Lessons learnt from glacio-hydrological modelling for Uttarakhand

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In Himalayan River basins, like the Bhagirathi basin in the Uttarakhand province, climate change and socioeconomic development put pressure on water resources which are vital for domestic use, industry, agriculture, electricity generation and the natural environment. Stakeholders realize that a "business as usual" approach is no longer suitable, and need better information on possible alternative pathways and scenarios. Glacio-hydrological modeling and water resources modeling is needed to assess those possible scenarios. These modelling exercises can feed into an Integrated Water Resources Management (IWRM) plan.

For the Bhagirathi basin, two glacio-hydrological models were set up using advanced scientific simulation software (SPHY): (1) a detailed model for the Din Gad sub-catchment that includes the Dokriani glacier and a large catchment upstream of Devprayag where Bhagirathi River confluences with Alaknanda River. The Din Gad model is set up at a very high spatial resolution (50 meters and daily time step). And (2) the larger scale Bhagirathi model which covers the upstream and downstream areas, with a total area of 7642 km^2, is set up at 500 meters spatial and daily time resolution.

The models were set up using climate data and satellite data for snow cover and glacier dynamics. Both models are simulated for the 1991–2020 time period to assess the current climate and 2021–2100 for future changes. Some learned lessons from these modelling exercises are summarized here.

The **present-day** water resources are characterized as follows:

- At the outlet of the Bhagirathi River, the rainfall-runoff and glacier are the dominant (34% of the total flow) and least contributor (6% of the total flow), the remainder is snow and baseflow.
- Although the snow contributes all-round the year, most of the snow melt starts from March/April and snow runoff peaks in July when most of the precipitation falls as snow over the high elevation of the Bhagirathi basin. The snow contribution again ceases in the winter season when the temperature is low and solid form of precipitation is stored as snow over the higher elevation (*Figure 3*).
- The glacier melt starts in May and peaks in August. Even though the annual contribution of glacier is the smallest at the outlet its monthly contribution reaches 14.6% in September when there is less water in the river system. The baseflow drains water to the river channel all-round the year but its contribution increases in the dry and cold season (September, October, November, December, January, February) and overall contributes to about 29.2% to the total flow.
- In contrast, the glacier runoff contributes to about 20% of the total flux (at Dokriani outlet calculate from small scale Dingad model). The main contributor is the snow runoff which contributes about 55% of the total flux. The snow runoff reduces in September and October as the temperatures get negative in higher elevations and snow melt does not occur. The third contributor is rain runoff, contributing to 13% of the total flux. Rain runoff starts to increase in June and peaks in August.

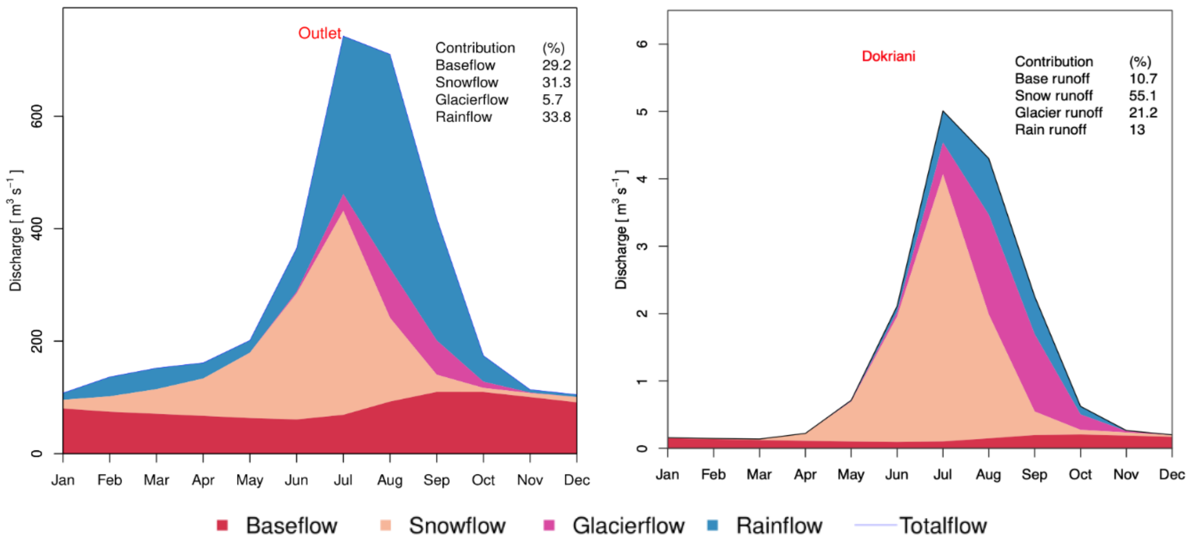

Figure 3: Baseline averaged monthly runoff with the distinction of flow components (base, snow, glacier, and rain-runoff flow at the outlet of (a) Bhagirathi basin (just before the confluence of the Alaknanda River) and (b) Dokriani sub-catchment for 1991–2020. The top right part of the figure shows the contribution of stream flow contributors to the total flow (expressed in %).

The **future** water resources for these catchments will face changes, principally:

- On a seasonal scale for the end-of-century time slice, the total flow increases in the future for the Bhagirathi basin and decreases for the Dingad sub-catchment (*Figure 4*).The rainfall-runoff contribution intensifies compared to the mid-century for both basins. The snow runoff reduces significantly by the end-of-century as compared to the baseline. The increase in glacier melt runoff seen in the mid-century recedes by the end-of-century. This signifies that the peak glacier melt runoff has already been attained by the mid-century and glacier-melt runoff will decline by the end-of-century for both the basins. The shift in the peak total runoff becomes more evident by the end-of-century for both scenarios.
- For the annual scale, snow and glacier melt runoff show a clear declining trend by the end of the century (*Figure 5*). The rainfall-runoff and baseflow components increase in the future. This increase is attributed to the increased precipitation in the basin. The increase in rainfall-runoff and baseflow components is leveled off by the decline in the snow and glacier melt runoff for the Bhagirathi basin. So, in the future, the annual total runoff stays relatively for the Bhagirathi basin. However, for the Dokriani sub-catchment, the decrease in snow and glacier runoff is much larger than the increased rainfall runoff and therefore an apparent decrease of more than 20% in total river flow is expected.

This state-of-art glacio-hydrological modelling work will feed into a number of adaptation scenarios for the region. These scenarios will be an important component of an IWRM plan for the Bhagirathi Basin. This IWRM plan integrates a data- and stakeholder-based situational analysis and presents several pathways to stakeholders that can be taken forward over the next years to meet the climate change and water resources challenges of the region.

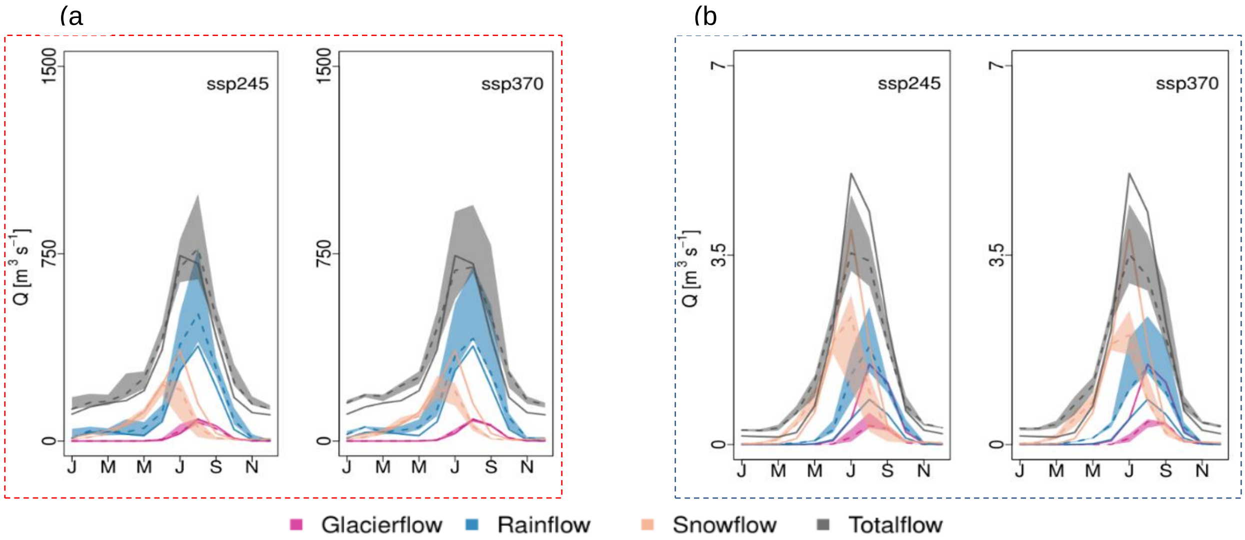

Figure 4: Seasonal changes in the hydrological regime for the end of the century (2071–2100) at the outlet of the (a) Bhagirathi basin (b) Dokriani sub-catchment. The shaded color represents the variability (minimum and maximum) of the flow contributors. The dashed and solid-colored line represent the median of the four climate models and the baseline flow (1991-2020), respectively.

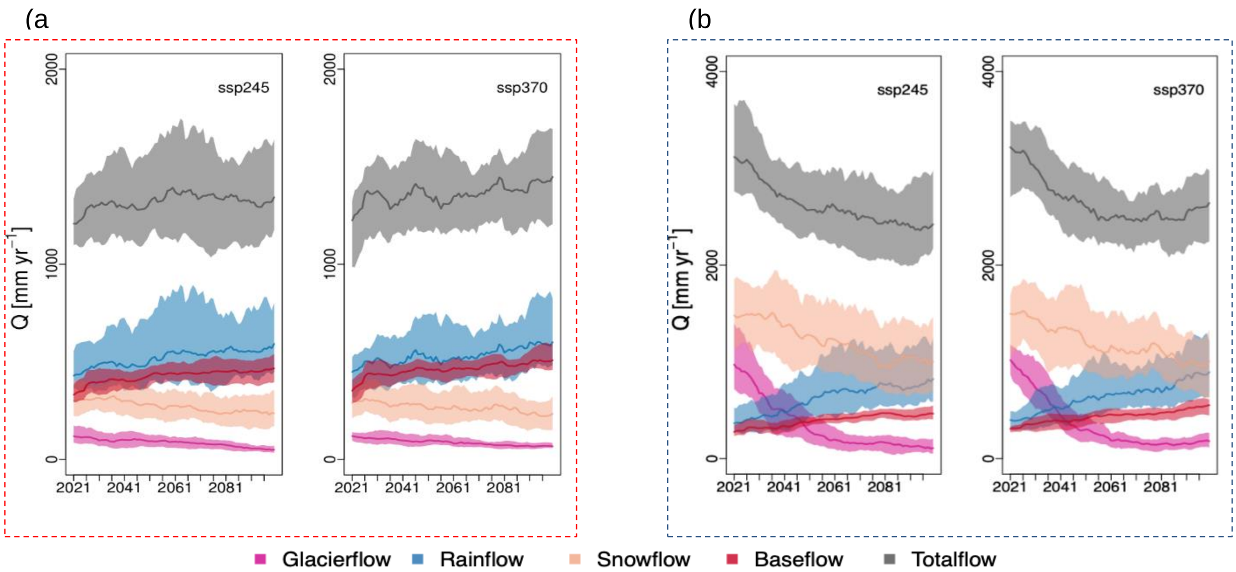

Figure 5: Annual changes in the hydrological fluxes at the outlet of (a) the Bhagirathi basin (just before the confluence of the Alaknanda River) (b) Dingad sub-catchment. The shaded color represents the variability (10-year running mean) of the median flow contributors from four climate models. The solid-colored line represents the median of four climate models.