Master thesis proposal: Peak water using the Open Global Glacier Model

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1 Motivation

Glacier mass loss has increased during the second half of the 20th century (Vaughan et al., 2013) and is predicted, in all current climate projections, to continue throughout the 21st century (IPCC, 2014). The magnitude of the end of century glacial mass loss varies greatly depending on the region and climate scenario – Huss and Hock (2015) found a global glacier volume decrease between 25% (RCP2.6) and 48% (RCP8.5) and regional losses varying between 20 and 90%.

Glaciers play an important role as a form of water storage, delaying up to 79% of the total precipitation falling on the glacier surface (Aral Basin), through the release of meltwater during the ablation season. The benefits of this seasonal delay is particularly important in regions with a warm and dry ablation season (Kaser et al., 2010). One of those areas is the Indus basin where, during the pre-monsoon season, up to 60% of the total irrigation volume comes from either snow or glacier melt – with a resulting an 11% increase of the total crop production (Biemans et al., 2019). The Indus basin is also an example of large river basins which under the present climate experiences water scarcity – threatening the food security for millions of people (Kummu et al., 2014). This in an area where large amounts of the freshwater resource is shared across state borders where the risk for armed conflict is high (Pritchard, 2019; Schleussner et al., 2016).

The populated areas on the dry, western, slopes of the Andes are other examples of regions depending on glacier meltwater for potable water and power generation. Vergara et al. (2007) estimate the cost of mitigation and adaption to retreating glaciers in the Andes to between US$300 million and US$ 1.5 billion.

2 State of the art – Glacial hydrology

Glaciers store water in multiple ways – as a liquid in surface snow and firn, in crevasses, drainage networks, englacial pockets and surface pools. Or as s solid as snow, firn and ice (Jansson et al., 2003). The main factors controlling the discharge hydrograph of an Alpine basin is the topographical structure, the seasonal air temperature gradient, the seasonal distribution of precipitation (Zappa et al., 2003), and the percentage of glaciated area (Jansson et al., 2003). Melt is the main contributing process to annual glacier runoff generation (Zappa et al., 2003). Thus, the ratio of summer runoff to the annual runoff will increase with an increasing glaciated area (Chen & Ohmura, 1990).

The estimated the societal importance of glacier melt water from Kaser et al. (2010) was made under the assumption that the glaciers were in equilibrium with the local climate – i.e.

none of the runoff estimations included any net mass loss. Bliss et al. (2014) showed that glacier net mass loss is an important part of the total glacier runoff, indicating that the societal importance of glacier melt water might be higher than the estimates from Kaser et al. (2010).

This is where I introduce peak water.

3 Peak water using the OGGM

State of the art peak water estimations (Huss & Hock, 2018; Rounce et al., 2020) have relied on parametrizing the re-distribution of mass throughout the glacier with so called mass re-distribution curve, developed by Huss et al. (2010). This parameterization is a clear step up in performance compared to previous ice flow parametrizations, but still relies on glacier DEMs for calibration. The flow of non-measured glaciers will be estimated from known glaciers of a similar size.

Employing the Open Global Glacier Model (OGGM, Maussion et al., 2019) for peak water calculations would be the first time a physical ice flow model is applied globally to calculate glacier runoff. It would be a step towards mitigating the problem of over parametrization present in the current global glacier models used for hydrological analysis. Including ice dynamics in global glacier simulations result in reduced ice losses compared to parametrized models (Zekollari et al., 2019). It also allow the glacier to not only shrink, a limitation of parametrized ice dynamics, but also to grow. Using the OGGM will thus provide a new view of global runoff and peak water estimations, expanding the comprehension of the subject.

In its current state OGGM does not save any hydrological outputs (not true any more...) so before any runoff calculations can be made this has to be added to the model. The common approach is to use a so called fixed gauge – a hypothetical measuring station at the terminus of the glacier, measuring all water leaving the initially glaciated area.

The runoff, Q, is calculated from the glacial melt α, the liquid precipitation p_{liquid}, and the refreezing of meltwater within the glacier R as:

$$Q = \alpha + p_{liquid} - R. \tag{1}$$

The runoff coming from snow melt and liquid precipitation is calculated on the initially glaciated area and is, as the glaciated area shrinks, divided into two parts: on glacier and off glacier runoff.

3.1 Research questions

For this thesis I will try to answer the following questions:

1. **How does the inclusion of ice dynamics in a global glacier model change the future temporal and spatial variation of peak water?** The inclusion of ice dynamics will results in a different annual mass balance compared to models relying on parametrization. Since the runoff estimations are based on the mass balance – any changes to its calculation should result in a different estimate of peak water.

2. **High mountain Asia, when will the basins most dependent on glacier runoff reach peak water?** This would basically be done to corroborate on the previous studies that have been done. The **Indus basin**.

3. **At which levels, and during what time, will runoff levels begin to stabilise again?** Peak water gives a measure of when the annual runoff from glaciers reaches a maximum, but what about the long term equilibrium? What will the future water supply look like?

4. **How will the seasonal hydrograph change for future runoff projections?** Will glaciers release water earlier in the season? Or later? Also connects to the previous question – how is the annual runoff affected?

References

Biemans, H., Siderius, C., Lutz, A. F., Nepal, S., Ahmad, B., Hassan, T., von Bloh, W., Wijngaard, R. R., Wester, P., & Shrestha, A. B. (2019). Importance of snow and glacier meltwater for agriculture on the Indo-Gangetic Plain. *Nature Sustainability*, *2*(7), 594–601.

Bliss, A., Hock, R., & Radić, V. (2014). Global response of glacier runoff to twenty-first century climate change. *Journal of Geophysical Research: Earth Surface*, *119*(4), 717–730. https://doi.org/10.1002/2013JF002931
_eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2013JF002931

Chen, J., & Ohmura, A. (1990). On the influence of Alpine glaciers on runoff. *IAHS Publ*, *193*, 117–125.

Huss, M., & Hock, R. (2015). A new model for global glacier change and sea-level rise. *Frontiers in Earth Science*, *3*. https://doi.org/10.3389/feart.2015.00054

Huss, M., & Hock, R. (2018). Global-scale hydrological response to future glacier mass loss. *Nature Climate Change*, *8*(2), 135–140. https://doi.org/10.1038/s41558-017-0049-x

Huss, M., Jouvet, G., Farinotti, D., & Bauder, A. (2010). Future high-mountain hydrology: A new parameterization of glacier retreat. *Hydrology and Earth System Sciences*, *14*(5), 815–829.

IPCC. (2014). *Climate change 2014: Impacts, adaptation, and vulnerability: Working Group II contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change* (C. B. Field & V. R. Barros, Eds.). Cambridge University Press.

Jansson, P., Hock, R., & Schneider, T. (2003). The concept of glacier storage: A review. *Journal of Hydrology*, *282*(1-4), 116–129.

Kaser, G., Großhauser, M., & Marzeion, B. (2010). Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences*, *107*(47), 20223–20227. https://doi.org/10.1073/pnas.1008162107

Kummu, M., Gerten, D., Heinke, J., Konzmann, M., & Varis, O. (2014). Climate-driven interannual variability of water scarcity in food production potential: A global analysis. *Hydrology and Earth System Sciences*, *18*(2), 447–461.

Maussion, F., Butenko, A., Champollion, N., Dusch, M., Eis, J., Fourteau, K., Gregor, P., Jarosch, A. H., Landmann, J., Oesterle, F., Recinos, B., Rothenpieler, T., Vlug, A., Wild, C. T., & Marzeion, B. (2019). The Open Global Glacier Model (OGGM) v1.1. *Geoscientific Model Development*, *12*(3), 909–931. https://doi.org/10.5194/gmd-12-909-2019

Pritchard, H. D. (2019). Asia's shrinking glaciers protect large populations from drought stress. *Nature*, *569*(7758), 649–654. https://doi.org/10.1038/s41586-019-1240-1

Rounce, D. R., Hock, R., & Shean, D. E. (2020). Glacier Mass Change in High Mountain Asia Through 2100 Using the Open-Source Python Glacier Evolution Model (PyGEM). *Frontiers in Earth Science*, *7*. https://doi.org/10.3389/feart.2019.00331

Schleussner, C.-F., Donges, J. F., Donner, R. V., & Schellnhuber, H. J. (2016). Armed-conflict risks enhanced by climate-related disasters in ethnically fractionalized countries. *Proceedings of the National Academy of Sciences*, *113*(33), 9216–9221.

Vaughan, D. G., Comiso, J. C., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot, E., Solomina, O., Zhang, T., Arendt, A. A., Bahr, D. B., Cogley, J. G., Gardner, A. S., Gerland, S., Gruber, S., … Lemke, P. (2013). Observations: Cryosphere. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (p. 66). Cambridge University Press.

Vergara, W., Deeb, A., Valencia, A., Bradley, R., Francou, B., Zarzar, A., Grünwaldt, A., & Haeussling, S. (2007). Economic impacts of rapid glacier retreat in the Andes. *Eos, Transactions American Geophysical Union*, *88*(25), 261–264.

Zappa, M., Pos, F., Strasser, U., Warmerdam, P., & Gurtz, J. (2003). Seasonal water balance of an Alpine catchment as evaluated by different methods for spatially distributed snowmelt modelling. *Hydrology Research*, *34*(3), 179–202.

Zekollari, H., Huss, M., & Farinotti, D. (2019). Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble. *The Cryosphere*, *13*(4), 1125–1146. https://doi.org/10.5194/tc-13-1125-2019