Modeling response of glacier discharge to future climate change, Glacier No.1, Ürümqi

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Abstract:
Glaciers are known to be prone to climate change. The Xinjiang Uyghur Autonomous Region, China, has approximately 20,000 glaciers, which accounts for half number of glaciers in China. One of important function of glacier is that it provides meltwater, therefore, the glacier response to a warming temperature in this area is becoming critical to be investigated in relation to water sustainable development. The Ürümqi Glacier No.1 (UG1), as one of the most important glaciers, has a dominant role of providing meltwater for the capital city, Ürümqi. In this thesis, the Distributed Enhanced Temperature Index Model (DETIM) was employed, and calibrated to perform UG1’s historical discharge pattern. Then the calibrated discharge model was grafted to future climate projection of four Representative Concentration Pathways (RCPs) from fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), in order to investigate UG1’s water supply potential in the future. Moreover, UG1’s water supply role was discussed under a dynamic interaction between water supply and human society in the end. The result showed that the computation meltwater volume is between 121 million m³ to 131 million m³ in 35 years, from 2016 to 2050.

Keywords: sustainable development, climate change, glacier, discharge model, water supply

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Summary:
Glaciers are an important source of fresh water and have gained increasing study interests worldwide. Currently, climate change has posed a long-lasting effect on glaciers, and glacier recession has been discussed and investigated from a water sustainable development perspective as never before. Many studies have been conducted on a global and regional scale with the aim to explore the glacier response to climate change, especially in areas that are relatively depending on seasonal glacier meltwater as the main source of water supply. This study picked up the Glacier No.1 (known as “UG1, located in Ürümqi, China), as the study area, and provided a comprehensive investigation starting from the calibration of discharge model to future discharge projection, and then the projected discharge was discussed in a dynamic interaction between water supply and human society. The Distributed Enhanced Temperature Index Model (DETIM) was employed to compute discharge, and calibrated with measured climate and discharge data of UG1. The future climate projection of four Representative Concentration Pathways (RCPs) were extracted and dynamically downscaled to UG1 location from ESM2G model, belonging to fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC).

Keywords: sustainable development, climate change, glacier, discharge model, water supply

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1. Introduction

Glaciers are important to humans and other beings as it is one of the major sources storing fresh water on earth (Brown et al. 2010; Fry 2010). Glacier can be found not only in vast ice sheets polar regions, but also in mountainous regions on every continent (Miller 1961). Approximately, glaciers cover about 10 percent of Earth's land surface.

However, glaciers are rather sensitive to climate change and has been continuously exposing to an increasing global temperature (Cazenave & Remy 2011; Lawson 2007; Steinegger et al. 1993). Some glaciers’ recession speed has exceeded its forming speed which often takes decades or even centuries of long-term snow accumulation (Grinsted 2013; Favier et al. 2014; Jenkins et al. 2010; Casassa 1987). Moreover, climate change has also significantly weakened the snowing process, which contributes to a faster glacier recession progress worldwide (Hock et al. 2005; Marshall 2007; Marshall 2014).

There are approximately 20,000 glaciers in Xinjiang Uyghur Autonomous Region, China, which account for roughly half of all glaciers in China. Since the 1950s, glaciers in Xinjiang have retreated by between 21 percent to 27 percent due to a globally warming temperature (Sun et al. 2013). In recent decades, a visible recession of Ürümqi Glacier No.1 (UG1) has been observed (Ye et al. 2005; P. Wang et al. 2014; Jing et al. 2006). This situation is becoming critical because a significant amount of water supply to the capital city (Ürümqi) is highly depending on the glacier meltwater (Sun et al. 2013; Du et al. 2006; Wang, Li, G. H. Huang, et al. 2015). It is estimated that 3.5 million people’s daily lives will be affected if the recession accelerates (Wang, Li, G. H. Huang, et al. 2015; Xu et al. 2015; B. Wang et al. 2017).

Statistics have shown that from 1962 to 2003, UG1’s glaciated area and length decreased by 0.24 km² (12%) and approximately 175 m (7.3%); and the cumulative mass balance was -10,032 mm, equivalent to 11.1 m of glacier ice, or 20% of the glacier volume (Jing et al. 2006). Meltwater discharge increased by 413 mm (62%) due to precipitation increase and enhanced glacier melt caused by climate change (Jing et al. 2006; Bolch 2007). Moreover, some research have proven that 1 °C increase in summer temperature leads to an increase of 486 mm glacier mass loss (Kääb et al. 2007; Chinn 1996; Alley et al. 2008; HALL & FAGRE 2003; Trüssel et al. 2015; Hock 2014).

Globally and historically, there are limited number of scientific papers on UG1, and the studied periods were between late 20th and early 21st century. Thus, an update study work based on recent years’ data needs to be conducted urgently, especially since climate change is becoming severer nowadays and threatening the water supply to the capital city. Furthermore, the Positive Degree Day (PDD) model used in previous papers have become antiques compared with modern models and therefore may fail to provide with supportive evidence for future research.

Secondly, there is a lack of discussion bridging the water governance adaptation associated with UG1’s discharge pattern under climate change, because glacier recession topics are more discussed in a global-wise scale which have less focus on its impacts on a regional scale, especially small glaciers, therefore there is less specific experience can be borrowed on UG1’s study, which is rather important to future water management work. This thesis will attempt to develop a dynamic summary of how human interventions interact with the change of hydrological process, which will be presented as an overall glacier response to climate change from a regional level.
2. Aim and research questions

This thesis is aiming to investigate UG1’s discharge variations associated with future climate change, according to different emission scenarios projected by projects of Intergovernmental Panel on Climate Change’s (IPCC), and the study result will be examined and discussed from a sustainable water governance perspective in order to reveal how the hydrology process interacts with human society. To be more specific, the follow research questions will be answered:

- How is the UG1’s discharge pattern in recent years?
- How the discharge pattern will change in a warming global temperature?
- How important is the discharge water to the regional water supply?

To answer the questions above, many programs, tools and analysis software are needed, and produce study materials, mainly data, for every next step. The flow chart below (Fig. 1) demonstrates a general work flow of this thesis, and the more details will be presented in the following chapters:

![Flow Chart](image-url)

Fig. 1. A general thesis workflow, and used programs, tools and analysis software.
3. Background

3.1. Study Area

UG1 (43.05 N, 86.49 E) is the headstream of Ürümqi River (Fig. 2), located 120 km in the southwest of the capital city, Ürümqi. UG1 is a small continental valley glacier facing northwest (Jing et al. 2006). Due to previous continuous glacier recession, it split to two separate branches in 1994, and experienced considerably negative thickness change (Fig. 3). Two branches are named geographically as “the east branch” (elevation between 3740 to 4220 m a.s.l.) and “the west branch” (elevation between 3740 to 4486 m a.s.l.), respectively (Fig. 29). The mean equilibrium line altitude (ELA) of UG1 from 1959 to 2008 was 4056 m a.s.l. (Dong et al. 2012).

3.2. The Importance of Ürümqi River and UG1

Ürümqi was built in the deserts, the Gurbantünggüt desert (50,000 km²) is in its north and the Taklamakan desert (337,000 km²) is in its south. Even if Ürümqi seems to be a naturally water scarce place due to its geographical location, in fact, it has been nurtured by Ürümqi River since the birth of civilization (Zhang et al. 2009). Ürümqi also has been continuously being prosperous, because of its historical importance as a major hub on the Silk Road; and currently, it is the largest city in China's western interior serving as a regional transport node, a cultural, political and commercial center (Robel 2004). As Ürümqi region's population and economy grow, the water demand incessantly exceeds the regular supply. This imposes a huge stress on the water supply system, which was built 2000 year ago and is continuously evolving until nowadays, consisting of thousands of miles of canals, reservoirs, and underground water transfer tunnels (known as “karez”), and redistributing the water.
Ürümqi River has a length of 214 km, and the river basin covers 5803 km². It is a river that consists of mixed types of water, including glacier meltwater (12%), snow meltwater (37%), rainwater (36%) and ground water (15%), with an annual runoff of 244 million m³ (Li et al. 2010). Along the river, there are 4 major reservoirs (with a total capacity of 180 million m³), and many water conservancy facilities to store and produce clean water treatment for Ürümqi. According to the published water supply records from Ürümqi Water Industry Group, the highest daily supply record was 100,400 m³ (2012), 107,300 m³ (2013), 110,380 m³ (2014), 133,000 m³ (2015) 128,000 m³ (2016) and 130,000 m³ (2017). From 2002 to 2012, the annual transferred water increased by 121 million m³, from 132 million m³ to 253 million m³. And these numbers are bound to grow in the future due to the city development, and Ürümqi River will continue being a major water source for Ürümqi.

In short, UG1 together with other glaciers can contribute approximately 50% of glacier and snow meltwater at the headstream of Ürümqi River. Moreover, the meltwater from UG1 is a dominant proportion among many sources according to studies (Kang et al. 2009; Ye et al. 2005; Wang, Li, G.H. Huang, et al. 2015; Mingjie et al. 2013).
4. Method and Data

4.1. Distributed Enhanced Temperature Index Model

The Distributed Enhanced Temperature Index Model (DETIM) belongs to the PDD model family, and was created by Regine Hock who also firstly employed in 1999 to compute hourly discharge in two melt seasons of Storglaciären, a small glacier in Sweden (Hock 1999). Since then, DETIM has been continuously updated and developed further in terms of its source code, simpler structure of needed input files and calibration process in order to reduce its complexity and improve its performance and accuracy on computing discharge. Currently, DETIM is using a temperature index approach combined with precipitation to compute surface melt. Moreover, DETIM has a better performance to capture melt-induced diurnal discharge cycles from hourly to daily time frequency based on the effects of surrounding topography, which other classical models might not be able to pronounce well (Hock 1999; Hock 2005; Hock 2003; Schuler et al. 2002). This model is freely available at: http://regine.github.io/meltmodel/

DETIM is a fully distributed model, i.e. computations are performed in each single grid cell of a digital elevation model (DEM). To receive the discharge value, there are two major sources of water are computed. Meltwater, is computed in three linear reservoir forms of firn, snow and ice, and converted into one stream in the defined drainage basin; the amount of precipitation, in each pixel within the drainage basin, is computed to flow into the steam, therefore, contributing to the overall discharge.

Melting is caused by the function of air temperature, therefore the most fundamental formulation based on the simple degree-day factor approach is employed and sufficient for the thesis purpose. The function is shown below:

\[
M = \begin{cases} 
\frac{1}{n} DDF_{\text{snow/ice}} T, & T > 0 \\
0, & T \leq 0 
\end{cases}
\]  

(1)

where \( M \) is the melt rate (mm d\(^{-1}\)); \( DDF_{\text{snow/ice}} \) is the degree-day factor (mm d\(^{-1}\) °C\(^{-1}\)) for snow or ice; \( T \) is the near surface air temperature (°C), and \( n \) is the number of time steps each day. The \( DDF \) for ice is supposed to be larger than \( DDF \) for snow, but, in certain conditions they can be identical due to the difference between albedo and other surfaces (Braithwaite 1995; Hock 1999). It is also assumed that the \( DDF \) for snow should be the same value for firn surfaces, and \( DDF \) for snow and ice are constant both spatially and timely (Hock 1999).

Moreover, the distribution of melt rate over a consistent area appears to be unvarying, and terrain effects caused by slope, aspect and topographic shading can be ignored (Hock 1999). Therefore, the function of air temperature is bonded with these factors to compute melt rate, and the melt cycles are ensured to be linearly proportional to the temperature cycles in computed time frequency.

After computing the melt rate with the respect to time frequency, a discharge-routing model is coupled in the next step to compute the overall discharge according to the water received in three different reservoirs (Baker & Oerter 1982). This can be described in the function below:

\[
Q(t_2) = \sum_{i=1}^{3} Q_i(t_1) e^{-\frac{1}{k_i}} + R_i(t_2) - R_i(t_2) e^{-\frac{1}{s_i}} 
\]  

(2)

where \( Q(t) \) is the computed discharge value (m\(^3\) s\(^{-1}\)) in each time step; \( R(t) \) is the rate of
water flowing into the reservoir $i$, notably, the value here includes both meltwater and precipitation; $k$ is the storage constant of each type of reservoir and assumed constant in time (Hock & Noetzli 1997)

4.2. Data

There are few input files that needed preparation in order to commence work with the DETIM (Table 1). The least input files are: 1) a DEM covering the whole study area, notably, the complete drainage basin where glacier is located must be included; 2) daily average air temperature records; 3) daily precipitation records; 4) optionally, measured discharge records, for model calibration.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Data content</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate data</td>
<td>Air temperature</td>
<td>Daxigou Meteorological Station</td>
</tr>
<tr>
<td></td>
<td>Precipitation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Air temperature of future scenarios</td>
<td>Project CMIP5, model GFDL-ESM2G,</td>
</tr>
<tr>
<td></td>
<td>Precipitation of future scenarios</td>
<td>Geophysical Fluid Dynamics Laboratory</td>
</tr>
<tr>
<td>Grid data</td>
<td>Elevation</td>
<td>U.S. Geological Survey (USGS)</td>
</tr>
<tr>
<td></td>
<td>Slope</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drainage basin</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glacier area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Firn area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Initial snow cover</td>
<td></td>
</tr>
<tr>
<td>Discharge data</td>
<td>UG1 discharge in melting season</td>
<td>UG1 station</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Historical and current climate data were provided by Mr. Jin Shuang, a technician who works at the Daxigou National Meteorological Station and has more than 20 years’ experience with UG1. The data including mean air temperature and precipitation records were collected at the Daxigou National Meteorological Station from 2000 to 2016 in daily resolution (Fig. 30), and some periods of discharge data of UG1 measured at UG1 station. The Daxigou Meteorological National Station (3539 m a.s.l.) is about 3 km away from UG1 in the east downstream, whereas UG1 station (3689 m a.s.l.) stays relatively close to UG1 and monitors specifically the melting discharge (Fig. 4). Air temperature and precipitation data will be presented at the last of this chapter.

![Fig. 4. Locations of meteorological stations, UG1 and basin boundaries, and Ürümqi River](image)
4.3. Model Setup

The source code of DETIM is constructed in C language, however, it is user-friendly to people who have no programming background but have interest in glacier-related research. There is no need to change any source code, all parameterization options, geographical data, model parameters and output files, computing period and so forth, are set in “input.txt” file. This allows users to use different model’s modules individually.

Five important parameters were used to compute UG1’s discharge: temperature gradient (tempgrad), storage constant for firn (firnkons), DDF for snow and ice. DDF for snow is suggested to be between 1.35 to 2.8 (mm d\(^{-1}\) °C\(^{-1}\)) whereas DDF for ice is suggested to be between 2.7 to 5.6 (mm d\(^{-1}\) °C\(^{-1}\)); temperature gradient is around -0.71 (K 100 m\(^{-1}\)) (Huintjes et al. 2010). In addition to this, DETIM requires DDF for snow to be less than or equal to DDF for ice.

A majority of input files were prepared by Arcgis, except for the climate files. Some in ASCII format were converted to binary format by “ascigrid.c”, launched by Cygwin, a Linux-like system for Windows. The “Elevation” file, which is contained in the DEM, was converted to coordinate system WGS 1984 UTM Zone 45N, and later clipped into the size including study area which served as the processing extent for the rest input files. The “Slope” was processed by the “slope” tool. The “Drainage basin” was calculated by the “hydrology” tool kit, in the order of using “fill” tool, “flow accumulation” tool, “flow direction” tool and “basin” tool.

The boundary files, “Glacier area”, “Firm area” and “Initial snow cover” were similarly processed by “reclassify” tool based on the original DEM, after using ‘extract by mask’ tool with a high-resolution glacier shapefile, provided by Global Terrestrial Network for Glaciers (GTN-G). More details can be seen in Table 2:

<table>
<thead>
<tr>
<th>Grid data</th>
<th>Description</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>Elevation value of all grid cells (in m) without missing value</td>
<td>To compute topographic elevation</td>
</tr>
<tr>
<td>Slope</td>
<td>Surface slope of all grid cells (in °)</td>
<td>To compute direct radiation</td>
</tr>
<tr>
<td>Drainage basin</td>
<td>Area where precipitation collects and flows into a common outlet</td>
<td>To collect all meltwater within the area as the computed discharge</td>
</tr>
<tr>
<td>Glacier area</td>
<td>UGI boundary</td>
<td>To identify glacier area and its topographic elevation</td>
</tr>
<tr>
<td>Firn area</td>
<td>Firn boundary within UGI boundary</td>
<td>To define the surface type of glaciated area</td>
</tr>
<tr>
<td>Initial snow cover</td>
<td>Area where snow covers at the end of the melting season</td>
<td>To add snow cover outside glacier area, not applicable but needed as an input</td>
</tr>
</tbody>
</table>

When creating firm file, it is rather important to understand how a glacier is constructed. In most cases, a glacier is divided by equilibrium line into two parts (Fig. 5). At the high end of the glacier where fresh snow piles up and accumulates is called the accumulation area. As more and more snow accumulates, the weight of newly overlaid snow and gravity compress the firm and release the air bubble in the ice, the whole part becomes solid, hard and dense glacier ice. This area gains more mass than its loss, and this accumulation area was assigned with value 1 (meaning firm area). Another part, below the equilibrium line, is called the ablation area. Ablation is a word used to describe all forms of mass loss, includes melting, sublimation, and calving. Since the form transformation is complex here, surface snow cover has been generalized as ice, therefore, the whole area was assigned with only one value (0). The area outside the glacier area was assigned with value -9999 telling DETIM there is no glaciered area or snow cover exists (Fig. 28).
All climate data was structured in ASCII format (Fig. 6). There were 6 columns in the climate file, “year”, “julian day”, “time”, “temperature”, and “precipitation” take one column for each, and measured discharge data from UG1 station was added at the last column in order to assess model performance. Each column’s information was written in the “input.txt” file which could be read by DETIM later. In addition, DETIM has set a certain range for each variable in climate file, the air temperature (°C) should be between -60 to 50; the precipitation (in mm d⁻¹) starts from 0 to 300; and the discharge data’s unit is m³s⁻¹, missing values is assigned with -9999. Moreover, to computationally start reading the climate file, it is required to have two dummy lines at the beginning and at the end of climate file, it has to be there even if it has no value or any numerical value.

<table>
<thead>
<tr>
<th>Year</th>
<th>Day</th>
<th>Time</th>
<th>Temp</th>
<th>Precip</th>
<th>Dis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>364</td>
<td>24</td>
<td>0</td>
<td>-9999</td>
<td>-9999</td>
</tr>
<tr>
<td>1999</td>
<td>365</td>
<td>24</td>
<td>0</td>
<td>-9999</td>
<td>-9999</td>
</tr>
<tr>
<td>2000</td>
<td>1</td>
<td>24</td>
<td>-12.7</td>
<td>0</td>
<td>-9999</td>
</tr>
<tr>
<td>2000</td>
<td>2</td>
<td>24</td>
<td>-10.2</td>
<td>0</td>
<td>-9999</td>
</tr>
<tr>
<td>2000</td>
<td>3</td>
<td>24</td>
<td>-14.5</td>
<td>0.4</td>
<td>-9999</td>
</tr>
</tbody>
</table>

Fig. 6. The ASCII format of climate input file.

4.4. Calibration

A large number of initial settings and parameters are critical to the final model performance. To tune these parameters can be achieved manually, simply by adjusting parameters one by one and running DETIM for every change. But this is time-consuming. Therefore, a program, coded in Matlab, named “MultiRun”, was used to perform the calibration in a faster way. MultiRun is particularly developed to facilitate parameter calibration of DETIM and able to tune random number of parameters. The calibration routine is designed to repeat the systematical and repetitive work, which means in one single run all given parameters within a certain range will run and given a computed discharge result according to the set step, i.e. all combinations will be computed and written in its individual result file. For instance, if 10 different parameter values are given for each parameter, there will be 10*10 computed results generated in one run. The program is available here: 
https://github.com/regine/matlab_MultiRun

The model performance is evaluated by Nash–Sutcliffe model efficiency coefficient in the following formulation:

\[ R^2 = 1 - \frac{\sum (Q_{mea} - Q_{sim})^2}{\sum (Q_{mea} - \bar{Q}_{mea})^2} \]  

(3)

where \( R^2 \) is the efficiency representing the worst agreement and the best agreement between \( Q_{mea} \) (measured discharge) and \( Q_{sim} \) (computed discharge); \( \bar{Q}_{mea} \) is the mean
value of all measured discharge. $R^2$ ranges from $-\infty$ to 1, where $-\infty$ corresponds to the worst agreement whereas 1 means the perfect correspondence. If $R^2$ is 0, that means the computed discharge is as same as the mean of all measured discharge. In short, the closer $R^2$ is to 1, the better the model is. It is a friendly method to quantitatively evaluate the accuracy of outputs, however, sensitive to extreme values and big outliers (Nash & Sutcliffe 1970; D. N. Moriasi et al. 2007).

4.5. Future Scenarios

The Representative Concentration Pathways (RCPs) are four new future scenarios, as a further and more complex development of previous Special Report on Emissions Scenarios (SRES) (Moss et al. 2008; van Vuuren et al. 2011; Jubb et al. 2013; Arora et al. 2011). The pathways are developed for climate modeling work and climate research purposes in support with the IPCC’s Fifth Assessment Report (AR5). It provides important studying materials for future climate change associated with the amount of greenhouse gas (GHG) emission. It is quantified by a possible range of radiative forcing values (+2.6, +4.5, +6.0, and +8.5 W/m²), and added respectively to the pre-industrial level serving the projection to 2100 (Fig. 7).

![Fig. 7. Forcing agents' atmospheric CO2-equivalent concentrations of four RCPs from 2000 to 2100. Source: https://en.wikipedia.org/wiki/Representative_Concentration_Pathways](https://en.wikipedia.org/wiki/Representative_Concentration_Pathways)

Each RCP was named after its added radiative forcing value, resulted from a large number of possible GHG emission changes caused by human activities which reflects in the form of atmospheric concentration (Fig. 7). Moreover, all RCPs are based on the assumption that there will be sufficient fossil fuel production in the future (J. Wang et al. 2017). RCP 2.6 indicates that the global GHG emissions will be peaking around 2010 to 2020, and will decline gradually afterwards; RCP 4.5 assumes that the emission peak will be in approximately 2040 and then reduce later; RCP 6’s peak will come at around 2080 and then go down, and RCP 8.5’s emission level will grow throughout the whole period (Jubb et al. 2013; van Vuuren et al. 2011). All RCPs, showed in Fig. 8, project the global mean temperature will likely range between 0.3 to 4.8 °C till 2100 (J. Wang et al. 2017; van Vuuren...
Both the earth and climate are rather complex systems (Donner & Large 2008; McGuffie & Henderson-Sellers 2005; Uk 2007). Therefore, many research institutions are using different approaches to codify the important components which consist of our earth and climate systems, for instance, the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, and developing their own climate models based on RCPs. The climate model which projects RCPs’ future temperature and precipitation data in this thesis was ESM2G, from Geophysical Fluid Dynamics Laboratory (GFDL), belonging to National Oceanic and Atmospheric Administration (NOAA). In addition to this, many studies have evaluated ESM2G, together with other Coupled Model Intercomparison Project (CMIP5) models, having realistically strong intensities on temperature and precipitation projections (Kim & Yu 2012; Su et al. 2013; Zhang & Wang 2013; Miao et al. 2014; Cattiaux et al. 2013; English et al. 2015; Barker 2007). Other considerations made to choose this also included data accessibility.

Fig. 8. Equivalent temperature variation of atmospheric CO2-equivalent concentrations. Source: https://www.researchgate.net/publication/299365813_Climate_Change_and_Sustainable_Water_Resources_Management
5. Result

5.1. Calibration Result

DETIM ran the whole period with measured temperature and precipitation from 2000 to 2016, and computed discharge value in melting season in a daily resolution. Although some years, e.g. 2000, 2011 and 2015, have no measured discharge can be used in comparison with the computed results to calculate $R^2$ value, the discharge patterns can still be observed clearly (Fig. 9). Moreover, due to UG1’s varying conditions from the past to nowadays, the calibration work was focused more on seeking the best agreement in recent years, from 2010 to 2016. However, this did not mean the model performance in historical periods was less scientific. The important settings of DETIM can be read from Table 3 to Table 6.

The calibrated DETIM was able to achieve a $R^2$ value of 0.7376, compared with the available measured discharge from 2010 to 2016, excluding two missing years (Fig. 10). It dynamically captured the majority of discharge patterns according to temperature and precipitation variations in the melting season, and had a relatively high agreement compared with the measured discharge. However, in the case of extreme weather conditions, such as significant temperature or precipitation fluctuation, DETIM computed lower discharge result, one reason was due to the limited number of climate variables are taken into consideration.
The extracted temperature projection from ESM2G cannot be used directly. This climate model was designed to project climate information in a (nearly) square area, divided (in degree) by every 2.0225° in Latitude and 2° in Longitude covering the whole earth. The extracted data was the averaged data on behalf of one grid cell which contains not only the study area but also other areas which contributes to the overall projection in this grid. Therefore, the extracted data need to be downscaled accordingly to the study area.

The measured data and the projection data of RCPs have an overlapping period (from 2006 to 2016), which made the correction process more bridging and scientifically convenient (Fig. 11). There were three corrections being performed: 1) correction of RCPs’ daily temperature from 2006 to 2016; 2) correction (not technically) of RCPs’ daily precipitation from 2006 to 2016; 3) and the computed discharge based on RCPs’ corrected temperature and precipitation, which was corrected in comparison with the computed discharge based on measured temperature and precipitation, from 2006 to 2016 in the same calibrated DETIM.
5.2.1. Temperature Correction

![Fig. 12. Measured temperature and four RCPs’ temperature records (before correction), from 2006 to 2016.](image)

The temperature projection of RCPs showed a relatively large difference in comparison with the measured temperature at study area from 2006 to 2016 (Fig. 12). By extension, this difference will continuously exist in the future period from 2016 to 2050. However, temperature itself is a continuous variable, and both temperature records are also continuous in a daily resolution, this simplifies the complexity and mathematical process to correct the projected temperature. Regine Hock has employed the method of exploring a linear correlation to reduce the difference between measured and projected data in one study for Yakutat Glacier (Trüssel et al. 2015). In addition to this, many other papers have suggested the applicability of using linear transfer function to describe the correlation between two sets of data (Joo et al. 2016; Rodriguez 2013; Vorberg & Schulze 2002).

Therefore, each RCP’s temperature record was grouped with measured temperature record individually, and the correlation in each group was plotted in four separate correlation plots (Fig. 13) in order to explore the linear transfer functions:

\[
\text{meaTemp} = RCP2.6\text{Temp} \times 0.5502 - 9.0810 \\
\text{meaTemp} = RCP4.5\text{Temp} \times 0.5566 - 9.1538 \\
\text{meaTemp} = RCP6.0\text{Temp} \times 0.5551 - 9.1048 \\
\text{meaTemp} = RCP8.5\text{Temp} \times 0.5504 - 8.9033
\]

Although four transfer functions were relatively close in terms of their constants, they were not generalized into one universal function. To do this was aiming to keep the uniqueness and individuality of each RCP’s temperature varying trend.
After applying four linear transfer functions to each RCP’s temperature record, the projected temperature was more realistic compared with the measured temperature records. In the new correlation plots (Fig. 14), all pairs of points were more tightly distributed and concentrated, and each case showed an agreement higher than 70%. In addition, the new temperature plot of RCPs and measured temperature records seemed to be more reasonable (Fig. 15).
5.2.2. Precipitation Correction

Unlike temperature, which is a continuous variable, precipitation is discrete (Piani et al. 2010; O’Gorman & Schneider 2009; Maraun et al. 2010; Wehner 2004). Even if precipitation is an important variable in climate modeling, it does not seem easier to be projected compared with the continually changing temperature. Giving a simple example, in the daily weather forecast, the temperature information is always expected and given, in other words, the presence of temperature always exists, but not precipitation. The extracted precipitation projection from ESM2G was poorly underestimated compared with the measured precipitation in the same period (Fig. 16), by extension, this poor performance will continually exist in the future projection.

Attempts had been given to explore the trend or correlation of each RCP’s precipitation
record grouped with measured precipitation record, but nothing had been found (Fig. 17). This repetitively proved that using a linear transfer method will not be applicable to discrete variable. Therefore, such discontinuity was treated in another way.

Regine Hock used a rather straightforward method to deal with the inaccurate projection in the study of Yakutat Glacier under RCP6.0. A decadal precipitation record from 2000 to 2010 was repeatedly used to replace the projected precipitation record until 2100, because there was no significantly obvious trend for any months in the projected precipitation, therefore, precipitation was set not to be adjusted in the warming scenarios (Trüssel et al. 2015). This seemed to be less reasonable at the first place, however, the advantage of doing so was stressed: repeating the decadal record can conserve extreme precipitation events and preserve the observed variability over the past decade (Trüssel et al. 2015). Therefore, the same method was performed in this thesis, by repeating measured precipitation record from 2006 to 2016, as the primary part of the solution to generate the projected RCPs’ precipitation record from 2016 to 2050. It resulted in a series of composition of three full repetitive rounds of 11 years’ precipitation records, and two years’ records of 2006 and 2007, covering 35 computing years. The four sets of new precipitation records were generated but did not differ from each other. As many studies have investigated, the warming temperature tends to be coupled with a small increase in yearly precipitation and the increase rate is highly related to the warming intensity (Dore 2005; Kunkel et al. 2013; Mahlstein et al. 2012; O’Gorman 2015; Bonebrake & Mastrandrea 2010; Groisman et al. 2005). Hence, the next phase of work was performed to remove the sameness by superimposing projection precipitation variation trends onto the repetitive records respectively. Notably, this was not a denial of applying this “repetitive” method, rather, an extension of returning the difference of each scenario by carving its (tiny) uniqueness on the sameness when the future projection cannot sufficiently serve the purpose.

Fig. 17. Correlation plots between each RCP’s daily precipitation and measured precipitation.
Taking and comparing 2006 precipitation records as an example (Fig. 18), the comparison of measured precipitation and projected precipitation records showed that they did not stand in the same numerical magnitude. The highest measured precipitation record was 19.5 mm, and the precipitation was distributed discretely over the year, and, with a more regular concentration during summer (melting season); while the highest projected precipitation value was 3.92 mm, nearly 5 times lower, and showed no trend all over the year, moreover, a considerably amount of precipitation records during melting season remained missing. The annual precipitation was 512.5 mm (measured) and 12.76 mm (projected).

Therefore, to superimpose both, a straightforward method was used without risking exaggerating the value numerically. The processing function was below, and the calculation process was performed for each projected precipitation record of RCPs, from 2006 to 2050:

$$|\Delta P| = \sqrt{(\text{meaPrecip} - \text{RCPPrecip})^2}$$  \hspace{1cm} (5)

If $|\Delta P| = \text{meaPrecip}$, $\text{NEWRCPPrecip} = \text{meaPrecip}$; or $\text{NEWRCPPrecip} = \text{meaPrecip} + |\Delta P|$; And if $\text{NEWRCPPrecip} > 40$, $\text{NEWRCPPrecip} = |\Delta P|$; or $\text{NEWRCPPrecip} = \text{meaPrecip} + |\Delta P|

There were two conditions were set to filter out four different cases and then assigned with the new precipitation record in each step, and one condition was set to limit the new precipitation record if the final value exceeds historical record: 1) only measured precipitation record exists; 2) only projected precipitation record exists; 3) both exist but measured precipitation record is higher; 4) both exist but projected precipitation record is higher; 5) the final superposition is higher than the historical threshold. This process was performed to generate new precipitation record from 2006 to 2050 for all RCPs, based on the repeating records that were assigned with each year. A comparison of precipitation records using only repetitive method and superimposing method can be seen in Fig. 22 and Fig. 23. And corrected daily temperature and precipitation can be seen together from Fig. 31 to Fig. 34.

5.2.3. Discharge Correction:

The computed discharge, based on measured and projected (after correction) temperature and precipitation from 2006 to 2016, were run with same calibrated DETIM, and later the annual cumulated discharge was compared, in order to explore the linear correlation between the reality and computation (Fig. 19). Then this correlation was used correct the final annual cumulated discharge projection from 2016 to 2050. Only in this way, the connection between final corrected discharge and corrected temperature and precipitation can be built, and the inaccuracy in a daily basis can be more linearly dealt with in an annual basis.
Fig. 19. Annual cumulated discharge correlation plots between computed discharge based on measured temperature and precipitation, and computed discharge based on corrected RCPs’ temperature and precipitation, from 2006 to 2016.

5.3. Scenarios Result

5.3.1. Temperature

Fig. 20. Historical annual temperature variation and future temperature variations of four RCPs.

The future temperature in four RCPs all showed a growing trend with different increments (Fig. 20). From 2016 to 2050, RCP2.6 showed an overall 0.061 °C increase in 35 years, followed by 0.319 °C (RCP4.5), 0.479 °C (RCP6.0), and 0.728 °C (RCP8.5). Moreover, the temperature variation trends, which are considered to be associated with different GHG
emission peaking years in RCPs’ assumption, can be observed. Notably, only RCP2.6’s assumed GHG emission peaking periods (between 2010 and 2020) were included at the very beginning of the computation, therefore, in the result, it showed a rather small increase in overall change, and resulted in a relatively steady temperature variation in the future. Other RCPs had more obvious increasing characteristics as the computing period was a part of the time slot before assumed GHG emission peaks. Such result was anticipated according to previous literature review, and more locally downscaled from a broaden globally mapped temperature trend (Fig. 21).

![Fig. 21. Temperature growing trend of each RCP after 2016 (historical record).](image)

5.3.2. Precipitation

The future precipitation in four RCPs also showed an overall growing trend with different increase rates (Fig. 23). From 2016 to 2050, RCP2.6 showed an 19.92% increase in 35 years, followed by 20.95% (RCP4.5), 23.39% (RCP6.0), and 20.98% (RCP8.5). Although the corrected precipitation showed a rough 20% increase in all RCPs, the projection was less anticipated as the RCP8.5 did not appear to possess the highest increase in relation to its highest temperature increase (Fig. 24). However, since the precipitation correction was created based on the repetitive historical precipitation records, and superimposed with the original projection from ESM2G, this result was more likely to serve as the role of a middle-step to provide necessary component of climate input file in order to run DETIM.
Therefore, the need to discuss the exact increase rate was less meaningful in contrast to if the superposition method has successfully dissimilated each RCP’s uniqueness and created a general growing trend in the warming temperature. In addition to this, the computed discharge was the final expected result for this thesis, and the impact of precipitation will be reduced in the discharge correction.
Depending on different warming scenarios (Fig. 25), UG1’s discharge was projected to increase by 5.23% (RCP2.6), 6.78% (RCP4.5), 9.68% (RCP6.0) and 17.45% (RCP8.5) from 2016 to 2050, because of the temperature increase of 0.061 °C to 0.728 °C, and related potential precipitation increase (Fig. 26). The total amount of discharge during these 35 years were computationally expected to be between 121 million m³ and 131 million m³. Moreover, the annual cumulated discharge in 2016 was 3.4 million m³ ,and between 3.5 million m³ to 4.0 million m³ in 2050. The daily discharge of four RCPs before correction (annual) can be seen from Fig. 35 to Fig. 38.
Fig. 26. Discharge growing trend of each RCP after 2016 (historical record).
6. Discussion

6.1. Model and Uncertainty

Models are the abstractions of the realities, which are constructed based on users’ perception and purpose of using it, therefore there are many uncertainties will be simplified or underestimated resulted from each assumption that is made in order to bring it one step closer to a more computationally and user-friendly programmed product (Wainwright & Mulligan 2013). Thus, the output may carry such uncertainty, or even amplified difference, due to the input data quality, and therefore the result will be affected (Oberkampf et al. 2002; Liu & Gupta 2007; Caers 2011).

The calibration result showed that DETIM does not perform well at discharge peaks. This could be explained reasonably. Firstly, the study area is located in a high elevation mountain valley which makes its drainage basin significantly complex when using a DEM to capture the actual precipitation routes, and the ground water contribution is excluded. In the reality, especially in high rainfall seasons, there will be much more water flows naturally and unpredictably into the drainage basin rather than DETIM’s linear and distributed setting. And ground water, which is often invisible in valley or flows below glaciers, accounts for a certain amount of contribution to the final discharge (Bælum & Benn 2011; Barrett et al. 2008). In addition to this, DETIM neglects any stream contribution outside the glaciated area. Second, in order to improve computational efficiency, the glaciered area was characterized into two types only, which are firn and snow/ice, this leads to a difference when melting starts, because firn, snow and ice have different storage constants. This gives a lower melting contribution from snow, because snow has a lower storage constant which is sensitive to temperature fluctuation and makes it easier to melt. In those short-term but high temperature difference periods, model cannot compute sufficient meltwater from snow. Thirdly, the initial snow cover was set to zero outside the glaciered area. However, even at the end of each melting season, there will be leftover snow stays around glacier which contributes a small portion to the final discharge. However, this contribution is manually excluded because the amount of snow in each year and future are different and unpredictable.

During the model calibration phase, the purpose is to seek a best set of parameters which ensures the computed results fit the measured data to an optimal extent. However, the equifinality may occur and remain unknown to the model users (Her & Chaubey 2015). In short, under usual circumstances, few sets of parameters can lead to a similarly optimal result. This poses a challenge to pick up the correct set. To tackle this uncertainty is highly depending on how deep the model users understand the abstracted system, and users are not recommended to be obsessed with the model evaluation result, for instance, highly focusing on $R^2$ value(Sverdrup 1996; Beven & Binley 1992). Although it is a relatively reasonable accuracy indicator and seems the only method could be employed in this thesis. This actually happened during the calibration, however, was easily avoided by splitting the whole computing period into individual year, and running the model with different sets of parameters and comparing the computed results with measured data. In addition to this, previous research work has provided credible parameter ranges which narrows the number of parameter sets.

6.2. A broad perspective on CMIP5 climate model biases

Many studies and research work have been conducted to examine the CMIP5 model family’s projection performance, unfortunately, the results showed that a majority of models have deficiencies and biases which led to uncertainties (C. Wang et al. 2014; Kim et al. 2012; Knutti et al. 2013; Knutti & Sedláček 2013). Compared with observation, models tend to
show a cooler or warmer prediction at polar regions and areas near equator, and the bias patterns appear to be independent from season, but amplitudes are associated with season and can vary (C. Wang et al. 2014). Moreover, the projection results have lower reliability in a smaller scale (at the level that is smaller than its designed resolution), because the design of the climate model is to create a dynamic atmospheric matters exchange in a certain range which is able to create obvious heat transfer pattern. Therefore, if a very small area would be examined individually, that mean such pattern would not be observed because this area was been isolated. In a way, climate models project future climate in a holistic view and there is a need to project the climate from different regions as a whole, in order to create a dynamic and consistent interaction internally, therefore, projections can to zoomed in within limited range.

6.3. Human-water System

![Diagram](image.png)

**Fig. 27.** The relation between hydrological process and human society (Di Baldassarre et al. 2013).

Hydrological process and human society often have an internal mutual shaping relation associated with the external influence (Fig. 27). Fundamentally, this concept describes the dynamic interactions between hydrological process and human society, the such relation shapes each other in turn over time (Di Baldassarre et al. 2013). The climate change, as an external influence, creates changes in the hydrological process; hydrological process can be also influenced internally by urbanization which often causes an imbalance between water availability and demand. Society is influenced by such internal imbalance therefore developing policies and infrastructures (as an external solution however in turn creating influence back again) to cope with water sustainable issues, which can be summarized as ‘societal responses to hydrological changes, water governance, and impact of hydrological extremes’ (Di Baldassarre et al. 2017; Di Baldassarre et al. 2013).

In this study, the external influences coming from both sides, and creating an increasing imbalance between water supply and city development, or potentially catalyzing a severer water scarcity situation due to the enriching illusion. Externally, on the one side is the warming climate that results in an increasing of melting discharge of UG1, and leads to an increasing water supply to the city; on the other side, from human society perspective, it is the development of policies and water governance that try to meet the needs of increasing population and urbanization which demands more water. Internally, the increase of water availability seems to facilitate the city’s development continuously, or conversely, the city’s growing demand on water is naturally supported with moresupply. This seems balanced at the first place. However, climate change is a double-edged sword which not only directly increases the discharge from UG1, but also increase UG1’s recession, in other words, weakening UG1’s water storage potential. Evidence has shown that UG1 has been gradually losing its mass and experiencing a negative mass-balance process for decades (Dong et al. 2012; Jing et al. 2006; Mingjie et al. 2013). Therefore, in the future, there might be a gradual decreasing in water discharge, at some point becoming a sharp decrease, compared with the computed result.
The regional government has been taking a series of actions from early 21st in terms of building water diversion facilities to direct more water from other sources to alleviate the water supply dependence on Ürümqi River and enhance the overall resilience of the city towards water sustainable issues. For instance, the Irtysh–Ürümqi Canal, known as a critical part (the east trunk) of Project 635, is the one of the major canals that is under construction in the north-eastern suburb of the city with a main reservoir called “Reservoir 500” (Lan et al. 2016; Zhang & Li 2017; Xie & Jia 2017). The canal is connected with Irtysh River, and transfers water through many dry endorheic basins in northern Xinjiang. The canal is planned to be approximately 420 km long, sourcing water from the 134 km long main trunk, and flowing towards Ürümqi for irrigation and city water supply. Along the east trunk canal, the water is mostly transferred underground in order to reduce evaporation through deserts and maximize the long distance water transfer efficiency. It is expected to have a 560 million m³ capacity after first-stage construction and be able to fill up not only the present reservoirs around the city but a newly planned water supply network which is connected with the South-to-North Water Diversion Project (Water Technology 2014; Desalle et al. 2010).

6.4. Further Study Based on Future Monitoring

Glacier monitoring in Xinjiang, China, started, unfortunately, in late 20th, due to the limited technicians, insufficient science equipment, and the unreachable rough nature condition. Moreover, at that time, Xinjiang was not being prioritized to be granted with resources for any scientific or research activities. Therefore, compared with the glacier monitoring work worldwide, there is less historical pattern has been observed, resulting in a lack of deep understanding of these glaciers. It was not until 1950s, the first obvious rescission was observed and recorded; thereafter, there were three more major rescissions were recorded between 1970s and 1990s (YAO 2004).

Glacier monitoring is a long-term work and requires precise records of such mass-balance, near-surface temperature, precipitation in glaciered area and so forth (Shrivastava et al. 2017; Della Ventura et al. 1983; Braithwaite 2002). With these information, it gives researchers a better understanding of glaciers and therefore project accordingly its response under the future climate conditions. So, more studies are needed to monitor glaciers’ response to climate change in Xinjiang, China, combined with the newest measured data and more accurate climate projection in a higher resolution.

Currently, more national-level meteorological stations are constructed with its automatic field stations spreading around major glaciers. However, the access to the recorded data from these devices are limited. Users have to apply for access in a less constructed data downloading platform and wait for authorization from the administrators through a rather complex and time-consuming censorship process. Even though the Chinese glacier monitoring work has joint in the world glacier monitoring service (WGMS), it has limited resources to get direct access regarding any recent monitoring data. This is one thing that limits the development of research on glaciers in China, generally.

6.5. Delimitation

There are three index approaches can be used in DETIM, and this thesis used the simplest one (classical degree-day approach); others are approach includes potential direct radiation, and approach includes potential direct and measured. Compared with classical degree-day approach, the other two can perform a more accurate discharge result, however, it also requires more (variables) than just temperature and precipitation, such as relative humidity, wind speed, global radiation, reflected shortwave radiation, net radiation, longwave incoming and outgoing radiation, cloud cover and so on. These variables of UG1 were not accessible.
Together with DETIM, there is another model DEBAM (distributed energy balance model), based on an energy balance approach, can be also employed to compute glacier discharge. One advantage of using this model is that the glacier’s condition can be dynamically computed according to the input variables, therefore, every new year, the glacier is “recreated” based on previous year’s glacier activities. It is a rather complex model that needs more input files and glacier information, which is beyond the cope of a master thesis. Moreover, the field station cannot provide such information of UG1.

Moreover, the RCPs’ correction part was a weak spot of this thesis, especially the precipitation part, but there was similar work has been conducted and supported with the scientific reason behind it. Due to climate change, the complexity of any change of a climate factor cannot simply be described linearly. Downscaling is important to regional study, however, to some point, such complexity can be reduced from a holistic modeling perspective, for instance, in global climate modeling. If more local climate information can be connected with climate modeling when it comes to regional study, the result is expected to be more accurate.
7. Conclusion

Glacier recession is an irreversible trend worldwide correlated with climate change. Globally, the magnitude of glacier recession can vary due to latitude, geography or elevation, therefore, this impact can be better investigated in a local resolution, and is expected to be put into consideration in a holistic perspective of exploring regional human and water interaction.

In this thesis, DETIM was calibrated with the measured climate data, and used to project future glacier discharge pattern according to different RCPs’ climate data extracted from ESM2G and dynamically downscaled to the study area, a small but critical continental valley glacier, located in Ürümqi, Xinjiang Uyghur Autonomous Region, China.

Four RCPs all showed growing trends in terms of temperature and precipitation for the computing period from 2016 to 2050. Under RCP2.6, the temperature at where UG1 located showed a 0.061 °C increase and resulted in a 5.23% discharge increase compared with the discharge in 2016; RCP4.5 and RCP6.0, as medium-high emission scenarios, would experience a 0.319 °C and 0.479 °C increase of temperature and lead to a 6.78% and 9.68% increase in discharge respectively; RCP8.5 showed a 0.728 °C temperature increase and 17.45% increase in discharge.

According to the discharge projection result, at the end of 2050, UG1 will be computationally possible to provide approximately between 3.5 million m³ and 4.0 million m³ meltwater in contrast to the annual cumulated discharge volume (3.3 million m³) in 2016. The total amount of meltwater from UG1 during there 35 years is likely to be between 121 million m³ and 131 million m³, continuing accounting for a very important proportion of water supply through Ürümqi River to the capital city Ürümqi in its development process.
8. Acknowledgement

I would like to sincerely thank Rickard Petterson, my kind supervisor, who is always there when I have problems and ensures at least three high-quality meetings per month, starting from the very beginning of last October. I do appreciate his humble attitude, professional knowledge and the way of being a great teacher. He is the one that simplifies the complexity to clarity.

Veijo Pohjola, thank you for being my evaluator, and giving very constructive advice at our first meeting. It was because of your encouragement, I became confident enough to contact Regine Hock, the DETIM creator, through emails, and received direct and professional tutorial.

Many thanks should also be given to Mr. Jin Shuang, the technician who works at the Daxigou National Meteorological Station and provides me with valuable manually-collected UG1 data for this thesis. Without his help, my modeling process would not even be possible to start.

At last, I cannot help expressing my grateful feeling to the people in my life, who directly or indirectly support me from the first day being in Sweden, these unforgettable days will be coined with your names and kept well in my heart. Thanks for your support and company!
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Appendix

Fig. 28. UGI’s elevation information.

Fig. 29. UGI’s accumulation area and ablation area.
Fig. 30. Daily temperature (°C) and precipitation (mm) from 2000 to 2016.

Fig. 31. Corrected daily RCP2.6 temperature (°C) and precipitation (mm) from 2016 to 2050.
Fig. 32. Corrected daily RCP4.5 temperature (℃) and precipitation (mm) from 2016 to 2050.

Fig. 33. Corrected daily RCP6.0 temperature (℃) and precipitation (mm) from 2016 to 2050.
Fig. 34. Corrected daily RCP8.5 temperature (℃) and precipitation (mm) from 2016 to 2050.

Fig. 35. Uncorrected RCP2.6 discharge (m³·s⁻¹) from 2016 to 2050.
Fig. 36. Uncorrected RCP4.5 discharge (m³·s⁻¹) from 2016 to 2050.

Fig. 37. Uncorrected RCP6.0 discharge (m³·s⁻¹) from 2016 to 2050.
Fig. 38. Uncorrected RCP8.5 discharge (m$^3$·s$^{-1}$) from 2016 to 2050
Table 3. “Input.txt” file’s setting, grid information.

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<tr>
<th>Value</th>
<th>Description</th>
<th>Short name</th>
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<tr>
<td>86.81</td>
<td>%geographical longitude [degree]</td>
<td>laenge</td>
</tr>
<tr>
<td>43.11</td>
<td>%latitude</td>
<td>breite</td>
</tr>
<tr>
<td>90</td>
<td>%longitude time refers to</td>
<td>reflongitude</td>
</tr>
<tr>
<td>237</td>
<td>%row in DTM where climate station is located</td>
<td>rowclim</td>
</tr>
<tr>
<td>165</td>
<td>%column of climate station</td>
<td>colclim</td>
</tr>
<tr>
<td>0/3695</td>
<td>%take this elevation for AWS yes/no</td>
<td>climoutsideyes/heightclim</td>
</tr>
<tr>
<td>26.4864</td>
<td>%gridsize in m</td>
<td>gridsize</td>
</tr>
<tr>
<td>24</td>
<td>%time step in hours</td>
<td>timestep</td>
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</tbody>
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Table 4. “Input.txt” file’s setting, climate data.

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<td>2</td>
<td>%1=midnight time is 0, 2=time is 24, 3=24 but previous day</td>
<td>formatclimdata</td>
</tr>
<tr>
<td>6</td>
<td>%number of columns in climate file</td>
<td>maxcol</td>
</tr>
<tr>
<td>4</td>
<td>%columns in climate input file: temperature</td>
<td>coltemp</td>
</tr>
<tr>
<td>5</td>
<td>%precipitation</td>
<td>colprec</td>
</tr>
<tr>
<td>6</td>
<td>%column of discharge data</td>
<td>coldis</td>
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</tbody>
</table>

Table 5. “Input.txt” file’s setting, discharge starting values.

<table>
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<td>%nodata value of discharge file</td>
<td>nodis</td>
</tr>
<tr>
<td>200</td>
<td>%storage constant k for firn</td>
<td>firnkons</td>
</tr>
<tr>
<td>38</td>
<td>%storage constant k for ice</td>
<td>icekons</td>
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Table 6. “Input.txt” file’s setting, temperature index method.

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<thead>
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</tr>
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<td>%which temp index method (1,2 or 3)</td>
<td>ddmетод</td>
</tr>
<tr>
<td>3.2</td>
<td>%degree day factor for ice</td>
<td>DDFice</td>
</tr>
<tr>
<td>3.2</td>
<td>%degree day factor for snow</td>
<td>DDFsnow</td>
</tr>
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