Peak Storage Working Doc

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## Intro

Glacial melt water in High Mountain Asia (HMA) currently supplies water to ~800 million people, and provides protection against episodic droughts (Pritchard, 2019) in one of the world’s most water stressed regions (Vorosmarty et al., 2000; Wada et al., 2011). Climate-induced glacier mass loss is projected to reduce and even eliminate many of the region’s glaciers by the end of the 21st century (Immerzeel et al., 2010; Bliss et al., 2014; Huss and Hock, 2018; Rounce et al., submitted), causing a decline and eventual cease in glacier runoff. The time of maximum glacial melt is termed “Peak Water”, and there is growing concern that after this point reductions in glacial meltwater will reduce runoff, with potentially substantial impacts to basins that rely on this water during the growing season (e.g, Biemans et al., 2019). HMA has another vast and threatened water reserve: groundwater. Drastic decreases in HMA aquifer storage have been observed over the past two decades (Rodell et al 2009; Russo, Devineni, and Lall, 2015), attributed at least in part to anthropogenic groundwater withdrawals for irrigation (Aeschbach-Hertig and Gleeson, 2012; Döll et al., 2014; Deng and Chen, 2017). While it is clear that declines in both these water resources are potential threats to HMA water security, no studies have recognized the potential for glacier melt to impact groundwater storage through surface water-groundwater interactions.

Paragraph here on rice paddy irrigation, alluvial aquifers, and percolation rates

Groundwater to surface water flows have been quantified for some Nepalese Himalayan rivers (Andermann et al. 2012), and the few studies that consider glacier runoff in surface water-groundwater interactions in Asia find cryosphere melt water to be a significant source of recharge (Meng et al. 2015; Zeng et al. 2015; Wilson et al. 2016), though to our knowledge no studies have assessed the role of irrigation on this recharge. The combination of high-permeability alluvial aquifers (Gleeson et al. 2014; Bhanja et al. 2019) with overlying irrigation systems including expansive seasonally-flooded rice paddies (Xiao et al. 2006, 2006) allow these irrigation systems to connect surface water and groundwater systems (Grogan et al. 2017). Glacier runoff impacts on aquifer recharge have been studied more in Swiss (e.g., Malard et al. 2016), Icelandic (e.g., Dochartaigh et al. 2019) South American (e.g., Baraer et al. 2014; Gordon et al. 2015), and North American (e.g., Langston et al. 2013) glaciated basins, but compared to HMA basins, these have significantly higher irrigation efficiencies (FAO, 2012) and often much less distance between the glacier terminus and the ocean; this combination means that less irrigation water is available to percolate into groundwater systems, and there is less irrigated area between the glacier terminus and the ocean over which percolation could occur. Additionally, most such analyses rely on stable isotope tracers to identify groundwater signals in surface waters (e.g., Wilson et al. 2016) and are therefore limited in spatial and temporal scale.

Here, we show that glacial meltwater is not exported directly to oceans as runoff; rather, glacial melt water is used for agriculture and recharges groundwater by way of percolation of excess irrigation water. This means that the drought-protection benefit of glacial melt water is transferred to the groundwater pool, extending the time frame of the benefit. Observed mass loss across many regions of HMA is occuring despite percolation of melt water. To understand how melt water percolation will impact downstream populations and how it contributes to the total water budget of basins - including both surface and groundwater - we need to know not only the timing and volume of glacier Peak Water, but also the volume and timing of “Peak Storage”, defined here as the maximum volume of glacial melt water stored in downstream aquifers.

## Methods and Data

# Climate drivers

8 GCMs drive two models: a glacier model (PyGEM) and a hydrology model (WBM) 2 RCPs: RCP 4.5 (low emissions) and RCP 8.5 (high emissions) Historical simulation: ERA-Interim (1980 - 2016)

# Cropland

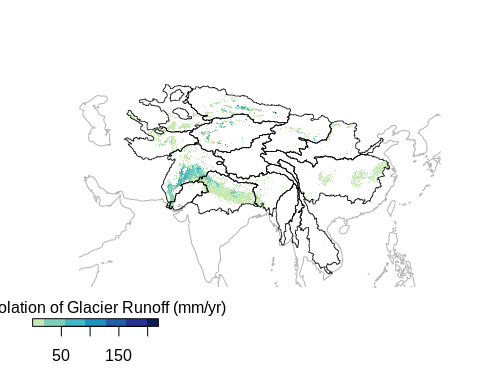
MIRCA2000 Parameters from Siebert and Doell 2010 Rice paddy percolation rates from Wisser et al (2010? check which paper)

## Results

## OGR data source with driver: ESRI Shapefile   
## Source: "/net/home/eos/dgrogan/git\_repos/Peak\_Storage/data/basins\_hma", layer: "basins\_hma"  
## with 15 features  
## It has 4 fields

## OGR data source with driver: ESRI Shapefile   
## Source: "/net/nfs/squam/raid/userdata/dgrogan/data/map\_data/land-polygons-generalized-3857", layer: "land\_polygons\_z4"  
## with 2346 features  
## It has 1 fields  
## Integer64 fields read as strings: FID

## Loading required namespace: ncdf4



# Glacier melt water percolation

# The role of paddy rice

Rice paddies are responsible for ~25% of glacier melt percolation (range: 21% - 26%, aggregated across all HMA basins)

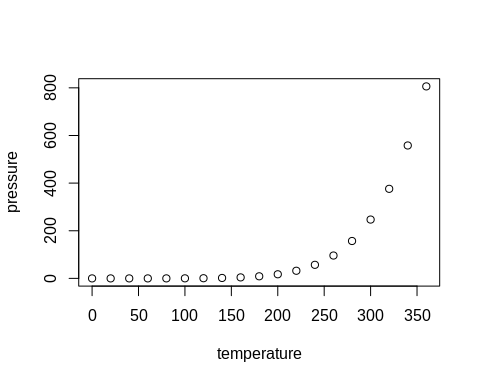
## Conclusions

summary(cars)

## speed dist   
## Min. : 4.0 Min. : 2.00   
## 1st Qu.:12.0 1st Qu.: 26.00   
## Median :15.0 Median : 36.00   
## Mean :15.4 Mean : 42.98   
## 3rd Qu.:19.0 3rd Qu.: 56.00   
## Max. :25.0 Max. :120.00

## Including Plots

You can also embed plots, for example:



Note that the echo = FALSE parameter was added to the code chunk to prevent printing of the R code that generated the plot.