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

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March 2021

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 climate scenario and the region – Huss and Hock (2015) found global glacier volumes to 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. 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 – resulting in an 11% increase of the total crop production (Biemans et al., 2019). Simultaneously, the Indus basin is one example of a large river basin which under the present climate experiences water scarcity – threatening the food security of 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), amplifying the consequences of water shortages. Mishra et al. (2020) found that during the period leading up to peak water, hydroelectric production from two basins in the Karakoram and Central Himalayan regions would benefit from increased flows. However, for the basin located in the Karakoram, post peak water benefits were highly variable, an indication of high spatial variations in the impacts of changes in glacial drainage.

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.

Brunner et al. (2019) found basins in Switzerland experiencing water shortage during the summer months in runoff simulations based on future climate scenarios. Shortages were elevated in basins highly dependent on runoff from ice and snow melt. However, the model used (PREVAH, see Viviroli et al., 2009) does not handle glacier evolution – i.e. mass changes, and is because of this likely overestimating the future contribution of glacial runoff to the seasonal water supply. 3 to 4% of the total annual energy production from hydropower in Switzerland currently originates from glacier mass loss, a finite resource that is expected to decline over the coming decades (Schaefli et al., 2019).

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 a solid in the form of 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 size of the glaciated area within the basin (Jansson et al., 2003).

Melt is the largest contributor to glacier runoff, hence the fraction of summer runoff to the annual runoff increases with an increased glaciation in a basin (Chen & Ohmura, 1990; Zappa et al., 2003). 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), where runoff estimates were done under an assumed equilibrium and thus neglecting any runoff resulting from net mass loss.

The term *Peak Water* is an adaption of the more well known term *Peak Oil* – which indicates the period in time when production of oil reaches a maximum, after which it begin to decrease (Gleick & Palaniappan, 2010). Recently this term has been applied to meltwater generation from glaciers (e.g. Huss and Hock, 2018) as a way to put the impacts of shrinking glaciers into a societal context. The mechanism behind glacial peak water is as follows (see Fig. 1): When climate change causes a glacier to recede, water is released from long term glacial storage. The annual runoff will increase until a maximum is reached i.e. Peak Water. At this point and forward the annual runoff will begin to decrease since the area of the shrinking glacier is no longer able to produce the same amounts of meltwater (Jansson et al., 2003). If the glacier reaches a new state of equilibrium (zero net mass loss), the annual runoff from the initially glaciated area might return to pre peak water levels. However, runoff levels during the melt season can be expected to fall below the pre peak water levels since melt water originating from long term storage will be reduced (Huss & Hock, 2018; Immerzeel et al., 2013; Ragettli et al., 2016).

3 Peak water using the Open Global Glacier Model

State of the art peak water estimations (e.g. Huss and Hock, 2018; Rounce et al., 2020) have relied on parametrizing the re-distribution of mass throughout the glacier with so called mass re-distribution curves, developed by Huss et al. (2010). This parameterization is a clear step up in performance compared to previous ice flow parametrizations (e.g. length-area scaling), but still relies on multiple digital elevation models covering the glacier for calibration of the flow as a function of the mass balance. As a consequence, the flow, or mass re-distribution, of non-measured glaciers will be estimated from known glaciers of a similar size, without considering topographical differences.

The common approach for calculating glacial runoff is to imagine a so called fixed gauge station – a hypothetical measuring station at the terminus of the glacier, measuring all water leaving the initially glaciated area. Runoff, Q, is calculated from the ablation α, the liquid precipitation p_{liquid}, and the refreezing of meltwater within the glacier R as:

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

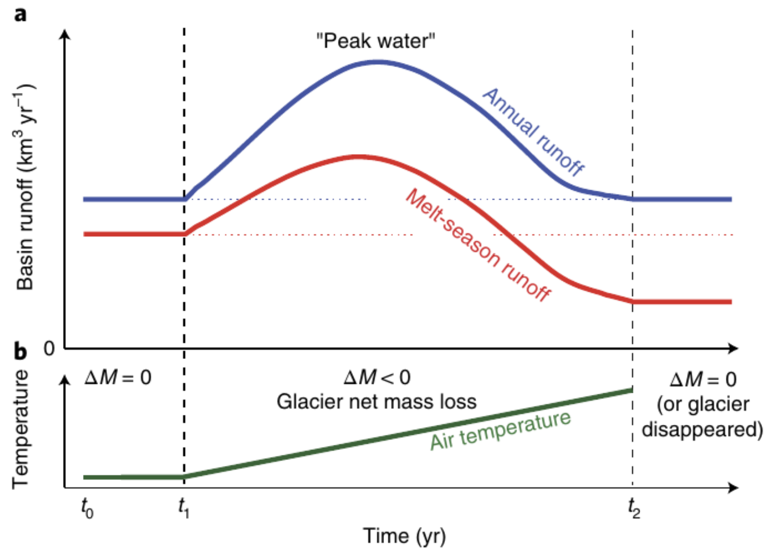

Figure 1: Schematised view of glacier runoff and peak water during a transient state. The annual glacier runoff will be constant from year to year during equilibrium. If the conditions change so that the glacier is no longer in equilibrium with its climate and the glacier begins to loose mass, the melt season runoff will increase with rising temperatures. Borrowed from Huss and Hock (2018).

The contribution from ablation is made up of ice and snow melt, also known as the excess melt water from the glacier. The total excess meltwater is equivalent to the total mass loss over a period of time. It is produced during years with negative mass balances, but since the mass balance can vary from year to year excess meltwater is only produced from committed mass loss. Because of this, excess meltwater has to be calculated retroactively for each mass-balance year, in order to maintain the total. This process starts with calculating the total excess meltwater for the selected time period, for instance the e.g. net mass change at 2100. The total excess meltwater can then be distributed, sequentially, to all negative mass-balance years where mass is not regained in the future. This way the total excess melt water is maintained, even if the cumulative sum of negative mass balance years exceeds the net mass change (Rounce et al., 2020). Runoff originating from liquid precipitation is measured from the initially glaciated area. As the glacier shrinks, this part of the runoff is divided into two parts: on glacier runoff and off glacier runoff. Other processes, such as evapotranspiration or ground-water recharge, are considered negligible and are not included in glacier runoff calculations.

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), possibly resulting in more accurate runoff estimations (meh not sure...). The inclusion of ice dynamics also enables the glacier to grow, if climatic conditions allow it, and not only to shrink, a limitation of mass re-distribution curves. Simulating Peak Water with the OGGM will provide a new, less parametrized, view of global glacier runoff and peak water estimations. It will expand what has already done and contribute valuable information on future water availability in alpine areas.

3.1 Research questions

For this thesis I will work towards answering the following questions:

1. **How does the inclusion of ice dynamics in a global glacier model change the temporal and spatial variation of peak water?** The usage of ice dynamics will results in a different annual mass balance compared to models relying on parametrizing the mass re-distribution. 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. **When will the basins most dependent on glacier runoff reach peak water? High Mounatin Asia** This would basically be done to corroborate on the previous studies. The **Indus basin** is interesting since this is a region where glacial storage is particularly important (e.g. irrigation).

3. **At what levels, and during which 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? European basins are interesting since peak water has most likely already passed. How will it affect water availability during warmer and drier summer seasons in Europe? Would actually be very interesting to have look at this in conjunction with extreme event indices (droughts etc.).

4. **How will the seasonal hydrograph change for future runoff projections?** When will the seasonal discharge occur under future scenarios and how might it affect the beneficial impacts of glacial water storage.

5. **Societal impacts???** There seems to be a gap in the knowledge about societal importance of glacier runoff with regards to glacier mass evolution. Impact estimates are not considering the possible runoff decline in some regions.

4 Schedule or something

Hydrological outputs were recently implemented in the OGGM, but still need to be evaluated and fully integrated into the model. The first step of this work is to make sure that runoff calculations in the OGGM are working as intended. This include testing the implementation, running a few simulations on a smaller scale and document it. Based on results from previous studies, a number of regions interesting in regards to peak water can be selected for long term simulations using the OGGM. To evaluate the affect of including ice dynamics in glacier runoff simulations, the results will be compared to previous studies (e.g. Huss and Hock, 2018; Rounce et al., 2020).

Runoff estimates of European basins can be analysed for patterns indicating a new equilibrium. The estimations can then be evaluated for their societal impacts.

Something about simulations with monthly output – to make it possible to observe seasonal changes in the hydrological output. Have to check the current state of the OGGM.

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