An Approach for Modelling the Hydrologic Role of Glaciers in WEAP

World Bank Project "Assessing the Impacts of Climate Change on Mountain Hydrology: Development of a Methodology through a Case Study in Perú"

October 2008

Prepared by David Purkey (SEI), Thomas Condom (IRD Perú), Marisa Escobar (SEI), Jean Christophe Pouget (IRD Quito), Cayo Ramos (UNALM Lima) y Wilson Suarez (IRD Perú)

General formulation

The general formulation of glaciers in WEAP will use the standard approach to building a WEAP rainfall-runoff model of a mountainous region as a point of departure. In WEAP, rainfall-runoff processes are simulated by first dividing a watershed into sub-watersheds which are the contributing areas above points of streamflow measurement or management control. Further, a sub-watershed area above a "pour point" is divided into \( i \) elevation bands. Each sub-watershed/elevation band is then represented as a unique WEAP catchment object within which temporally variable land cover and temporally variable yet spatially homogeneous climatic conditions can be imposed on a time step-by-time step basis. This document describes an approach for adding a representation of evolving glacial contributions to simulate hydrologic processes to be incorporated into the WEAP rainfall-runoff representation by dividing each elevation band, \( i \), into either a glaciated (\( j=1 \)) or non-glaciated (\( j=2 \)) portion.

The calculations made in implementing the procedure will occur on two time scales, a monthly time step, \( t \), and an annual time step, \( T \), as indicated in a particular equation. In this notation, a subscript \( t=0 \) suggests that the expression pertains to conditions at the beginning of a hydrologic year, \( T \), before any of the monthly time step calculations are carried out. Conversely, the subscript \( t=12 \) indicates that the expression pertains to conditions at the transition between hydrologic years following the completion of all
monthly time step calculation within a year. In this notation \( T, t=12 \) is equivalent to \( T+1, t=0 \). The notation for initial conditions is \( T=0, t=0 \).

**Step 0 – Initial Conditions**

The first step in the process of representing glaciers within a WEAP application will be to define the initial conditions within each computational object used to simulate hydrologic processes. This document deals only with the role played by glaciers located within these computational objects in determining sub-watershed scale hydrologic response as the hydrologic processes in non-glaciated areas will be captured using a separate rainfall-runoff routine that has already been integrated into the WEAP software (Yates et al. 2005).

From recent GIS databases of the spatial extent of glaciers, the surface area of glacial ice within each elevation band of each sub-watershed (a unique WEAP Catchment model object) can be calculated. The overall initial allocation of the actual area within each Catchment, \( A_i \), defined in units of km\(^2\) will then be defined as:

\[
A_j = \sum_{j=1}^{2} A_{T=0, t=0, i, j}
\]

and the total initial extent of glaciers in a sub-watershed will be defined as:

\[
A_{\text{glacier}, T=0, t=0} = \sum_{i=m}^{n} A_{T=0, t=0, i, j=1}
\]

where \( n \) is the total number of elevation bands within a sub-watershed and \( m \) is the lowest elevation band containing glacial ice. This glacier area value has already been calculated for each of the twenty sub-watersheds in the Rio Santa WEAP application suggesting that the GIS analysis pursued to estimate the initial glacial extent is feasible in the Peruvian context. Note that \( A_i \) is constant but the relative proportion between \( A_{j=1} \) and \( A_{j=2} \) will vary after the end of each hydrologic year.

Based on a published empirical relationship that relates glacier ice volume (\( V \)) expressed in km\(^3\) to glacier area for individual glaciers (Bahr et al. 1997), the initial glacial volume in each sub-watershed will be estimated as:

\[
V_{\text{glacier}, T=0, t=0} = c \cdot A_{\text{glacier}, T=0, t=0}^b
\]

Where \( c \) and \( b \) are scaling factors related to the width, slope, side drag, and mass balance of a glacier. Analysis of 144 glaciers around the world glaciers worldwide suggests that factor values of \( b = 1.36 \) and \( c = 0.048 \) (Bahr et al. 1997, Klein and Isacks 1998). The research team decided to use these volume-area correlation factors (Fig. 1 in Bahr et al.
1997) despite the fact that no Andean Glaciers were included in the correlation due to the lack of studies in the zone. It is expected that similar studies will be developed for Andean Glaciers, in which case the correlation factors will be verified (JC Pouget, personal communication). Note that this volume corresponds to the entire initial ice mass within a WEAP sub-watershed and that in using (3) there is an implicit assumption that water equivalent depth over the total glacier surface is uniform. An allocation of this volume between glaciated elevation bands is not attempted. The reason why the volume is not allocated between elevation bands stems from the fact that the existent area-volume relations are based on total glacier volume and area (Fig. 1 in Bahr et al 1997).

**Step 1 – Estimate Runoff from Melting Snow and Ice**

For each monthly time step, $t$, within a hydrologic year, $T$, the contribution to surface runoff from the glaciated portion of a unique Catchment area, $i$, will be estimated based on a modification to the method proposed by (Schaefli et al. 2005). This method, which was developed for the estimation of daily contributions to streamflow from melting snow and ice from glaciers, was modified by Suarez et al. (2008) for use in modeling Peruvian glaciers on a monthly time step. The streamflow contribution due to snow melt from the surface of a glacier within a particular elevation band is:

$$Q_{snow, T, t, i, j=1} = \left\{Q_{snow, T, t-1, i, j=1} \cdot e^{-\frac{t-(t-1)}{K_{snow}}} + \left[P_{liq, T, t, i, j=1} + M_{snow, T, t, i, j=1}\right] \left[1 - e^{-\frac{t-(t-1)}{K_{snow}}}\right]\right\}$$

(5)

where for monthly time step, $t$, during hydrologic year, $T$:

$Q_{snow, T, t, i, j=1}$ = *ith* Catchment discharge from snow reservoir (mm/month)

$K_{snow}$ = time constant (month)

$P_{liq, T, t, i, j=1}$ = liquid rainfall on snow surface in *ith* Catchment (mm/month)

$$P_{liq, T, t, i, j=1} = \begin{cases} P_{T, t, i}, & T_{T, t, i} \geq T_0 \\ 0, & T_{T, t, i} < T_0 \end{cases}$$

(5a)

$P_{T, t, i}$ = *ith* Catchment total monthly precipitation, also used in $j=2$ (mm/month)

$T_{T, t, i}$ = *ith* Catchment monthly average temperature, also used in $j=2$ (°C)

$T_0$ = threshold temperature (°C)

$M_{snow, T, t, i, j=1}$ = snow melt from glacier surface in *ith* Catchment (mm/month)

$$M_{snow, T, t, i, j=1} = \min\left\{S_{Initial, T, t, i, j=1}, M_{pot snow, T, t, i, j=1}\right\}$$

(5b)

$S_{Initial, T, t, i, j=1}$ = snow water equivalent on the glacier surface in *ith* Catchment (mm)

$$S_{Initial, T, t, i, j=1} = S_{Final, T, t-1, i, j=1} + P_{snow, T, t, i, j=1}$$

(5c)
\[ P_{\text{snow}, T, t, i, j=1} = \text{snow accumulation on glacier surface in } ith \text{ Catchment (mm/month)} \]

\[
= \begin{cases} 
0, & T_{T, t, i} \geq T_0 \\
P_{T, t, i}, & T_{T, t, i} < T_0 
\end{cases}
\] \tag{5d}

\[ M_{\text{pot snow, T, t, i, j=1}} = \text{potential snow melt in the } ith \text{ Catchment (mm/month)} \]

\[
= \begin{cases} 
\alpha_{\text{snow}}(T_{T, t, i} - T_0), & T_{T, t, i} \geq T_0 \\
0, & T_{T, t, i} < T_0 
\end{cases}
\] \tag{5e}

\[ \alpha_{\text{snow}} = \text{degree-day factor for snow melt (mm/month/°C)} \]

\( T_0 \) constitutes a threshold value for conversion of liquid precipitation into snow that is defined by the user and may constitute a calibration parameter. According to 5c, for the first month of each hydrologic year the value of \( S_{\text{Initial}} \) will be exclusively the value of \( P_{\text{snow}, T, t, i, j=1} \) given that at the end of the previous year snow either melted or was converted to ice. After the first time step of the water year, each month \( P_{\text{snow}, T, t, i, j=1} \) is defined as function of the current temperature and the threshold temperature for converting water to snow according to 5d.

At the end of each monthly time-step the snow water equivalent accumulated on the surface of the glacier must be updated to account for snow melt runoff.

\[ S_{\text{Final}} T, t, i, j=1 = S_{\text{Final}} T, t-1, i, j=1 + P_{\text{snow}, T, t, i, j=1} - Q_{\text{snow}, T, t, i, j=1} \] \tag{6}

In (5b) it is possible that the potential snow melt in a given month, \( t \), will exceed the actual accumulated amount of snow water equivalents on the surface of the glacier within elevation band \( i \). In this case, all of the snow water equivalents within the band will be melted and the surface of the glacier ice will become exposed. To calculate the portion of a monthly time step during which the glacier surface is snow free, the expression

\[ S_{\text{Free}}_{T, t, i, j=1} = \begin{cases} 
0, & S_{\text{Initial}}_{T, t, i, j=1} \geq M_{\text{pot snow, T, t, i, j=1}} \\
(1 - \frac{S_{\text{Initial}}_{T, t, i, j=1}}{M_{\text{pot snow, T, t, i, j=1}}}), & S_{\text{Initial}}_{T, t, i, j=1} < M_{\text{pot snow, T, t, i, j=1}} 
\end{cases} \] \tag{7}

is evaluated once the final snow melt contribution to runoff is calculated. The fraction inside the parenthesis indicates the portion of the time that the surface was covered with snow, so the complement indicates the portion of the time that the surface was free of snow.

The preceding set of equations will be executed during each time-step, \( t \), to approximate the contribution of melting snow on the surface of the glacier within a given band to surface flow in the Catchment. During time-steps, \( t \), when \( S_{\text{Free}}_{T, t, i, h=1} \) is non-zero, an additional set of equations will be executed to estimate the contribution of melting glacier ice to surface flow in the \( ith \) Catchment.
Where the preceding definitions for snow apply for ice with the modifications that

\[ M_{\text{pot ice}, T, t, i, j=1} = \text{potential ice melt from the } ith \text{ Catchment (mm/month)} \]

\[ a_{\text{ice}} = \text{degree-day factor for ice melt (mm/month/°C)} \]

In (8) the term \( P_{\text{liq}, T, t, i, j=1} \) corresponds to the portion of rain that falls in snow free area, so it was not accounted in (5) where what is accounted for is the portion of rain that falls in show covered area. (8) is only estimated when ice is exposed, in other words when \( S_{\text{Free}} \) is non-zero.

The assumptions implicit in (8) are that ice melt from the snow-free exposed surface of a glacier within an elevation band is not volume limited and that ice melt is blocked when there is snow covering the glacier.

In the preceding equations the parameters \( k_{\text{snow}}, k_{\text{ice}}, a_{\text{snow}} \) and \( a_{\text{ice}} \) were calibrated by Suarez based on observations of glaciers in Peru. These values will be used as the starting point for the WEAP modelling that will occur for the current project.

Note that the output from (5) and (8) are in units of mm, or equivalent depths of water. The actual volumes of water in m^3 associated with precipitation on the surface of a glacier with an elevation band \( i \), the contribution of snow and ice melt to surface flow from the \( ith \) Catchment, and the accumulation of snow on the surface of the glacier are determined by accounting for the surface area of the glacier within the elevation band.

\[ V_{Q_{\text{snow}}, T, t, i, j=1} = \left( \frac{Q_{\text{snow}, T, t, i, j=1}}{1000} \right) \cdot A_{T, t=0, i, j=1} \cdot 1000^2 \text{ (m}^3) \]  

\[ V_{Q_{\text{ice}, T, t, i, j=1}} = \left( \frac{Q_{\text{ice}, T, t, i, j=1}}{1000} \right) \cdot A_{T, t=0, i, j=1} \cdot 1000^2 \text{ (m}^3) \]  

\[ V_{P_{\text{liq}, T, i, j=1}} = \left( \frac{P_{\text{liq}, T, i, j=1}}{1000} \right) \cdot A_{T, t=0, i, j=1} \cdot 1000^2 \text{ (m}^3) \]  

\[ V_{\text{Final}_{T, t, i, j=1}} = \left( \frac{\text{Final}_{T, t, i, j=1}}{1000} \right) \cdot A_{T, t=0, i, j=1} \cdot 1000^2 \text{ (m}^3) \]

\( V_{\text{Final}_{T, t, i, j=1}} \) in (9c) is the synthesis of the volume of water that fell within the time step, which uses the same \( P_{\text{liq}, T, i, j=1} \) variable and is intended for volume calculation, different from the use of \( P_{\text{liq}, T, i, j=1} \) in (5) and (7) to estimate snow and ice melt. The annual balance of \( \Delta V_{\text{liq}, T, i, j=1} \) is estimated in (11) to identify how much liquid water did not make part of snow or ice contributions to streamflow. The sum of liquid and snow phase that do not runoff from the subwatershed at the end of the year is converted to ice and added to the total glacier volume (Step 3, eq. 13).
According to the approach presented in the previous section there is outflow from each band as snow melt and ice melt, however areas and volumes at each elevation band are not tracked. Instead, the volume of ice melt, snow melt and liquid runoff are added at the end of the year to estimate total runoff that is compared to actual runoff measured data at the downstream point of the subwatershed. This comparison constitutes the main criterion for calibration of the model.

**Step 2 – Surface Runoff at the Sub-Watershed Level**

For each monthly time-step then, the volume of surface runoff within a sub-watershed will be the sum of the contribution of melting snow and ice for the glaciated portion of the sub-watershed and the runoff coming from the simulation of rainfall-runoff processes in non-glaciated portions of the sub-watershed.

\[
Q_{\text{sub-watershed}, T, t} = \sum_{i=1}^{n} \left( V_{\text{snow, T, t, i, j=1}} + V_{\text{ice, T, t, i, j=1}} \right) + \sum_{j=2}^{n} Q_{\text{WEAP, T, t, i, j=2}} \quad (m^3) \quad (10)
\]

Note that in (10) the simulate contribution to surface runoff from non-glaciated portions of the sub-watershed will be provided by the internal rainfall runoff routines already implemented in WEAP (Yates et al. 2005). Also note that the WEAP model assumes that all contributions to surface runoff flows from a sub-watershed coming the several elevation bands arrive at the sub-watershed pour point within the time step, \( t \), during which they are generated. Ice and snow flows on the other hand as calculated based on Schaeffli et al. (2005) and Suarez et al. (2005) contain an autocorrelation component that imply that the flow from a current time step is function of the flow from the immediately preceding time step. For monthly time step this autocorrelation may tend to 0 in relation with the glacial area in the watershed.

**Step 3 – Annual Mass Balance**

At the end of the 12 monthly time steps, \( t \), in a hydrologic year, \( T \), it is possible to carry out a mass balance that can be used to assess changes in the overall volume glacial ice within a sub-watershed. This will be done by implementing a mass balance, carried out in units of \( m^3 \) on each of the \( n-m+1 \) elevation bands within a sub-watershed that contained glacial ice at the start of a hydrologic year. The goal is to account for all water that has entered a particular elevation band, \( i \), and has not flowed from the band during the hydrologic year. The input of water to a band comes either through liquid precipitation or snow fall. Outputs of water include the estimated runoff from melting snow and the melting of glacial ice, (5) and (8), which take into consideration runoff associated with liquid precipitation falling on the surface of a glacier within elevation band \( i \), \( P_{\text{liq}, T, t, i, j=1} \). Considering first the liquid phase, the annual mass balance is:

\[
\Delta V_{\text{liq}, T, j=1, i} = \sum_{i=1}^{12} \left( \sum_{j=1}^{12} V_{\text{liq, T, t, i, j=1}} \right) = \left( \sum_{j=1}^{12} V_{\text{snow, T, t, i, j=1}} + \sum_{j=1}^{12} V_{\text{ice, T, t, i, j=1}} \right) \quad (m^3) \quad (11)
\]

If this balance is positive the implication is that some portion of the liquid water that has fallen within the elevation band has not been offset by liquid water leaving the band, and
as a result, on net, there is a volume of liquid water free within the elevation band at the end of the hydrologic year.

The annual mass balance in snow is actually being calculated dynamically throughout the hydrologic year based on (5) and (6). The mass balance for the snow phase at the end of the hydrologic year $T$ is

$$\Delta V_{\text{snow}, T, t=12, i} = VS_{\text{Final} T, t=12, i, j=1} \quad (m^3)$$

expressed as a water equivalent. The total net accumulation of water within the $i$th Catchment during hydrologic year, $T$, expressed as a mass ($\Delta M$) in units of g, is

$$\Delta M_{\text{water}, T, i=12, i} = (\Delta V_{\text{eq}, T, t=12, i} + \Delta V_{\text{snow}, T, t=12, i}) \cdot \rho_{\text{water}} \cdot 100^3 \quad (g)$$

where $\rho_{\text{water}}$ is the density of liquid water expressed in units of g/cm$^3$.

Here an assumption is invoked that at the end of the hydrologic year, $T$, all mass of water within a Catchment, $i$, is frozen and converted to ice. In this case the change in the volume of ice within the $i$th Catchment during hydrologic year, $T$, is

$$\Delta V_{\text{ice}, T, t=12, i} = \frac{\Delta M_{\text{water}, T, i=12, i}}{\rho_{\text{ice}} \cdot 100^3} \quad (m^3)$$

where $\rho_{\text{ice}}$ is the density of frozen ice expressed in units of g/cm$^3$.

Based the change in ice volume within each elevation band $i$ in (13) it is possible to estimate the position of the point where the change in mass is essentially zero for the hydrologic year. This will be done by sequentially comparing $\Delta V_{\text{ice}, T, i=12, i}$ to $\Delta V_{\text{ice}, T, i=12, i+1}$ to find a point where the mass balance transitions from a negative value to a positive value. Once this point is found the approximate elevation of the point of equilibrium will be:

$$E_{\text{equib}} = \frac{E_{i+1} - E_i}{\Delta V_{\text{ice}, T, i=12, i+1} - \Delta V_{\text{ice}, T, i=12, i}} - E_i$$

Where $E_i$, $E_{i+1}$, and $E_{\text{equib}}$ are the mid-elevations of bands $i$ and $i+1$ and the elevation of the approximate point of annual water balance equilibrium.

From the annual mass balance conducted on each of the $m$ elevation bands containing ice at the start of a hydrologic year $T$ it will also be possible to estimate the overall change in the mass of glacial ice within a sub-watershed.
\[ \Delta V_{\text{glacier}, T, t=12} = \sum_{i=0}^{m} \Delta V_{\text{ice}, T, t=12, i} \]  
\text{(m}^3\text{)}  
\text{(16)}

**Step 3 – Annual Glacier Geometry Evolution**

Based on the value of (16), it will be possible to adjust the overall volume and extent of the glacial ice within a sub-watershed prior to moving on to the subsequent hydrologic year. Ideally this would be done by assessing the internal dynamics of ice movement within the glacier. This is likely beyond the scope of both the current project which focuses on the water management implication of glacial change and the available data in most glaciated regions of the world. As such a simplifying model of the redistribution of ice, which assumes that changes in the total volume of ice manifest themselves at the low part or tongue of the glacier, will be used. The first step in the process is to estimate the new estimated surface area of the glacier at the end of the hydrologic year \(T\).

\[ A_{\text{glacier}, T, t=12} = \frac{V_{\text{glacier}, T, t=0} + \Delta V_{\text{glacier}, T, t=12}}{1000^3} \]  
\text{(km}^2\text{)}  
\text{(17)}

The next step is to assess the estimated change in the surface area of the glacier during the hydrologic year.

\[ \Delta A_{\text{glacier}, T, t=12} = A_{\text{glacier}, T, t=12} - A_{\text{glacier}, T, t=0} \]  
\text{(18)}

Two approaches will be explored for adjusting the area of the glacial at the lowest elevation bands.

**Approach 1: Defining a maximum glacial area \(\text{Max}A_i\) at the lowest band**

The assumption is that the change in surface area will be concentrated within the lowest elevation band containing ice, \(i=m\), during the hydrologic year, within limits. The minimum limit is that all of the glacier surface area within the band is removed and the maximum limit is a user defined maximum extent of glacial ice within the elevation band, \(\text{Max}A_i\). In this case the updated area in elevation band \(i=m\) will be

\[ A_{T, t=12, i=m} = \begin{cases} 0, & A_{T, t=0, i=m} + \Delta A_{\text{glacier}, T, t=12} < 0 \\ A_{T, t=0, i=m} + \Delta A_{\text{glacier}, T, t=12}, & \text{Max}A_i \geq A_{T, t=0, i=m} + \Delta A_{\text{glacier}, T, t=12} > 0 \\ \text{Max}A_i, & A_{T, t=0, i=m} + \Delta A_{\text{glacier}, T, t=12} > \text{Max}A_i \end{cases} \]  
\text{(19)}

With this approach, \(\text{Max}A_i\) could be defined based on geomorphic parameters that would indicate the likelihood of an area within the elevation band glacier to be lost. For instance, the slope of sub-bands within a given elevation band could be used to decide what portion of area is likely to be lost, so that areas with higher slopes will be likely to melt and areas with lower slopes will be likely to stay. \(\text{Max}A_i\) will be an estimate of the glacial areas that
are likely to stay. A drawback of this approach is that the model will be dependent on additional GIS processing implying additional controlling variables inside the glacier model.

From (18) it is possible to calculate the residual of the overall change in the glaciated area that could not be accounted for within elevation band \( i=m \).

\[
RA_{T,t=12,i=m} = \begin{cases} 
A_{T,t=0,i=m} + \Delta A_{\text{glacier},T,t=12}, & A_{T,t=0,i=m} + \Delta A_{\text{glacier},T,t=12} < 0 \\
0, & Max A_i \geq A_{T,t=0,i=m} + \Delta A_{\text{glacier},T,t=12} > 0 \\
A_{T,t=0,i=m} + \Delta A_{\text{glacier},T,t=12} - Max A_i, & A_{T,t=0,i=m} + \Delta A_{\text{glacier},T,t=12} > Max A_i 
\end{cases}
\quad (20)
\]

If \( RA_{T,t=12,i=m} \) is negative then (18) is repeated for next upslope elevation band, \( i=m+1 \), by replacing \( \Delta A_{\text{glacier},T,t=12} \) with \( RA_{T,t=12,i=m} \) in the expression. In an extreme case of \( \Delta A_{\text{glacier},T,t=12} \) a residual for \( RA_{T,t=12,i=m+1} \) could also be calculated according to a recalculation of (19) and (18) could be implemented for the elevation band \( i=m+3 \), and so on.

If \( RA_{T,t=12,i=m} \) is positive then a new downslope elevation band that contains ice will be added for the subsequent hydrologic year. Here \( A_{T+1,t=0,i=m-1} \) will be set equal to \( RA_{T,t=12,i=m} \) with the possibility in the extreme case that \( RA_{T,t=12,i=m} \) exceeds \( A_{max_{m-1}} \) that additional downslope elevation bands could be added.

The final step in the annual adjustment to the glacial extent in a sub-watershed will be to compensate for change in the extent of glacial ice in the areas defining the non-glaciated portion of a particular elevation band \( i \).

\[
A_{T,t=12,i,j=2} = A_i - A_{T,t=12,i,j=1}
\quad (21)
\]

**Approach 2: Defining a depth parameter** \( k_{i=m} \) **at the two lowest bands**

An alternative approach to the one proposed above involves the assumption of a differential depth at the two lowest elevation bands. Instead of defining \( Max A_i \), the adjustment of the areas within the two lowest elevation bands will be based on a depth parameter \( k_{i=m} \) and \( k_{i=m+1}=c \cdot k_{i=m} \), so that the area is reduced as function of the depth of the glacier in the elevation band.

\[
A_{T,t=12,i=m} = A_{T,t=0,i=m} \cdot k_{i=m}
\quad (22)
\]

\[
A_{T,t=12,i=m+1} = A_{T,t=0,i=m+1} \cdot c k_{i=m}
\quad (23)
\]

An implication of this approach would be that the depth of the glacier would not be uniform anymore. With and initial \( c=1.2 \), \( k_{i=m} \) would constitute a parameter that will be adjusted during calibration and would allow the control of the depth evolution of the two lowest elevation bands, given that

\[
h_{T,t=12,i,m} = \bar{h}_{ave} \cdot k_{i=m}
\quad (24)
\[ h_{T,i,j=12,i=m+1} = h_{\text{ave}} \cdot c_{i=m} \tag{25} \]

Where

\[ h_{\text{ave}} = \frac{A_{\text{glacier},T,i=12}}{V_{\text{glacier},T,i=12}} \tag{26} \]

The final implementation of Approach 2 will depend on whether there are depth data to corroborate the parameters \( k_{\text{sam}} \) and \( c \). It may be possible to obtain data on specific subwatersheds, but there may not be data for corroboration at the scale of the whole watershed.

**Step 4 – Calibration**

The key criterion for calibration is the adjustment of parameters to obtain measured glacier flow. The volume of ice melt and snow melt and liquid runoff are added at the end of the year and compared to actual runoff measured data at the downstream point of the subwatershed. The observed streamflow at the sub-watershed pour points will be used as another calibration target through a comparison with the results of (10).

The threshold value for conversion of liquid precipitation into snow, \( T_o \) will be defined by the user and although the value needs to be between a physically based range, it can also be used as calibration parameter.

The approaches for adjusting the area of the glacier at the lower elevation bands will also make use of calibration parameters, either \( \text{MaxAi} \) or \( k_{\text{sam}} \). Depending on data availability for comparing model data to glacier areas and depths, the parameters will be calibrated until modelled areas are comparable to actual areas.

An additional calibration metric will be using the \( E_{\text{equib}} \) calculated in (15) and compare it to field data where available and to the value to the position of the Equilibrium Line Altitude (ELA) which is defined for the hydrologic year according the equation derived in Condom et al. (2007):

\[
ELA_T = 3427 - 1148 \left( \log_{10} \left( \sum_{i=1}^{n} A_{T,i,j=1} \frac{1}{12} \sum_{j=1}^{12} T_{i,j} \right) + \frac{\sum_{i=1}^{n} A_{T,i,j=1} \frac{1}{12} \sum_{j=1}^{12} T_{i,j}}{0.007} + \frac{1}{n} \sum_{i=1}^{n} E_i \right) \tag{27} 
\]

The calculation of ELA will allow additional check of the results for calibration runs, but will also allow the tracking of the evolution of the glacier for future climate change scenarios.

The values of the calibration parameters \( k_{\text{snow}}, k_{\text{ice}}, a_{\text{snow}}, a_{\text{ice}}, \) and \( T_o \) will be adjusted until a reasonable correspondence between the observed and simulated streamflows at the pour points is obtained, and until a correspondence between annual evolution of \( E_{\text{equib}} \), ELA field data and \( ELA_T \) in (27) is achieved.

**References**


