SWAT+GL:
Opportunities & Challenges in Hydroglaciological Modeling Using SWAT+

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Motivation

SWAT+ widely used in alpine & glaciated catchments

- Despite strong deficiencies with respect to glaciers!

Are glaciers neglected?

Past efforts often focus on simplistic approaches

Shouldn‘t we provide an advanced „built-in“ glacier routine?

Past efforts not freely or easily accessible

- FAIR principles

Shouldn‘t we promote accessibility & transparency?

2023/2024: **SWAT-GL**

Based on SWAT2012

2024/2025: **SWAT+GL**

Based on SWAT+

SWAT+GL

SWAT+GL = A revised version of **SWAT+**:

incorporating **Glacier Processes!**

Core Elements:

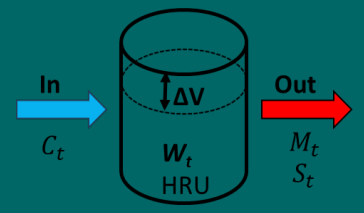
1. **Glacier Mass Balance Routine**
   - Melt, Accumulation, Sublimation (daily)
2. **Glacier Evolution Routine**
   - (Dynamic) Glacier Change
   - Retreat, Advance (restricts e.g. flow)

SWAT+GL – Core Elements

SWAT+GL: A revised version of **SWAT+** accounting for **glacier processes** & **extended snow processes**

1. Mass Balance

- Melt
- Accumulation
- Sublimation



$$W_t = W_{t-1} - M_t \cdot (1 - \beta_f) - S_t + C_t$$

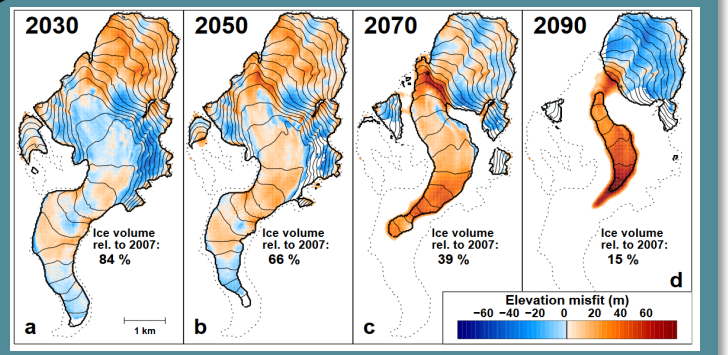
W:	*Water Equivalent of Ice [mm]*
M:	*Glacier Melt [mm/d]*
β_f*:*	*Refreezing Rate [-]*
S:	*Sublimation [mm/d]*
C:	*Glacier Accumulation [mm/d]*

Annual Dynamic

2. Glacier Evolution

Dynamic Glacier Change

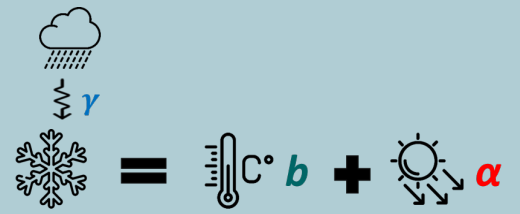
- Retreat & Advance
- Δh-parameterization: ice thickness change Δh = function of elevation



Reference: Huss et al. 2010

3. Snow Extensions

- 4 additional snowmelt routines
- Time-varying lapse rates
- Mixed precipitation



$$Melt_{default} = b(T - T_{melt})$$
$$Melt_{HTI} = (b + \alpha \cdot Rad)(T - T_{melt})$$
$$Melt_{ETI} = b(T - T_{melt}) + \alpha \cdot Rad$$
$$b_{wet} = b + \gamma(P - P_{thr})$$

Glacier Module:
1. Mass Balance

Mass Balance: Glacier Melt

$$W_t = W_{t-1} - \boxed{M_t \cdot (1 - \beta_f)} - S_t + C_t$$

$$M_t = \begin{cases} \left(\frac{T_{ice} + T_{mx,t}}{2} - T_{gmlt}\right) \cdot b_{gmlt}, & if\ T_{mx,t} > T_{gmlt}\ and\ A_{sc} < A_{gc} \\ 0, & if\ T_{mx,t} < T_{gmlt}\ or\ A_{sc} < A_{gc} \end{cases}$$

Wt:	*Water Equivalent of Ice [mm H20]*
Tmx:	*Max. Daily Temp. [°C]*
Tgmlt:	*Threshold Temp of Glacier Melt [°C]*
bgmlt:	*Ice Melt Factor [mm/(d*°C)]*
Asc:	*Snow Cover Fraction of Subbasin [-]*
Agc:	*Glaciated Fraction of Subbasin [-]*
Tice:	*Ice temperature*

$$b_{gmlt} = \frac{(b_{gmlt,mx} + b_{gmlt,mn})}{2} + \frac{(b_{gmlt,mx} - b_{gmlt,mn})}{2} \cdot \sin\left[\frac{2\pi}{365}(t - 81)\right]$$

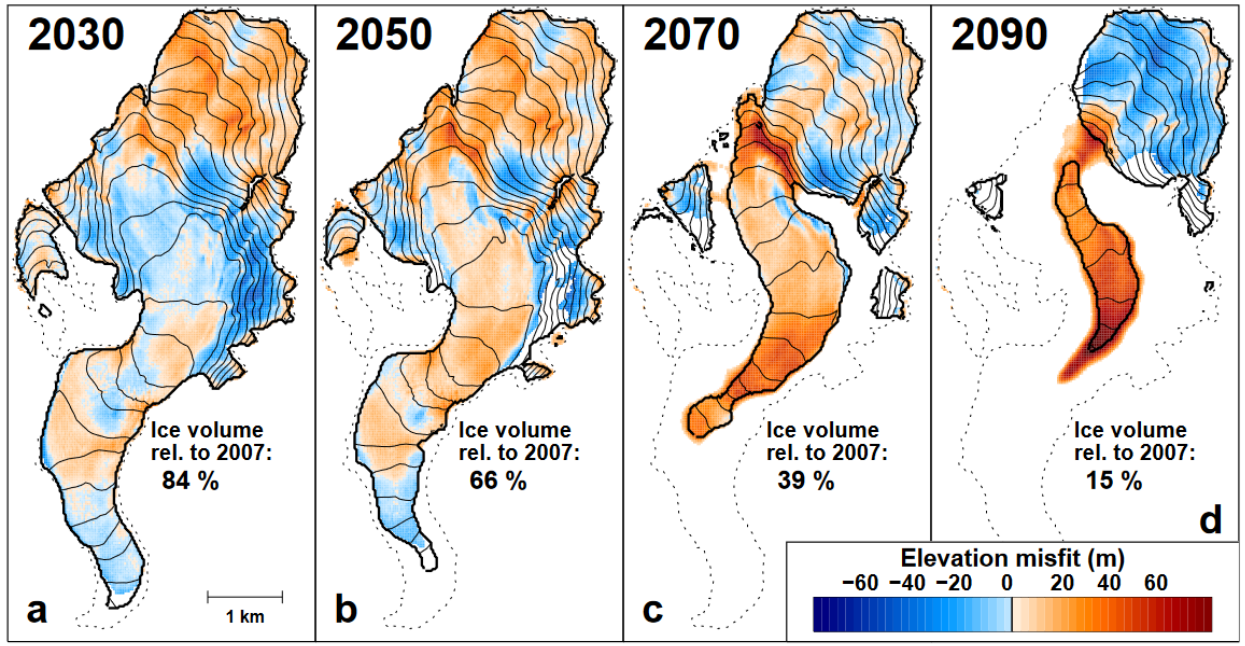
bgmlt,mx:	*Melt factor June 21 [mm/(d*C°)]*
bgmlt,mn:	*Melt factor December 21 [mm/(d*C°)]*
T:	*Day of year [-]*

- **Degree-Day Approach** like for snow
- Occurs when $\boldsymbol{T_{gmlt}}$ **exceeded** & **snow-free**
- **Albedo** of ice < albedo of snow
  - Thus: $b_{gmlt} > b_{smlt}$
  - If $b_{gmlt} < b_{smlt}$ then $b_{gmlt} = b_{smlt}$ (user choice)
- **Refreezing factor β_f** to control high melt rates
  - 0-30% of glacier melt able to refreeze
- Ice temperature considered via ice lag factor to offer delay opportunities

Glacier Module:
2. Glacier Evolution

SWAT+GL: Glacier Evolution

Glacier Evolution = Representation of **spatio-temporal** glacier **dynamics** such as **advance** & **retreat**



Reference: Huss et al. 2010

Concept

- Annual **mass balance changes translated** to **glacier area changes**
  - Elevation-dependent transfer
- **Δh-Parameterization** *(Huss et al. 2008)*
  - Rlationship of ice thickness change & elevation

Glacier Evolution: Δh-Parameterization

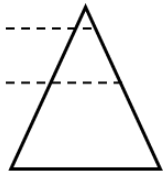
Δh = Normalized ice thickness change

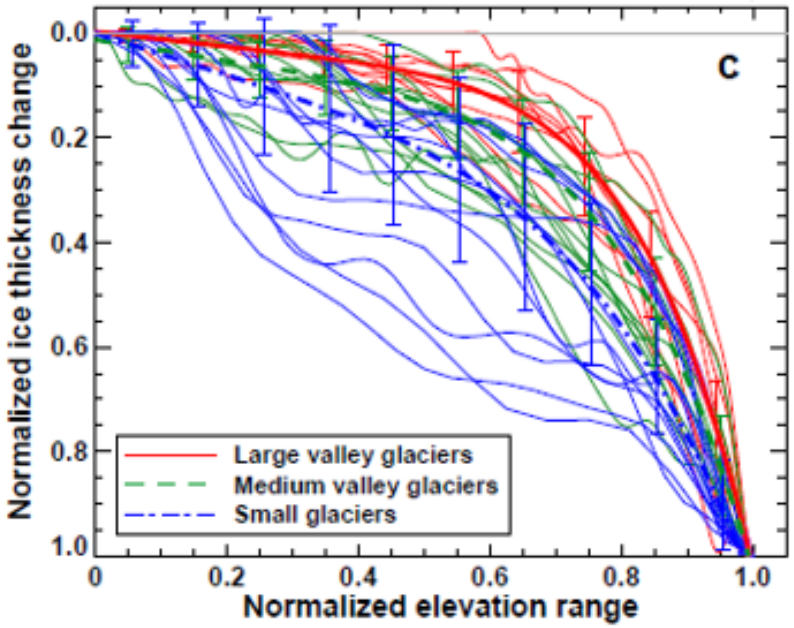
- Relationship depends on glacier size!
- Glacier is split in Elevation Sections (ES)

Daily MB Calculation (HRU)

Annual Aggregation (Subbasin)

Δh_1 ⟷ Elevation 1
Δh_2 ⟷ Elevation 2
…
Δh_n ⟷ Elevation n





Source: Huss et al. 2010

$\Delta h = (h_n + a)^\gamma + b \cdot (h_n + a) + c$

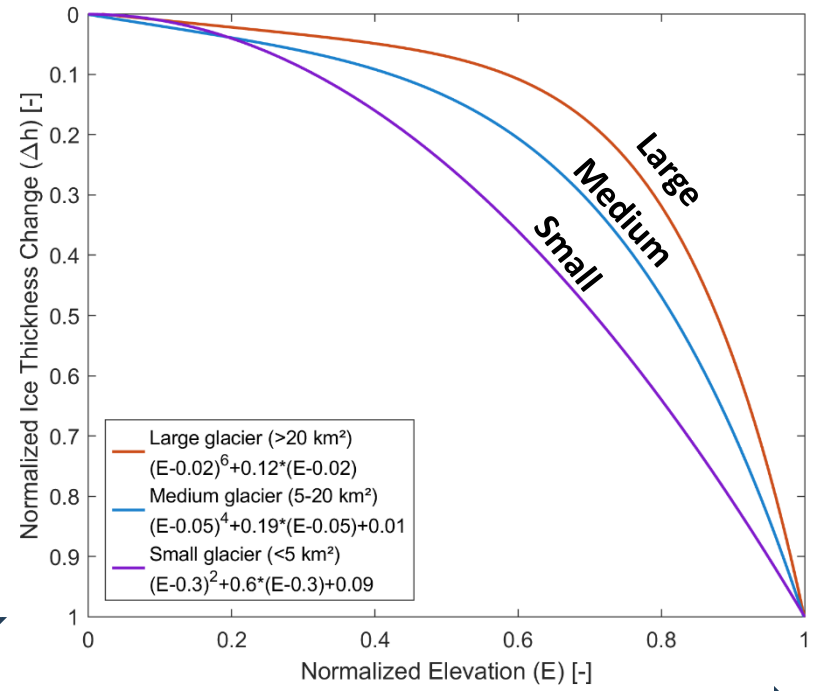
$$f_s = \frac{dV_a}{\sum_{i=1}^{n} A_i \cdot \Delta h_i}$$

$$h_{i,1} = h_{i,0} + f_s \cdot \Delta h_i$$

If $h_{i,1} \leq 0$ retreat

Lowest Ablation

Highest Ablation



Highest Part → Glacier Terminus

SWAT+GL:
Technical Implementation

SWAT+GL: Requirements

Inputs

Data Requirements
- Glacier thickness
- Glacier outlines

Input Files
- 4 new input files
- 5 modified input files

glacier_hrus.gl
swat_gles.gl
swatgl_codes.gl
swatgl_parameters.gl

cal_parms.cal
file.cio
hydrology.hyd
parameters.bsn
snow.sno

Preprocessing

- Define ES spacing
- Modify Land Use map & add new class to crop database
- Determine initial glacier thickness & area per ES

Outputs

Output Files
- 1 new output file
  - Infos on mass balance estimations
- Modified files w. infos on melt, accumulation etc. for different spatial objects:
  - hru_wb files
  - lsu_wb files
  - basin_wb files

gl_mb_aa.txt

basin_wb_aa.txt

...

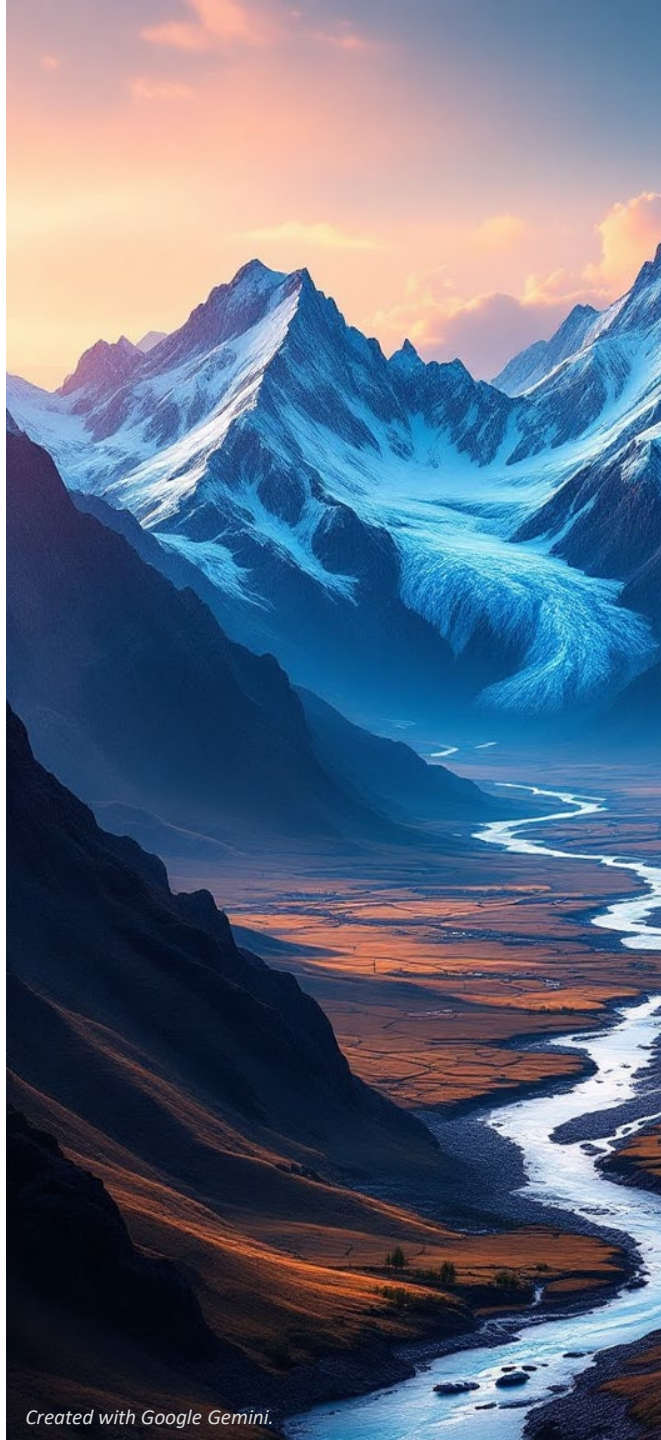
Created with Google Gemini.

SWAT+GL: Example Output Water Balance File

E.g. *basin_wb_aa.txt*

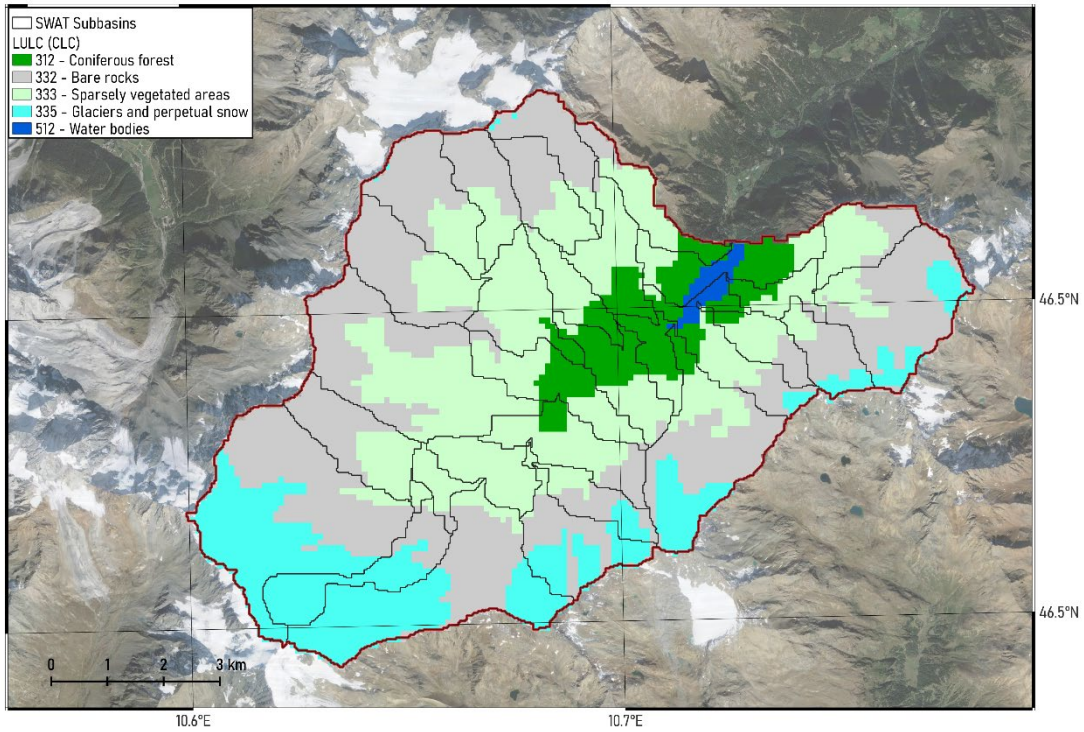
MODULAR Rev 2024.61.0

precip	snofall	snomlt	glmlt	glacc	surq_gen
mm	mm	mm	mm	mm	mm
2287.661	2086.251	1159.888	967.103	907.794	1418.407



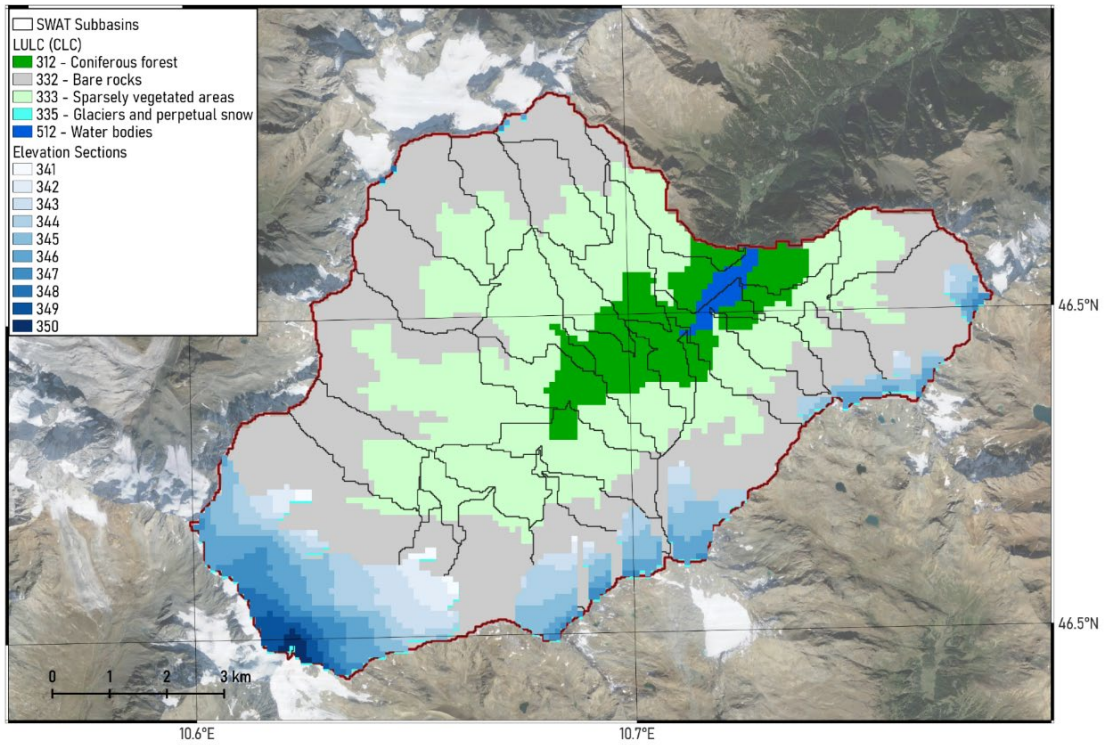
SWAT+GL: Preprocessing Land Use Map

Status Quo



- Standard Land Use Map

What we Need



- Modified Land Use Map
  Considering Sections of Glacier Elevation
  Logically, DEM information required here

SWAT+GL: New Parameters

Glacier

GLMTMP: Glacier melt temperature

GLMFMX: Max. glacier melt factor

GLMFMN: Min. glacier melt factor

F_frz: Refreezing factor

F_accu: Accumulation factor

Gl_lag: Glacier melt lag factor

Tfac_i: Temperature index factor for HTI/ETI (ice)

Rfac_i: Radiation factor for HTI (ice)

Srfact_i: Short-wave radiation factor for ETI (ice)

Snow

Tfac_s: Temperature index factor for HTI/ETI (snow)

Rfac_s: Radiation factor for HTI (snow)

Srfac_s: Short-wave radiation factor for ETI (snow)

Pr_fac: Melt factor for rain on snow events

F_exp: Exponential melt factor for ExpTi

Tmix_ul: Mixed precipitation threshold

Pthr: Rainfall threshold for additional melt

Other

Klat: Lateral hydraulic conductivity

Surlag: Spatially distributed runoff lag factor

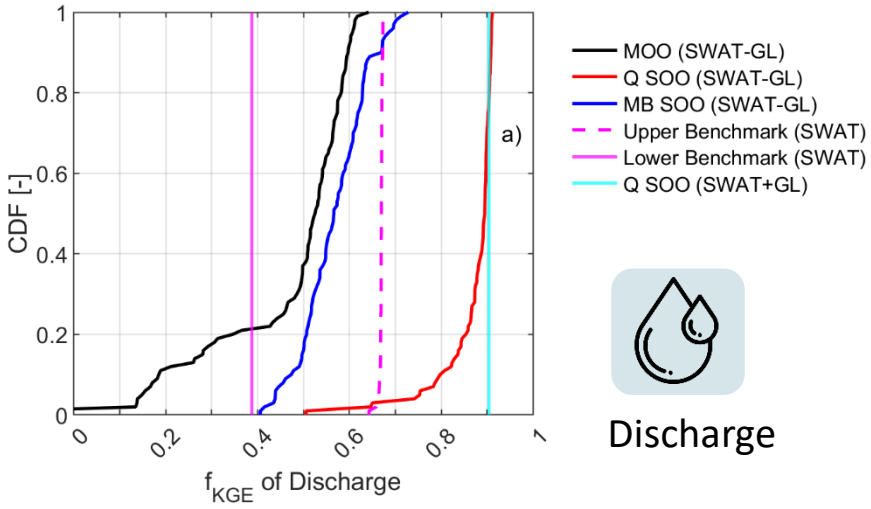
TLAPS: Spatially distributed temperature lapse rates

PLAPS: Spatially distributed precipitation lapse rates

Note:
Different parameter combinations exist as not all parameters are active but dependent on what concepts uses trigger via the swatgl_codes file
Italic parameters indicate already existing global parameters that were changed to be spatially distributed represented

SWAT+GL:
What Can You Expect?

Example Application: Benchmarking SWAT-GL (SWAT+GL coming soon)

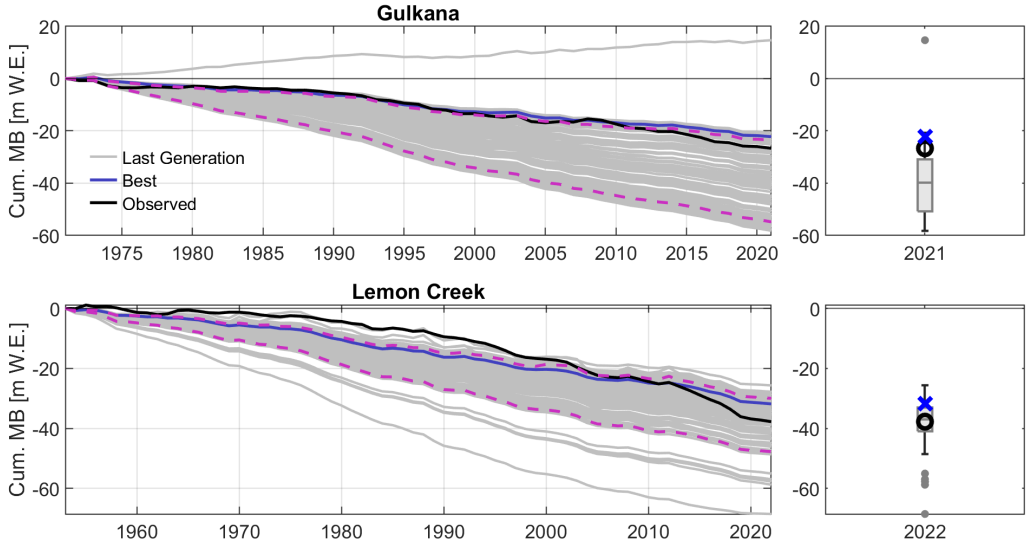


Discharge

Published applications of SWAT-GL (not yet SWAT+GL):

- *Merits and Limits of SWAT-GL (2024):*
  Schaffhauser, T., Hofmeister, F., Chiogna, G., Merk, F., Tuo, Y., Machnitzke, J., Alcamo, L., Huang, J., and Disse, M.: Merits and Limits of SWAT-GL: Application in Contrasting Glaciated Catchments, Hydrol. Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/hess-2024-89, in review, 2024.
- *SWAT-GL: A new glacier routine for SWAT (2024):*
  Schaffhauser, T., Tuo, Y., Hofmeister, F., Chiogna, G., Huang, J., Merk, F., & Disse, M. (2024). SWAT-GL: A new glacier routine for the hydrological model SWAT. JAWRA Journal of the American Water Resources Association, 60(3), 755–766. https://doi.org/10.1111/1752-1688.13199

High transferability of SWAT-GL results to SWAT+GL!



Glacier

SWAT+GL:
Further Changes

SWAT+GL: New Snow Concepts

Snowmelt:

I. Wet Degree-Day Model (**Rain-on-Snow**)

II. Temperature-Index (TI) after *Hock et al. 1999* **(HTI)**

III. Enhanced TI after *Pelicciotti et al. 2017* **(ETI)**

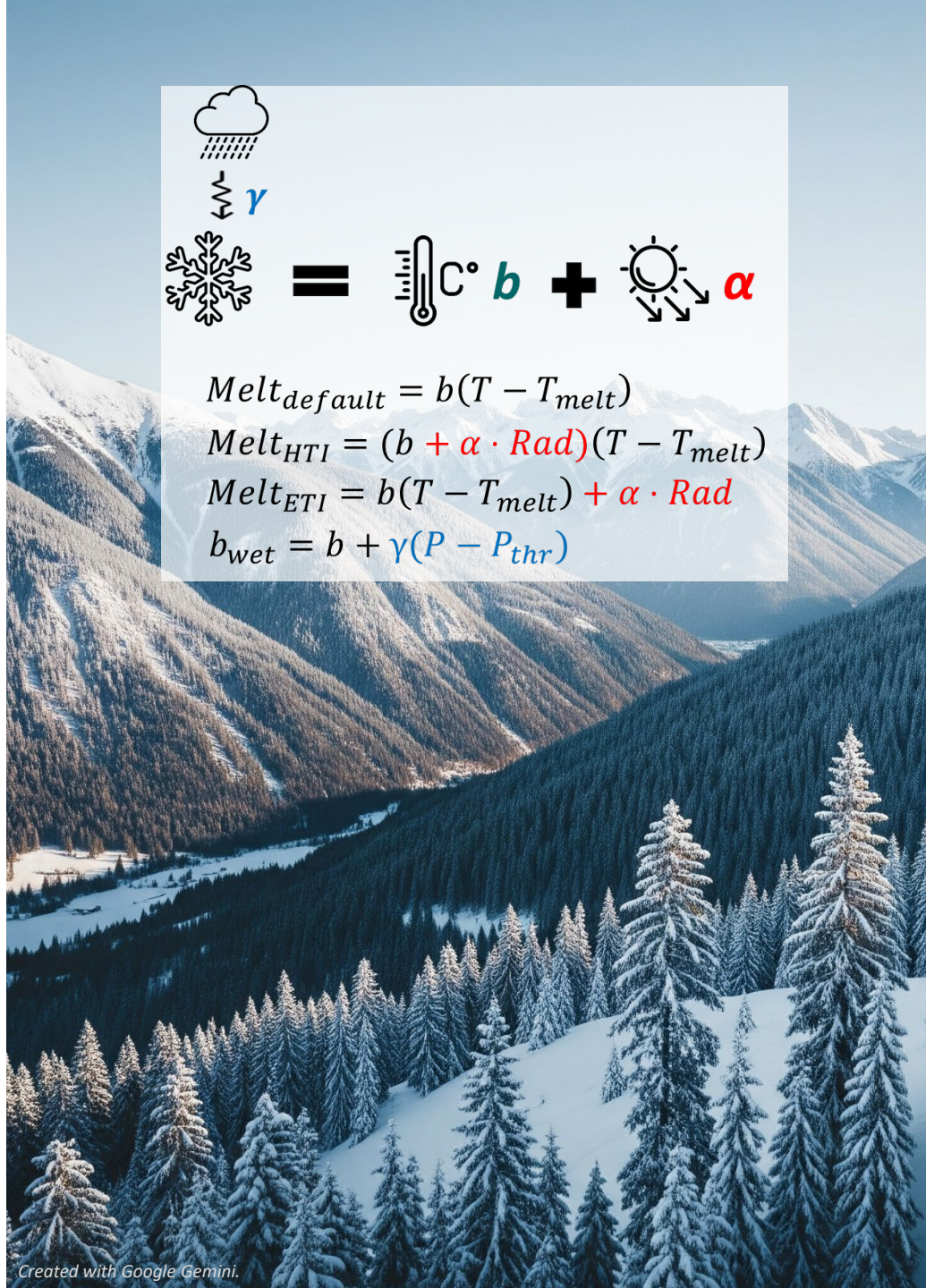
IV. Exponential TI after *Magnusson et al. 2014* **(ExpTI)**

Precipitation:

I. Mixed Precipitation (Rain & Snow)

II. Seasonally Varying Lapse Rate

III. Snow Redistribution (coming soon)



SWAT+GL:
Summary, Limits, Outlook

SWAT+GL: Challenges & Outlook

Spatial integration via subbasins & land use modification

- Future version: Glaciers “own” object (like gwflow, wetlands etc.)

Further concepts will come!

- Permafrost!

Currently working on official SWAT+ integration

- Hopefully coming soon!

Created with Google Gemini.

Summary & Conclusion

- SWAT+GL provides built in opportunities to robustly model mountain hydrology
  - …high applicability in data-scarce environments!
- Readily & easily accessible to encourage the community to share code and models and to foster model development
- We encourage SWAT+GL application in mountain regions to compensate for weaknesses in SWAT+ standard

How to access?

SWAT+GL

Via GitLab

SWAT-GL

Via GitLab

Thanks for your attention!

Backup Slides