightforward and broad classes "sensitive" vs "insensitive", which may be too much of a black and white approach to be really useful in practice. High heterogeneity and variability exist among glaciers in their sensitivity and hydrological response, and this is for a considerable part irrespective of glacier surface type. It may be due to other geomorphological specifics of a glacier that are not considered in the proposed classification (e.g. slope, elevation, bed lithology, aspect etc.), but also due to differences in local climate, local anthropogenic disturbances, and possible feedbacks therein. Could some of these components be included somehow? Wouldn't an (even simple) modelling approach allow for a more informative estimation of the actual sensitivity of the glaciers? I would suggest the authors to at least elaborate on the limitations of such a simple classification and place it into a context of other, more developed approaches such as regional and/or individual glacier modelling. "Advanced" approaches would also be better to identify potential tipping points and transient effects, which could be very important arguments in policymaker discussions and conveying the urgency of expected changes in hydrology.

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. We also state that using such physically-oriented numerical models to identify tipping points (e.g. "peak water") could provide very helpful information for policy decisions. 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.

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.

I do not really understand the difference between landform and glacier used in the manuscript. A glacier seems to me as single entity, especially since it is hydrologically connected, but here it is suggested that a glacier is actually a landform that can consist of multiple glacier types. I would suggest using a better description of and distinction between these terms.

RESPONSE: We agree and have changed all instances of “landform” to “glacier” in the manuscript.

Also, taking the most sensitive part from a geomorphological perspective in a “hydrologically-connected” case to represent the sensitivity of the entire glacier/landform is not necessarily valid. The system should rather be classified as a whole. This goes back to my previous point: will this simple classification adequately represent sensitivity of the existing wide range of glaciers and glacier systems? For all glaciers, but particularly for a multi-type ones, sensitivity very much depends on the type of external forcing that causes a potential disturbance. If, for instance, the lower part of a glacier system is heavily debris-covered, it could be relatively insensitive to climate warming due to the insulation the debris provides in the ablation zone, but could be highly sensitive to processes that affect accumulation zone albedo such as the snowfall frequency or black carbon deposits.

RESPONSE: We have added a sentence on line 123 to indicate that assigning a level of protection associated with the most sensitive category is an initially conservative approach. When more information becomes available, the sensitivity level can be downgraded if justified.

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. We also state that using such physically-oriented numerical models help identify tipping points (e.g. "peak water") which could provide very helpful information for policy decisions. Finally, we have explicitly identified the limitations of the quantitative approach presented in this paper at the beginning of this paragraph (line 228).

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We agree that the sensitivity could change along the length of the glacier (ablation versus accumulation area). However, we expect that the variability in sensitivity within a given class (e.g. ablation versus accumulation area of an insulated glacier) will be less than the variability in sensitivity between classes. Since our aim is to propose a classification system that can differentiate between classes, we think that the proposed scheme is sufficient as an initial classification, which can later be modified using more sophisticated methods as described in the discussion.

SPECIFIC COMMENTS

L159-166. This is a good point, but it further reveals the complications with the sensitivity classification. I agree that a protection plan should evolve over time, but it should ideally already account for these temporal processes and effects from the get go. Is there any way temporal evolution could be included in the sensitivity classification approach? How would this affect the discourse and development of GPL?

RESPONSE: Yes, the temporal evolution could be included in the sensitivity classification approach. Since this approach distinguishes between different glacier types, it would be possible to renew the classification of glaciers every 10 years or so and in that way incorporate changes in glacier type. If for example a debris-covered glacier has evolved into a rock glacier over time, the classification would change and this would potentially impact the level of protection assigned

and hydrological role associated with that landform (e.g. short-term contributor to streamflow versus long-term reservoir). This would help to facilitate a discussion on and offer an opportunity to incorporate glacier evolution over time and the associated changes in streamflow contribution and hydrological role into the GPL.

L261-263. I am not sure why it is necessary or even desirable that non-experts can determine the sensitivity of a glacier. A well-developed database of glacier sensitivities created by experts using thorough analysis will deliver a much more insightful indication of the sensitivity of glaciers in a region or catchment and will serve policymakers better.

RESPONSE: We agree. Initially we proposed that the classification could be done by non-experts since there are no trained glacier professionals in the EIA system or local government departments in Chile. However, the Dirección General de Aguas (DGA, Chilean Water Authority, from the Ministry of Public Works) has a small unit that focuses on snow and ice that could complete a database or a glaciologist with knowledge of glaciers in Chile/Argentina could be contracted to do this. We have added a sentence on line 274 stating that the initial classification proposed in this manuscript could potentially be completed at a national scale by glaciology professionals who created the national inventories (DGA in Chile, IANIGLA in Argentina).

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