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 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. By capturing and holding precipitation as snow and ice until it is released later in the ablation season as meltwater, up to 79% of the total annual precipitation falling onto the glacier surface can be delayed. Regions that benefits from this delay are particularly those that experience 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 that basins in Switzerland experience 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 for this reason it is 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 – Glacier basin 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 are 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, i.e. peak water, is reached. 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 is 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

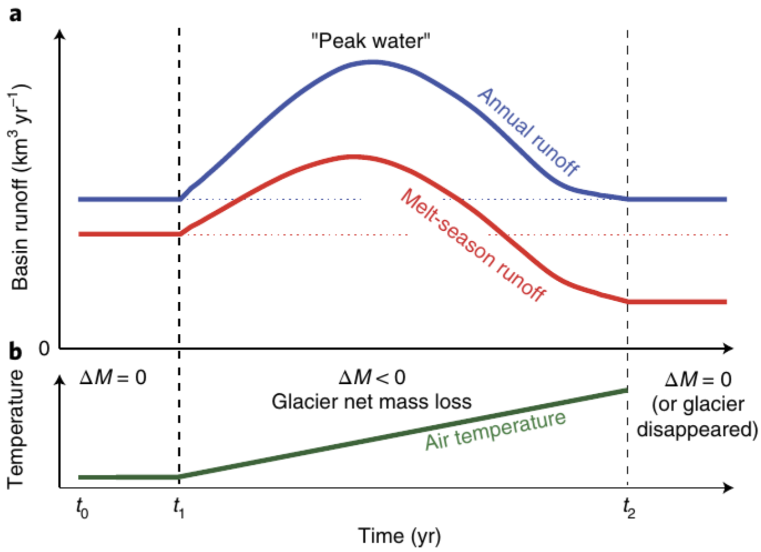

Figure 1: Schematised view of glacier runoff and peak water during a transient state. The annual glacier runoff will be constant from year to year during equilibrium. If the conditions change so that the glacier is no longer in equilibrium with its climate and the glacier begins to lose mass, the melt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

precipitation p_{liquid}, and the refreezing of meltwater within the glacier R as

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

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, in order to maintain the total, excess meltwater has to be calculated retroactively for each mass-balance year. This process starts with calculating the total excess meltwater for the selected time period, 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 results in reduced ice losses compared to parametrized models (Zekollari et al., 2019), possibly leading to more accurate runoff estimations. 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 view of global glacier runoff and peak water estimations with fewer parametrizations. This approach will build on the previous peak water research and provide valuable information on future water availability in glaciated areas.

3.1 Research questions

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

1. **When will glaciated basins, in different geographical settings, reach peak water?** Depending on the geographical setting, glaciers will react differently to a changing climate. In low altitude/latitude regions peak water is most likely already reached, while in other regions peak water is decades away. An established estimation of the timing of peak water is crucial for the adaption to future runoff levels in glaciated basins. Especially in regions where the societal importance of glacier meltwater is high, such as the Indus basin. Using the OGGM for global glacier runoff simulations builds on top of previous studies of peak water (Huss and Hock (2018) and Rounce et al. (2020)) by adding runoff estimations based on a different modelling framework.

2. **How important is glacier melt water for the water supply of glaciated basins during periods of low precipitation?** Kaser et al. (2010) estimated the importance of glacier melt water in glaciated basins under the current climate, assuming glaciers in equilibrium. Since most glaciers will not be, if they aren't already, in equilibrium with future climate, their method do not extend onto future climate projections. The novel method from Ultee and Coats (2020, In review) somewhat alleviates this problem by directly quantifying the influence of glacier melt water on the standardised precipitation-evaporation index (SPEI). This is done by dividing the basin into the glaciated and non-glaciated area. For the non-glaciated area the available moisture is calculated directly from the GCM data, whereas for the glaciated area the available moisture is calculated by a glacier model. This gives the moisture content of the basin with the inclusion of glacier runoff
$$\tilde{p} = \frac{A - A_g}{A} p + \frac{A_g}{A} r, \tag{2}$$
where p is the GCM precipitation, A the basin area, A_g the glaciated area, and r is the glacier runoff. $\tilde{p}$ can then be used in calculations of SPEI. Since SPEI can be calculated using climate projection data, the future role of glacier as a buffer to drought in glaciated basins can be evaluated.

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. In the current state OGGM outputs hydrological measurements on an annual scale. However, monthly outputs will be added, enabling the analysis of the seasonal runoff.

When the hydrological diagnostics of the OGGM are fully implemented, glaciers in the 56 basins can be simulated, forced with different climate projections. Outputs can then be analysed for the evaluation of peak water and compared to the results of previous studies. This makes up working package 1 (WP1).

For working package 2 (WP2) the outputs of WP1 are used to evaluate the influence of glacier runoff on basin wide moisture availability. This includes calculating SPEI both without glacier runoff and with glacier runoff, as described in Eq. 2. The results can then be evaluated in a number of ways. For instance, what runoff levels (which year) are needed to buffer periods of drought in future runoff scenarios.

Working package 3 (WP3) consists of creating materials/visualisations used to present the results, and working package 4 (WP4) is dedicated to the writing of the thesis. WP1, 2 and 4 are done sequentially while WP3 is worked on simultaneously with the other wps from when results are available.

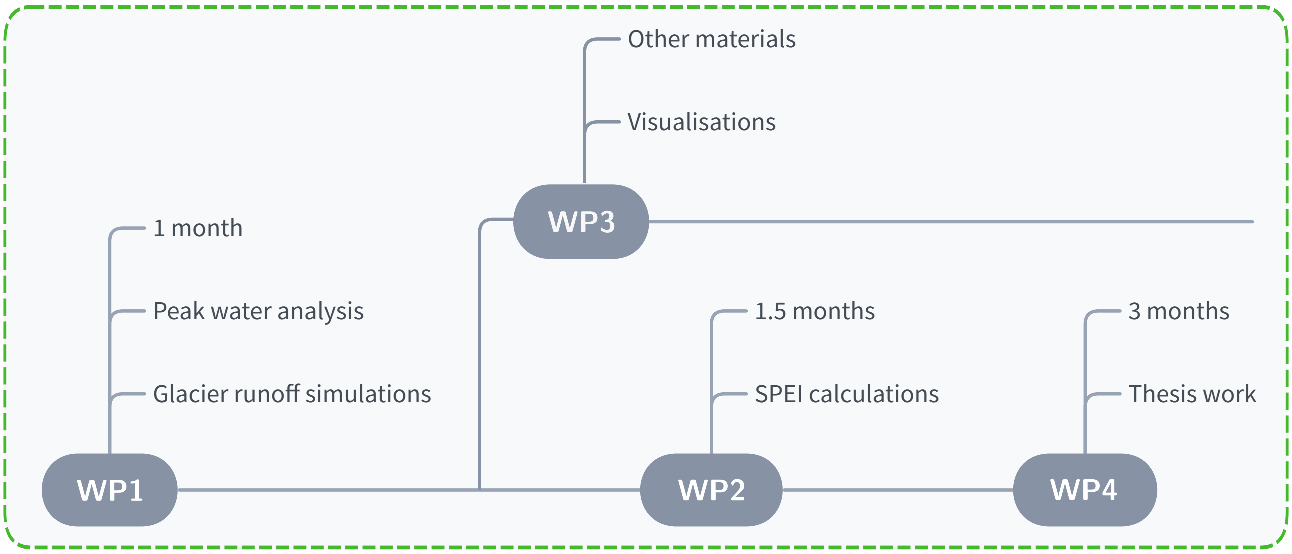

Figure 2: Illustration detailing the timeline of the project.

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