Glacier Model Setup

This document is largely based on the DHSVM Glacier Model Tutorial made by Chris Frans (University of Washington) and the Master Thesis (https://cedar.wwu.edu/wwuet/461/*) of Ryan Murphy in Western Washington University.*

Compiling

1. Run Makefile in Lib/ directory
This will create the libcxsparse.a file required to compile the main source code

2. Run Makefile in sourcecode directory
This will create the DHSVM3.2 executable that will run the model

DHSVM Coupled Glacier-Hydrology Model Options

To calibrate and run the glacier dynamic glacier model for use with the DHSVM version 3.2 is a multi-step process requiring iterative runs of the model under different settings. DHSVM has four glacier model run options:

1. NO_GLACIER = Runs DHSVM routine without simulating glacier ice. Snow that reaches the density of ice is removed.

2. GLSPINUP = Runs glacier model independently (i.e. not running DHSVM modules) with annual average mass balance forcing at an annual time step for 1000 years to "grow glaciers" to steady state (need to specify Glacier Mass Balance File in input configuration file)

3. GLSTATIC = Runs DHSVM simulation representing a glacier ice layer (Surface Topography Input – Bed Topography Input), however no glacier flow dynamics are included (ice is static and does not flow cell to cell; mass is finite)

4. GLDYNAMIC = Runs DHSVM simulation representing glacier ice and glacier ice dynamics (ice flows cell to cell based on glacier ice physics)

Note: For grid cells prescribed with canopy gap structure, the cells are always considered free of glacier (regardless of glacier mask map), and will not perform any glacier relevant calculations.

General Outline for Setting up and Running the Glacier-Hydrology Model:

1. Estimate bed topography
2. Estimate Mass Balance Field
3. Run "GLSPINUP" with mass balance field to grow steady state glaciers
    - Iterate by perturbing mass balance field until glacier extent matches historical extent
    - Once satisfied with simulated extent, use ice thickness and bed topography to create surface topography field
4. Use surface topography field as input to initialize glacier states (Glacier Ice = Surface Topography – Bed Topography) in coupled glacier-hydrologic simulations (GLDYNAMIC, GLSTATIC)

In order to run the coupled glacier-hydrology model properly, several steps must be taken. A representative mass balance field for the domain, as well as a surface topography field must be estimated. The DHSVM is used to estimate these parameters under the GLSTATIC and GLSPINUP glacier options. Once these files have been created, the dynamic model can be run and the static model can be run with more confidence.

Necessary Inputs:

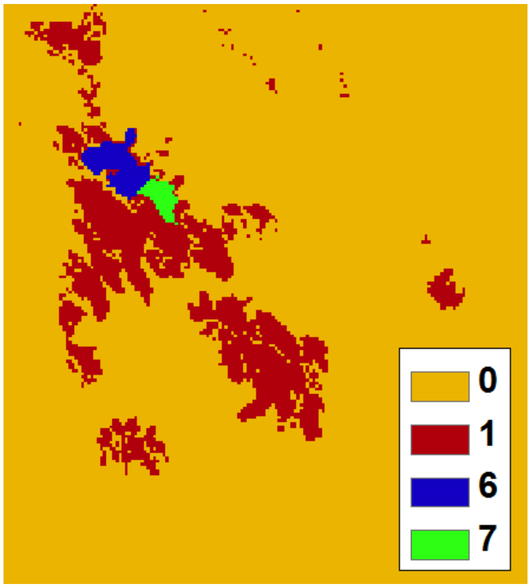
All inputs for the glacier portion of the model can be created or altered in ArcMap. The user should first decide which years they would like to model the glacier (i.e. starting with current glacier extent vs starting with the extent from the year 1950 for example). Typically the oldest observed glacial extent is used. This will largely depend on what GIS datasets (NOCA, GLIMS, etc.) are available. Make sure to specify the correct cell size and extent for your raster data. The grid spacing and number of rows/columns must match the other inputs to the model (DEM, mask, land cover, etc.).

Note: Pixels with no data should have values of 0 rather than -9999.

- ***Glacier Mask File***

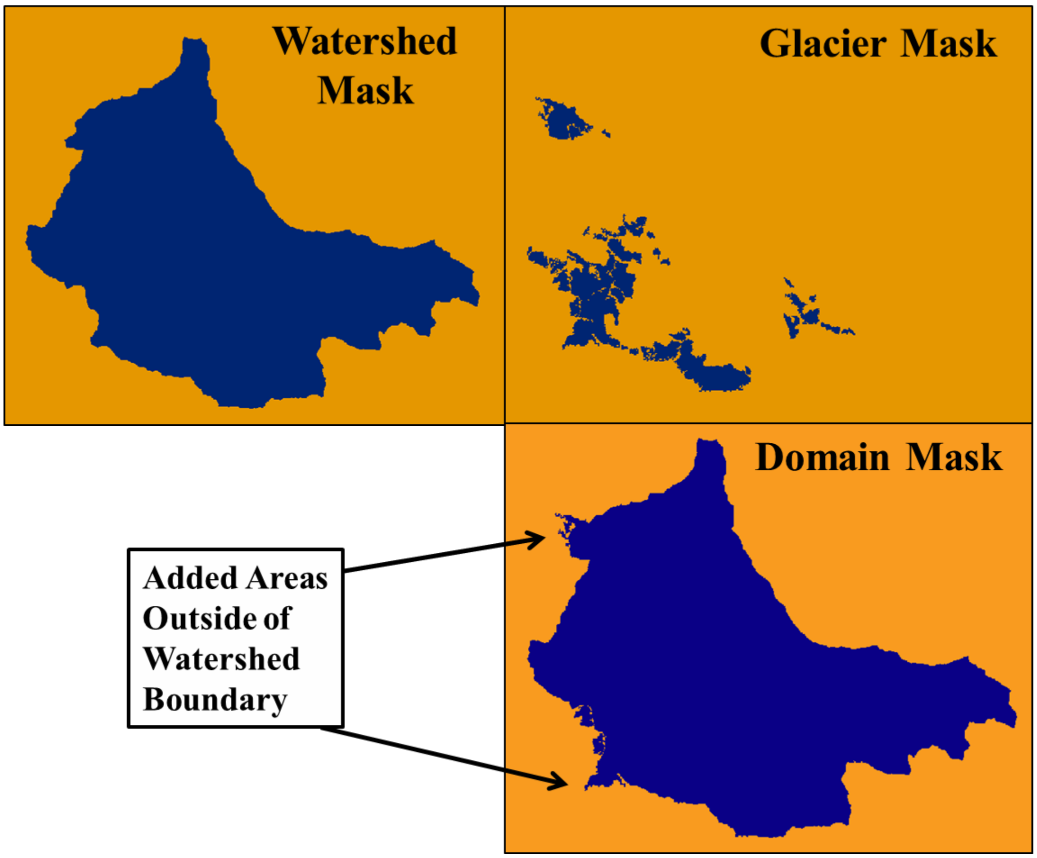
After obtaining the historical glacier GIS dataset, isolate the glaciers that have at least part of their extent within the watershed of interest. Glaciers directly adjacent to the study area watershed should also be selected. Create a subset layer with just these glaciers. Do not clip to the watershed boundary. Include the entire glacier in the new layer even if only part of it enters the watershed. If this layer is a polygon, convert to a raster using the polygon to raster tool.

Reclassify the raster so that non-glaciated pixels have a value of 0. Currently, the code is set up to output glacier mass balance and area for two individual glaciers, which should be reclassified with integer values 6 and 7. All other glaciated areas should have a value of 1 (see below for example).



- ***Glacier Domain Mask***

Similar to the watershed mask, this file identifies an area that includes all the glacial bodies connected to the watershed. Glacier flowsheds do not always correspond to watershed boundaries. Because ice at watershed boundaries can flow into and out of the watershed, this larger mask is required for the glacier model. This domain should be large enough to include all of the ice bodies that have portions that flow into the watershed. Glaciers directly adjacent to the study area watershed should also be included (the same ones as in the glacier mask). See figure below.



The domain should not have any holes in it. If necessary, buffer the glacier extent to remove any "NoData" pixels within the domain.

This can be created using the Mosaic to New Raster tool in ArcMap using the watershed mask and the glacier mask file as inputs.

- ***Glacier Bed Topography***

This file is the elevation field of the entire domain, and represents the topography under the current glacier extent. Simply stated, this file is equal to the DEM outside of the glacier and is less than the DEM under the glaciated areas. The methods *Clarke et al*. 2012 have been used to estimate bed topography in past applications.

Unless ground penetrating radar or other data are available for the study area, the basin domain DEM is used. This likely provides a good estimate where glaciers are relatively small. I used a DEM clipped to the entire rectangular extent, not just the basin mask, since there were some glaciated areas outside of the basin.

- ***Glacier Surface Topography File***

This file is an estimate of the initial ice thickness. This file cannot be created until the SPINUP mode is run, but there are several steps before that can happen. A run using the GLSTATIC option ***must be*** performed, which is necessary to estimate mass balance which is needed for the surface topography file. These steps are outlined below in the "*Running the Model*" section.

One DEMs is needed for the first GLSTATIC run and one DEM is needed for calibration:

1. Create a grid file that represents a thick layer of ice across the entire domain. This can be done by adding 1000m to the domain DEM of the entire area using the Raster Calculator. This layer will ultimately help track changes in mass balance over time (explained more in the "Running the Model" section).

2. Create a DEM that represents a thick layer of ice across only the glaciated areas. Do this by adding 1000m (or some large number) to the glaciated areas. This can be done in a number of ways. I extracted the glaciated DEM area using the Extract by Mask tool with the original DEM being the input file and the glacier mask being the "mask" file. I then used the Raster Calculator to add 1000 to the newly created DEM of just the glacier area. The Raster Calculator can then be used again to add the glacier area DEM plus 1000m layer to the original DEM. This layer will ultimately help determine how much streamflow is coming from the static glaciated areas (explained more in the "Running the Model" section). This can be used in the calibration process. Note: this is not strictly necessary but does help to get baseline glacier melt results during calibration.

- ***Basin Mask File***

This is the same as the watershed mask.

- ***Glacier Mass Balance File***

This file will be created by the DHSVM after the GLSTATIC mode is run. An output file called "balance_sum.bin" will be produced. Convert this file from binary to ascii, add in the basin header (six lines containing the spatial information, gid size, and NoData values), and import back into ArcMap using the ASCII to Raster tool. This file represents the cumulative mass over time and needs to be divided by the number of years in the simulation run (using the Raster Calculator) to get the mean annual mass balance (explained more in the "Running the Model" section).

Running the Model

Model with No Glacier

To run the model without any glacier component (no glaciers are simulated, static or otherwise), set the glacier option under the constants section to NO_GLACIER. This will produce a simulation for basin hydrology that does not include glacier melt. Under this mode type, snow that reaches the density of snow will be removed by the DHSVM.

Dynamic Glacier Modeling

To run the dynamic glacier model, two simulations must be performed first to estimate the mass balance and glacier ice thickness. Note: this is a general procedure for setting up and running the dynamic glacier model and does not include all of the steps for the initial glacier calibration. For more detailed calibration procedure/recommendations, see the “Calibration” section.

1. Run the DHSVM with the glacier component option set to GLSTATIC. This step will estimate the mass balance field for the area. Input files are as follows:

- **Domain Mask File** = the file generated in the *Glacier Domain Mask* step above
- **Glacier Mask File** = the file generated in the *Glacier Domain Mask* step above

➢ In this case, the full domain is used instead of the glacier mask for calibration purposes.

Typically DHSVM can have a habit of accumulation of snow/ice in areas where glaciers do not exist. This phenomena is really small when the model is well parameterized and calibrated, but can be large when not. The problem when running future warmer climate scenarios is that this ice will eventually melt, in turn simulating a future source of water that should not be there. Therefore, the mass is removed as it accumulates. So, prior to imposing this constraint where ice outside of the glacier mask is removed, what I have done, and what I recommend, is that when doing initial model calibration and testing, set the glacier mask to be the same as the domain mask. This way ice can accumulate and the glaciers can flow anywhere they want. In the end when you have a good calibration, the glaciers should stay close to where they are observed to be, and only a minimal amount of ice will accumulate outside the mask. At this point you can go ahead and use the glacier mask file reflecting real historical glacier outlines and you can run your simulations without the worry of generating small artificial ice reservoirs that will melt in the future.

- **Glacier Bed Topo File** = basin DEM from the *Glacier Bed Topography* step above
- **Glacier Surface Topo File** = use the DEM that represents a thick layer of ice across the entire domain (DEM+1000m everywhere).
- **Basin Mask File** = watershed mask
- **Glacier Mass Balance File** = not required. I use a placeholder such as the glacier surface topo file

Change the input file for the DHSVM. I recommend saving a new input file for the GLSTATIC model run. This simulation should be run for a time period of 10 years or more to get an accurate measure of mean annual mass balance.

After the model finishes, an output file called “balance_sum.bin” will be produced. This represents the mass balance for the simulation period. The annual mass balance is calculated by tracking the changes in ice and snow water equivalent through time. Having a thick layer of ice everywhere is required so that negative mass balances can be tracked at elevations outside of the current ice extent.

Convert this file from binary to ascii using “MyConvert,” add in the basin header (six lines containing the spatial information, gid size, and NoData values), and import back into ArcMap using the ASCII to Raster tool. This file represents the cumulative mass over time and needs to be divided by the number of years in the simulation run (using the Raster Calculator) to get the mean annual mass balance.

Convert the mean annual mass balance layer to ascii, transfer to the Unix machine, convert into binary using “MyConvert.” This file will be used as the Glacier Mass Balance file for the SPINUP run.

Temperature and precipitation fields have also been used with a temperature index model to generate the annual mass balance field; however, using DHSVM to generate the field includes the representation of energy balance terms as well as the effects of topography (shading, skyview, etc.).

2. Now that the bed topography (the DEM) and mass balance fields have been created, you must estimate initial glacier ice thickness. This requires running the model for a spin-up time period so that the ice thickness profiles are physically realistic and mathematically stable. Change the glacier mode to SPINUP. Executing the model with this option will run the glacier model independently at an annual time step for 1000 years using the annual mass balance field that is specified as an input (Glacier Mass Balance File). Input files should be as follows:

- **Domain Mask File** = the file generated in the *Glacier Domain Mask* step above
- **Glacier Mask File =** the file generated in the *Glacier Domain Mask* step above
- **Glacier Bed Topo File** = basin DEM from the *Glacier Bed Topography* step above
- **Glacier Surface Topo File** = not required. I use the DEM that represents a thick layer of ice across the entire domain (DEM+1000m everywhere) as a placeholder.
- **Basin Mask File** = watershed mask
- **Glacier Mass Balance File** = mass balance file created from the previous model run (GLSTATIC) that was divided by the number of simulation years.

Change the input file for the DHSVM. I recommend saving a new input file for the SPINUP model run. This will output the ice thickness file (h_spinup.bin). Surface topography of the watershed including the glaciers can be calculated from this file.

Import h_spinup.bin into ArcMap using the steps outlined in the previous section. Visualize the simulated glacier extent at end of spinup period and compare with the observed extent. If the mass balance field does not accurately represent the forcings that control the glaciers' current extent, the mass balance field may need to be iteratively altered so that the glaciers will grow to appropriately match the observed extent. For example, if the mass balance field was generated from recent meteorological forcing data that was much warmer than the historical time period, the mass balance field is likely too low to grow glaciers of size comparable to what is observed.

Once satisfied with the simulated glacier extent from the spinup time period, use the raster calculator in ArcMap to add the ice thickness (h_spinup) to the DEM. This will serve as the calculated glacier surface topography (ice thickness + bed topography) as an input for the coupled model simulations (GLDYNAMIC).

3. To run the dynamic coupled glacier-hydrology model, change the input file for the DHSVM and set the glacier mode to GLDYNAMIC.

- **Domain Mask File** = the file generated in the *Glacier Domain Mask* step above
- **Glacier Mask File =** the file generated in the *Glacier Domain Mask* step above
- **Glacier Bed Topo File** = basin DEM from the *Glacier Bed Topography* step above
- **Glacier Surface Topo File** = Use the ice thickness + DEM layer that was created in the SPINUP.
- **Basin Mask File** = watershed mask
- **Glacier Mass Balance File** = not required.

Calibration

Calibrating the glaciers before calibrating the hydrology is recommended.

Recommended glacier calibration procedure:

1. Run the simulation for just glacier areas and SNOTEL locations under the GLSTATIC option to calibrate the model for accumulation and ablation processes. This is done in ArcMap by altering the domain mask by setting the parts of the watershed that you want to run (i.e. glacier extent and SNOTEL areas) to 1 and the other areas to 0. You can run this for the entire watershed, but the computational efficiency will improve if only the areas of interest are used in the domain. Since the model is set to the static glacier option, the glaciated cells are independent of each other (for the glacier component of the DHSVM) and the entire watershed mask is not needed. Compare mass balance model results to where observations are available. Ideally you would want to compare with accumulation on the glacier because glaciers are at higher elevations than SNOTEL sites, but you have to work with what you have.

sensitive parameters: temperature lapse rate, precipitation lapse rate, maximum snow albedo, glacier albedo

Note: make vegetation class at SNOTEL locations bare, as most of these locations are in clearings

2. Now that you have an accurate simulation of mass balance processes, calculate mean annual mass balance across the entire domain with this calibration (running the model with 1000+ meters of ice everywhere) using the GLSTATIC option. The model will output a mass balance file, which needs to be divided by the number of years in the simulation.

3. Use the mean annual mass balance field to force the spin-up (GLSPINUP option). Since the mass balance reflects current climate which is warmer, the glaciers will not likely grow to historical extent.

4. Iteratively adjust the mass balance field to grow the glaciers to the historical extent. You can do this by adding or subtracting a small amount (e.g. 1 or 2 or 3) to the mass balance field using the raster calculator or by altering parameters within the DHSVM and rerunning the static glacier model to produce a new mass balance output. This will force the model to accumulate more ice, better reflecting historical glaciation. If the glacier is producing too much ice, iteratively decrease the mass balance field until satisfied with the glacier extent.

5. After the glacier calibration is complete, the DHSVM can be calibrated to hydrology.

   Calibration notes:

   - Using the static glaciers option (GLSTATIC), glaciers that have finite mass and cell to cell ice flow is not simulated. Over short timescales of 1-10 years this is a valid assumption depending of the watershed location, relative glacier cover, and drainage area. This will allow the user to calibrate watershed properties (soil, vegetation, temperature, precipitation lapse rates) and have some contribution of glacier melt included. For this application, a surface topography file will need to be created that reflects ice mass with the glacier masked area (e.g., Surface Topography = 100m (or more) + Bed Topography in areas located within the glacier mask.
   - In snowmelt dominated basins, most of the hydrograph will be related to snowmelt. Using the NOGLACIER option, watershed calibration can also be conducted as long as it is recognized that in months where glaciers are expected to contribute the most, streamflow will be biased low.
   - Later calibration efforts to match glacier rates of recession and glacier mass balance

observations will be conducted with the GLDYNAMIC run option.

Calculating Contribution of Glacial Melt to Streamflow

The easiest way to determine the contribution of glacial ice melt to streamflow is to run the calibrated and validated model using the NO_GLACIER mode and then run it again using the dynamic glacier mode. The melt contribution to streamflow is the difference between the streamflow outputs of the two model runs.

Glacier Model Output

gl_sn_cov.txt
Reports snow and glacier extent (km^2) and ice volume (m^3) at monthly timesteps.

gl_cov_glac6_7.txt
Reports glacier area and volume for 2 individual glaciers denoted in the glacier mask file with integers 6 and 7.

balance_glac6_7.txt
Reports specific net balance at a monthly time-step for 2 individual glaciers denoted in the glacier mask file with integers 6 and 7.

balance_sum.bin
Grid of cumulative mass balance across the simulated domain. This can be used to calculate mean annual mass balance field for the SPINUP run.

h_spinup.bin
Grid of ice thickness at the end of the glacier ice spin-up run

Additions to existing DHSVM output files
Glacier ice water equivalent and glacier melt have been added to the Mass.Balance and Aggregated files. Maps of glacier ice water equivalent can be dumped (variable ID #705). IceRemoved is variable included in the calculation of mass balance to track ice mass that is removed from the simulation with NO_GLACIER option.

Miscellaneous

Estimated bed topography: the method suggested above, among others in the literature, require multiple inputs (e.g., thinning rates, distributed mass balance) and the applicability of these methods are limited by the resolution and accuracy of the DEM and size of the glaciers being simulated. Experiments in areas where glacier masses are relatively thin with respect to the DEM resolution, suggest that using the DEM as bed topography does not yield significantly different results than using bed topography estimated using a more complex method.

Comparing the effects of using estimated bed topography and a DEM as inputs for bed topography in the model spinup step in the Bow River Basin (Naz et al., 2014), demonstrated that using the estimated bed topography yielded 10% more glacier volume, and almost no difference in glacier area. The glaciers in the Bow River Basin were estimated to be up to over 300 m thick.

Steady state glacier thicknesses from this spinup method may not be representative of the current/historical transient state of the glaciers. If the glaciers in the couple simulation do not initially recede but do lose mass (and the actual glaciers were observed to recede) it is likely that the glaciers are actually in a thinner transient state. To thin the glaciers to a transient state from the steady state condition one can run the model with current climate forcings, thinning the glaciers without changing their area. The amount of years required to do this is an iterative procedure and is validated when rates of recession are well simulated.