Coupling a Global Glacier Model and Hydrological Model: Constraining Cryospheric Contributions in the Data-Scarce Indus Basin

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OESCHGER CENTRE CLIMATE CHANGE RESEARCH

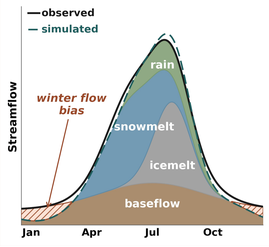
Relevance

- Meltwater from snow and glaciers sustains streamflow in the Upper Indus basin, supporting mountain communities, irrigation and hydropower
- In snow drought conditions, glacier melt can nearly double and shift 1-2 months earlier, partially compensating for reduced snowpack (Nepal et al, 2025)
- As glaciers retreat, groundwater may sustain river flows for some time, before the aquifer itself depletes (Somers et al, 2019)

Reliable water-security projections require accurate representation of baseflow dynamics alongside glacier and snow processes (Mourot et al, 2025).

Problem

Hydrological models often underestimate winter flow in glaciated catchments, pointing to insufficient representation of subsurface storage and processes.



Aim

- Run the coupled **Raven-GloGEM** (Berg et al, 2026) model on eight glaciated Upper Indus catchments.
- Add **deep reservoir** layer for multi-year storage representation
- Add **glacier ↔ groundwater connectivity**, with a fraction (f_{GW}) of the glacier runoff entering the subsurface slow reservoir
- Calibrating on **KGE** and a low-flow **weighted KGE** to specifically target low flows during calibration

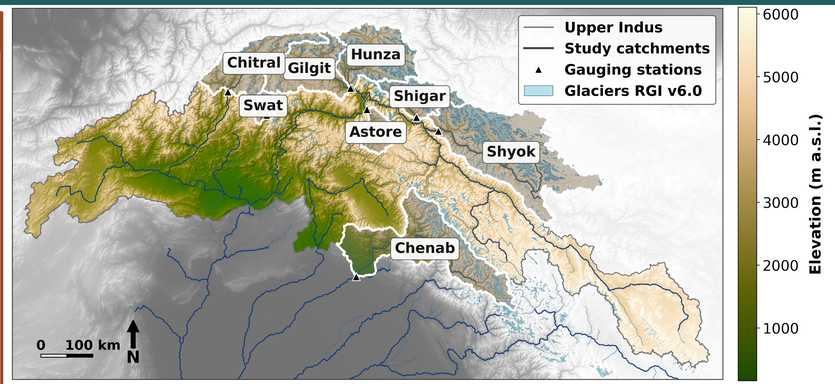
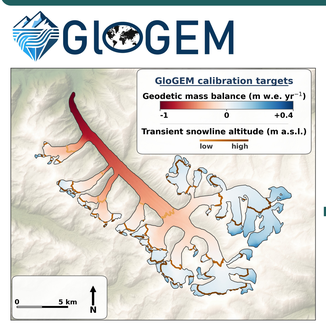


Figure 1: Map of Upper Indus basin with 8 glaciated catchments highlighted and RGI v6.0 glacier outlines as light blue polygons.

Coupling a global glacier model (GloGEM) and hydrological modeling framework (Raven)



Details in Berg et al. (2026, preprint)

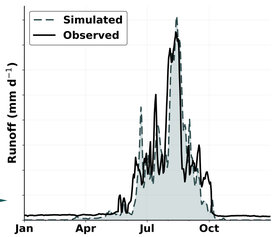
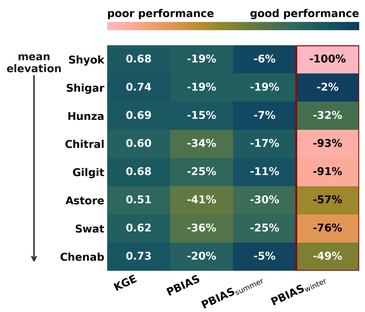




Figure 2: Global Glacier Evolution Model GloGEM (Huss et al, 2015) simulates glacier runoff which is used as input on glaciated areas in the hydrological modeling framework Raven (Craig et al, 2020). GloGEM is calibrated against geodetic mass balance (Hugonnet et al, 2021) and transient snowline altitude (Loibl et al, 2025). The calibration method follows von der Esch et al. (2026, manuscript under review). Raven is calibrated using observed streamflow data.

Baseflow is underestimated across catchments and configurations



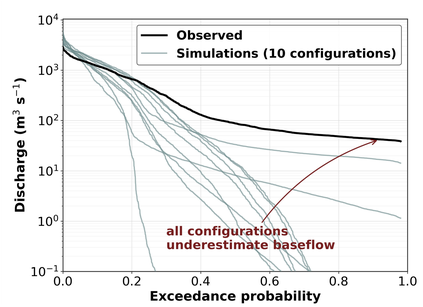


Figure 3: Left: Performance metrics for Raven-GloGEM (HBV emulation with ERA5Land) across catchments (sorted by mean elevation), for the validation period, calibrated on KGE. $PBIAS_{summer}$ = JJAS (high flows); $PBIAS_{Winter}$ = DJFM (low flows) Right: Flow duration curve for Shyok catchment (22.5 % glaciated). Observed vs simulations with multiple forcing, coupling and model configurations.

Subsurface reservoirs and pathways

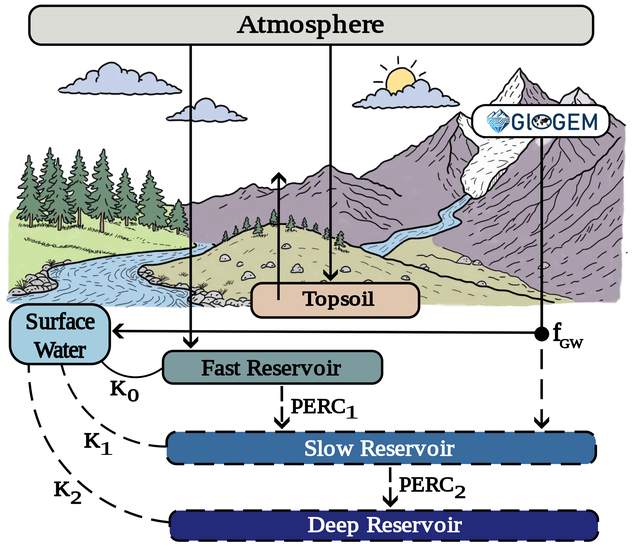


Figure 4: Schematic of the subsurface reservoirs and their connections to the atmosphere, surface water, and GloGEM glacier runoff. Solid elements (boxes and arrows) are present in every configuration used in this study; dashed elements indicate optional reservoirs and pathways. K_i = linear-reservoir recession constants (smaller K_i → slower release); $PERC_i$ = maximum percolation rates between adjacent reservoirs; f_{GW} = fraction of GloGEM glacier runoff bypassing the soil and fast reservoir, entering the slow reservoir directly.

Tested structures

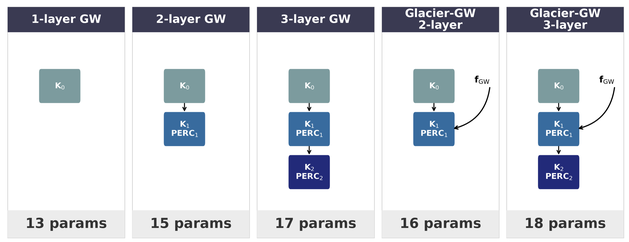


Figure 5: Subsurface structures evaluated, ordered left-to-right by complexity. From a single linear reservoir (1-layer GW) up to three reservoirs with a glacier-to-groundwater connectivity (Glacier-GW 3-layer). Reservoir labels list the parameters introduced when each reservoir is added; the curved arrow represents f_{GW}. Footer reports the total number of calibrated parameters per configuration.

Performance across catchments and structures

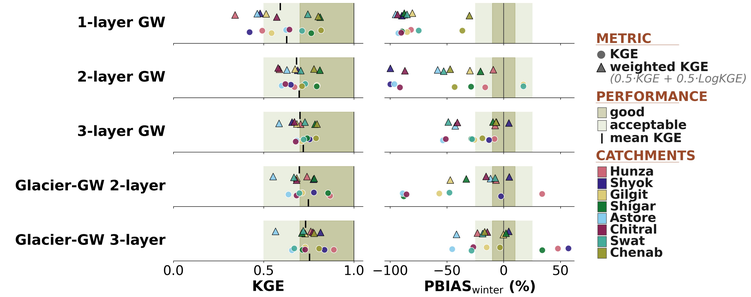


Figure 6: Performance of each subsurface structure (rows) across catchments (colour) during the validation period. Left: KGE. Right: $PBIAS_{winter}$ (DJFM). Marker shape indicates the calibration metric (○ = KGE; △ = weighted KGE = 0.5 KGE + 0.5 log-KGE). Background bands show good and acceptable performance zones. Black ticks in the KGE panels mark the mean KGE across catchments per calibration metric.

Streamflow contributions

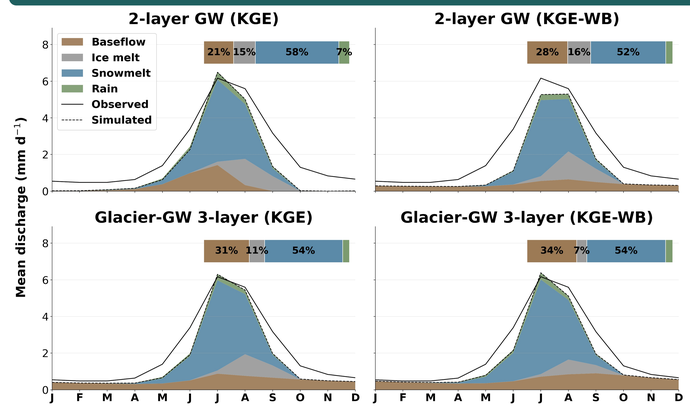


Figure 7: Monthly streamflow regime, catchment Chitral, validation period. Stacked bands: baseflow (brown), ice melt (gray), snowmelt (blue), rain (green). Solid line = observed; dashed = simulated. Panels: two subsurface structures × two calibration objectives. Inset bars give each component's % share of mean yearly simulated Q.

Conclusion

- All tested Raven-GloGEM configurations underestimate winter flow across the Upper Indus
- Adding a deep reservoir (3-layer GW) reduces winter bias and improves overall KGE with both calibration metrics
- Including Glacier ↔ GW connectivity (Glacier-GW 3-layer) improves overall KGE further, but only reduces winter flow bias if calibrated with the weighted KGE
- Glacier ↔ GW connectivity redistributes simulated streamflow components: less direct icemelt, more baseflow

Open Questions

- How to improve **shoulder seasons**?
- Optimal length of the **spin up period** for deep reservoirs?
- Other baseflow algorithms or structures?
- Do these structures diverge under **future climate scenarios**?

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