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Modeling Runoff Components and Assessing Future Water Availability Due to Climate Change in the Karnali Basin Using the SPHY Model

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Abstract. This study evaluates the hydrological behavior and future water availability of the Karnali basin under changing climatic conditions using a distributed hydrological modeling approach. Despite the basin's importance for water resources and hydropower development in Nepal, there is no significant study of the relative contributions of different runoff components and their response to future climate change. The Spatial Processes in Hydrology (SPHY) model was applied to simulate rainfall runoff, snowmelt, glacier melt, and baseflow contributions. The model was calibrated for the period 2005–2014 and validated for 2015–2022. The model performance was found to be satisfactory, with Nash–Sutcliffe Efficiency (NSE) values of approximately 0.79 during calibration and 0.83 during validation, coefficient of determination (R^2) values exceeding 0.75, and Percent Bias (PBIAS) within acceptable limits (-5.1% - +7.19%). The results indicate that rainfall runoff is the dominant contributor, accounting for approximately 53% of total streamflow, followed by baseflow (16.4%), while snowmelt and glacier melt contribute around 27% and 3.3%, respectively. Snow and glacier melt contributions are particularly significant during the pre-monsoon and early monsoon periods. Further, future streamflow projections were also carried out using bias-corrected CMIP6 climate data under SSP245 and SSP585 scenarios. The results suggest an increase in mean annual streamflow by 24.2% and 58.3% for mid-future climate and by 28.4% and 62.1% for far-future climate under SSP245 and SSP585 respectively relative to the baseline period (1985–2014). Seasonal analysis indicates a potential increase in peak monsoon flows by 25.92% and 46.2% under SSP245 and SSP 585 respectively by the end of the century, while changes in dry season flows remain comparatively moderate. Uncertainties associated with climate projections, model structure, and input data remain, particularly in representing cryosphere processes. However, the findings provide important quantitative insights into water resource planning and hydropower development in the Karnali Basin under future climate conditions.

Keywords: Cryosphere; Climate change; SPHY; Water availability; Snowmelt; Glacier melt.

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1. INTRODUCTION

The Himalayan region is often called the ”Water Tower of Asia” because it provides water for more than one billion people. This water is used for drinking, farming, and various economic activities [21]. However, climate-related changes in the cryosphere (frozen water areas) are seriously disturbing the region's water cycle [32]. The Himalayas and nearby areas are highly sensitive to rising temperatures and changing rainfall patterns caused by climate change [10]. These changes threaten water supplies and are likely to make future water problems worse [18]. Research shows that over the past 50 years; the region's temperature has risen by 1.8°C. This rate is higher than the global average [12]. Rainfall patterns have also shown an overall increase, but with large differences across space and time [20]. Given these changes, it is very important to measure runoff patterns and their variations in high-altitude areas. This helps us understand what drives these changes and supports better water management.

Runoff is a key part of river water systems. Knowing how different components contribute to runoff at the catchment scale is essential for measuring available fresh water. The distribution of major runoff components—such as rainfall runoff, base flow, snowmelt, and glacier melt—across a basin plays a major role in determining water availability and its seasonal changes. Changes in weather factors like temperature and rainfall can greatly affect river systems. In the Himalayas, changes in snow and ice reserves also cause notable shifts in total runoff [31]. Rainfall runoff is the main component across most of the Himalayas and nearby high-altitude areas. In major Himalayan rivers that start from the Tibetan Plateau—including the Upper Yellow, Upper Yangtze, Upper Mekong, Upper Salween, Upper Brahmaputra, and Upper Indus—rainfall contributes more than 50% of the total runoff [21]. However, snow and glacier melt are also very important processes in this region. Climate change is increasingly affecting how these melts occur. Therefore, the contribution of meltwater from snow and ice to total runoff cannot be ignored. Even in basins where glaciers cover less than 5% of the area, ice melt can still add a significant amount to summer river flow. Thus, studying the water regime and its runoff components is crucial for understanding how climate change is affecting freshwater systems across both space and time.

Although glacier retreat may initially increase runoff due to more melting, continued loss of glacier mass will eventually reduce total water output [24]. Over the past century, faster warming in the Himalayas has caused major declines in snow and glacier coverage [17]. These changes, together with shifting rainfall patterns, are altering the region's water systems and affecting both the amount and quality of water resources. Because the Himalayas are highly vulnerable to climate change—and because this affects downstream water availability, research in this region has grown significantly in recent decades. Studies have increasingly focused on melting processes, runoff generation, and how water resources are distributed across space and time. However, due to practical difficulties and limited ground-based observations, our understanding of water regimes in the Himalayas remains incomplete and uncertain. In this situation, hydrological modeling offers a useful tool for assessing how water systems respond to climate change and for filling knowledge gaps. The water behavior of Himalayan river systems is shaped by a mix of seasonal rainfall, steep terrain, and forested and glacier-covered landscapes. Future climate scenarios generally suggest an increase in river flows, but projections vary widely. [19] estimated that streamflow at Chisapani could increase by as much as 55% under the SSP245 scenario and up to 90% under SSP585 by the end of this century. Similarly, [19] projected annual discharge increases of 8.2% (2021–2045), 12.2% (2046–2070), and 15% (2071–2095), while noting a likely decline in post-monsoon flows. [25] emphasized that high-altitude northern areas are more vulnerable to changes in water availability compared to the southern lowlands. As temperatures continue to rise and rainfall patterns shift, the region may face greater risks of both monsoon flooding and dry-season water shortages. This could have cascading effects on farming, energy production, and ecosystem health. In Nepal, most climate impact studies on water resources have relied on CMIP5 projections cite{Dahal2020,Pandey2020,Pradhan2021}. However, the move to CMIP6 offers several important improvements. First, CMIP6 provides a wider range of possible future changes in temperature and precipitation, allowing for a more thorough exploration of climate uncertainties [6]. Second, it improves the representation of rainfall variability and intensity, addressing known weaknesses of CMIP5 [8]. Third, CMIP6 has better spatial resolution, updated process representations, reduced structural uncertainties, and more integrated Earth system components. This results in simulations that more accurately capture real-world conditions [3]. These improvements highlight the value of adopting CMIP6 to generate more reliable climate projections and support informed decision-making.

The Karnali River Basin is a typical medium-scale basin located in western Nepal, it is a perennial mountain river system that supplies water for drinking, farming, and industrial needs to more than one million people across Nepal and India. The basin is also ecologically significant. It contains four national parks, one wildlife reserve, one hunting reserve, and two buffer zones. It also provides habitat for several endangered species [15], all of which depend on its natural flow pattern. With its steep terrain and large discharge, the Karnali River remains the largest largely unregulated river in Nepal. Its considerable hydropower potential has drawn national attention to support economic development. At the same time, its ecological importance requires careful management. Therefore, a detailed understanding of current hydrological processes at fine spatial resolution is essential. Establishing such a baseline is critical for analyzing streamflow components and evaluating the basin's sensitivity to future changes caused by climate variability and land use changes.

A limited number of studies have been carried out in the Karnali Basin to understand its hydrology and sensitivity to climate change. Research using observed discharge records from the Karnali River Basin shows that long-term flow patterns do not follow a clear upward or downward trend. Instead, they show large year-to-year variations [16] Further work by [9] found a strong link between river discharge and groundwater contributions. Their study also noted a decline in groundwater flow over time, especially during the monsoon months (June to September) within the period 1979–2007. Several studies have used semi-distributed hydrological models to improve our understanding of water balance components and climate change sensitivity across the basin and its major sub-catchments. cite{Dahal2020,Pradhananga2025}. These efforts have provided an important foundation for understanding the hydroclimatic behavior of the Karnali River Basin. Despite these contributions, significant challenges remain. First, the analyses are limited by sparse and inconsistent ground observations. Most monitoring stations are located at lower elevations (below 2,000 m), which means high-altitude areas are not well represented. Second, many studies rely on lumped modeling approaches that simplify spatial variability. In contrast, using fully distributed models with grid-based inputs would allow for a more detailed representation of spatial heterogeneity. This would include capturing the effects of snow and glacier dynamics, thereby improving assessments of regional water availability within the basin.

To achieve this, we use the Spatial Processes in Hydrology (SPHY) model [30], which represents snow and glacier processes at an intermediate level of detail. We used SPHY version 3.1. The source code is freely available along with installation instructions [13]. SPHY is a widely used tool. It is a spatially distributed glacial-hydrological model designed for basin-scale hydrological analysis. The model is built on the PCRaster dynamic modeling framework and simulates river hydrology using a conceptual approach [29]. SPHY has been extensively applied in hydrological research, particularly for quantifying the contributions of different runoff components and assessing climate change impacts [14].

The use of SPHY in the Karnali River Basin improves the spatial representation of hydrological parameters, with a particular focus on snow properties that are important for the basin's water balance. Using the calibrated model, this study focuses on the following main objectives: (i) to set up the SPHY model for the Karnali River Basin; (ii) to simulate the respective contributions of rainfall, base flow, snowmelt, and glacier melt to total runoff; and (iii) to assess climate change scenarios using CMIP6.

2. STUDY AREA

The basin covers an area of about 45,438 km^2, of which around 43,000 km^2 lies within Nepal and the remaining area extends into the Tibetan region of China. The Karnali River originates from the high Himalayan glaciers in the Tibetan Plateau at elevations exceeding 5,000 meters above

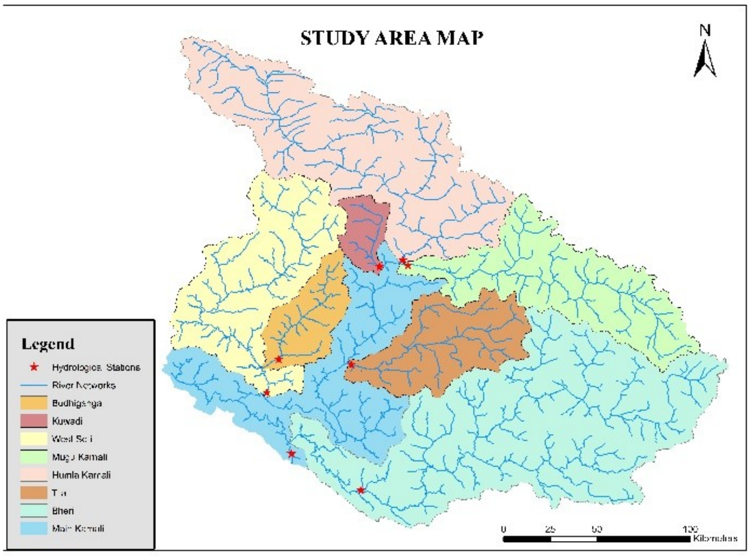

FIGURE 1. Study Area Map of the Karnali Basin

sea level and flows through diverse physiographic regions including the High Himalaya, Middle Mountains, Siwalik Hills, and the Terai plains before entering India. This wide altitudinal range results in substantial climatic and hydrological variability across the basin. The Karnali River Basin is characterized by steep topography and complex terrain, which strongly influence hydrological processes such as runoff generation, snow accumulation, glacier melt, and sediment transport. The basin includes several major tributaries such as the Humla Karnali River, Mugu Karnali River, Bheri River, and Seti River, which contribute significantly to the overall discharge of the basin. These tributaries originate from high-altitude glacierized and snow-fed regions, making the basin highly dependent on cryosphere processes. FIGURE 1 shows the sub-basins of Karnali watershed highlighting each sub-basin with different colors. Similarly, FIGURE 2 shows the elevation map of Karnali Basin with different elevation bands.

Climatically, the basin experiences strong seasonal variability influenced by the South Asian Monsoon, which contributes approximately 70–80% of the annual precipitation during the monsoon season (June–September). Winter precipitation in the higher elevation regions occurs primarily in the form of snowfall due to the influence of western disturbances. The spatial distribution of precipitation varies significantly across the basin, with higher precipitation observed in the middle mountain regions and relatively lower precipitation in the trans-Himalayan areas [2]. Temperature patterns within the basin are strongly influenced by elevation. High-altitude regions experience cold climatic conditions with significant snow accumulation during winter, while the lower elevations in the Terai plains exhibit subtropical climatic conditions. These temperature variations play an important role in controlling snowmelt and glacier melt processes that contribute to river discharge, particularly during the pre-monsoon and early monsoon seasons [11].

3. METHODOLOGY

3.1. **MODEL.** The full form of the SPHY model is "Spatial Processes in Hydrology." It is a distributed hydrological model designed to simulate water-related processes in complex environments, including mountain basins that contain glaciers. The model includes several key hydrological processes: rainfall turning into runoff, snow buildup and melting, glacier melting, evaporation and transpiration (evapotranspiration), changes in soil moisture, and groundwater movement. SPHY was created as a flexible modeling tool. It can simulate hydrological processes at different spatial scales (from small to large areas) and different time scales (from days to years). The model works

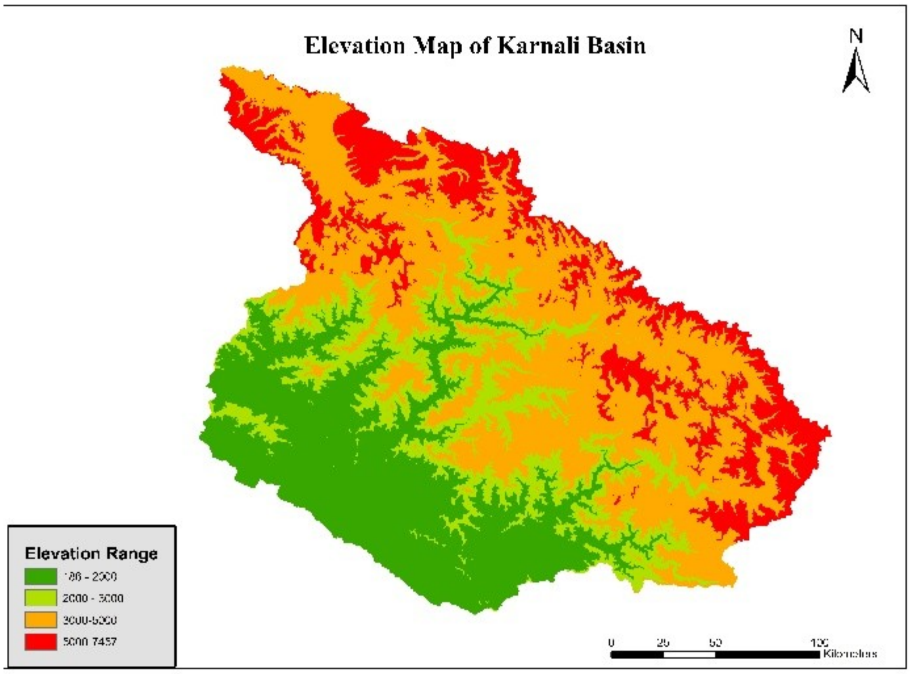

FIGURE 2. Elevation Map of the Karnali Basin

on a grid-based system. It uses spatial data layers such as digital elevation models (DEM), land use maps, soil property maps, and weather data to simulate how water moves across a basin. The SPHY model brings together several components: rainfall-runoff processes, cryosphere (snow and ice) processes, evapotranspiration, plant growth dynamics, and the operation of reservoirs. Because of this wide coverage, the model can be used for both glacier-fed catchments and non-glacierized catchments. One of its main strengths is its ability to simulate snow and glacier processes. For this reason, SPHY has been widely applied in Himalayan river basins to study how climate change affects water resources [30]. It has been used in various basins of Nepal like Tamor, Chameliya River Basins [23] exhibiting the capability of model in various hydrological scale. Similarly, we used SPHY model in Karnali basin in this study with a spatial resolution of 1000x1000m and was run for the period (2005- 2022) of 18 years in a daily time step. The model requires climate forcing such as precipitation, Average Temperature, Minimum Temperature and Maximum Temperature as climate data input. After simulation, the model generates total runoff incorporating glacier melt, snowmelt, rain-runoff and baseflow and each contribution separately generated and can be analyzed individually.

3.2. **DATA.** This study used USGS HydroSheds hydrologically conditioned DEM of 90m resolution. Available DEM was further processed and used to determine the slope and drainage networks of the Basin. Meteorological forcing data were obtained from the ERA5-Land developed by the European Centre for Medium-Range Weather Forecasts. ERA5-Land is a high-resolution land surface reanalysis dataset that provides consistent and long-term meteorological information by combining numerical weather prediction models with observational data. After downscaling, the dataset has a spatial resolution of approximately 0.1° (˜9 km) for the period 2005 to 2022.
The glacier boundary employed in the model was derived from the Randolph Glacier Inventory version 5 (RGI5 available in SPHY database. For each grid cell with a spatial resolution of 1000 meters, we calculated the glacier fraction—distinguishing between debris-covered and clean ice—following the approach of [18]. The thickness and mean elevation values assigned to glacier grid cells were taken from the dataset provided by [7]. ESA makes available land cover maps, which cover 2 periods: December 2004 - June 2006 and January - December 2009. This GlobCover Land

uses map of resolution 300m and was resampled into model resolution and used in this study. We obtained the crop coefficient (kc) values for each land cover type from [1].
We obtained root-zone and subzone soil hydraulic properties for the model from the global HiHydroSoil v2.0 database [28]. This database provides 250-m resolution maps of saturated hydraulic conductivity, field capacity water content, and critical and permanent wilting point, which we resampled to match the model resolution. However, root-zone and subzone soil depths were treated as calibration parameters later during calibration of the model. Further, we get hydrological daily discharge data from Department of Hydrology and Meteorology (DHM) for the period of 2005 to 2022 at Chisapani Station (280) and Bheri at Samajhighat Station (269.5) for calibration and validation purposes.

3.3. **MODEL CALIBRATION AND VALIDATION.** The hydrological model SPHY was set up for Karnali River Watershed upto Chisapani Gauging site, Station Index 280. The Chisapani gauging site is located at the lower end of the Karnali basin therefore represents the flow for the entire basin. We have calibrated the model for the year 2007 to 2014 and validated the model for year 2015 to 2022, while two years period (2005- 2006) remains as spin up period for the model. Further validation was done at Bheri Samajhighat Station (269.5) To validate the skill of calibrated SPHY models, we use multiple statistical measuring metrices such as coefficient of determination (R square), Net- Sutcliffe Efficiency (NSE) and Percentage of Bias (PBIAS). Model calibration was performed manually varying different parameters for Glacier, Snowmelt and Ground water storage. While the model achieved acceptable performance, no formal parameter uncertainty analysis was conducted. Consequently, the potential for equifinality, where different parameters yield similarly good results, remains unquantified, representing a key limitation of this study.

3.4. **BASIN WISE RUNOFF GENERATION.** The calibrated and validated model was subsequently run over the 2005–2022 period, with output reporting configured at eight strategically selected outlet points i.e. at outlets of each sub-basin. This setup enabled the model to comprehensively report all major runoff components, including glacier melt, snowmelt, baseflow, and rainfall-induced runoff. Such detailed output allowed for a thorough analysis of each basin's runoff contribution from different hydrological sources. Furthermore, it facilitated the assessment of sub-basin variability in both spatial and temporal dimensions, thereby providing valuable insights into the heterogeneous hydrological responses across the study area.

3.5. **GCM SELECTION AND CLIMATE DATA PROCESSING.** In our study, four GCMs were chosen for daily precipitation data and for maximum and minimum temperature, covering both historical periods and future scenarios under SSP245 and SSP585. The historical period, spanning from 1985 to 2014, provided a baseline for assessing each GCM's performance, utilizing daily mean values of the respective variables. These models were employed on previous studies in this region [19]. The four GCMs used in this study are INM-CM5-0, MPI-ESM1-2-LR, EC-Earth3 and NorESM2-MM based on performance ratings. [22] developed daily bias-corrected data of precipitation, maximum and minimum temperatures at 0.25° spatial resolution for South Asia. The bias-corrected dataset is developed using Empirical Quantile Mapping (EQM) for the historic (1951–2014) and projected (2015–2100) climate for the four scenarios (SSP126, SSP245, SSP370 and SSP585) using output from 13 General Circulation Models (GCMs) from Coupled Model Inter-comparison Project-6 (CMIP6). The bias-corrected dataset was evaluated against the observations for both mean and extremes of precipitation, maximum and minimum temperatures. Bias corrected at 0.25° resolution data for Nepal was used in this study with 70 grid points available for Karnali basins.
Uncertainty in projecting specific climate variables can be significantly reduced by using the mean time series from a multi-model ensemble (MME) of well-performing general circulation models (GCMs). While various methods exist to generate ensemble means—ranging from simple arithmetic averaging to advanced machine learning, this study adopted the simple mean approach. We computed ensemble mean time series for precipitation, maximum temperature, and minimum temperature using outputs from the four highest-ranked GCMs based on performance evaluation. We chose the simple mean method for its transparency, ease of use, and proven ability to combine

multiple model outputs into a representative dataset. Integrating results from the best-performing models yields more consistent and reliable climate projections, thereby enhancing overall robustness. Furthermore, the climate data were pre-processed as a gridded dataset for model input.

3.6. **PROJECTION OF FUTURE SCENARIO.** After calibration and validation, we run the SPHY model with the historical (1985 to 2014) and future climates (2040 to 2100) as projected under SSP245 and SSP585 that represents a rise in the radiative forcing levels up to 4.5 and 8.5 W/m^2 by the end of the century. We analyze the future total flows and their components for two different climates such as mid-future (2040-2069) and far-future (2070 − 2099) with comparison with the historical period (1985- 2014). Our analysis particularly focuses on the shifts in timings of the future hydrographs, mean flow changes, in addition to the mean annual flows' evolution throughout the 21st century under all SSP scenarios.

4. RESULTS AND DISCUSSION

4.1. **MODEL PERFORMANCE.** The model was calibrated using an eight-year period from 2007 to 2014 and validated over another eight-year period from 2014 to 2022, with daily discharge observations from the Chisapani hydrological station (Station ID: 280) as shown in FIGURE 3. Hydrograph of the Karnali River Basin (a) for calibration at Chisapani (280), (b) for validation at Chisapani and (c) for validation at Bheri River at Samajhighat. An additional validation was performed using data from the Bheri at Samajhighat Station (ID: 269.5). In this study, six sensitive parameters were manually varied in the SPHY model: the recession coefficient (RC), alpha groundwater (alphaGW), degree-day factors for clean ice-covered glaciers (DDFG), degree-day factors for debris-covered glaciers (DDFDG), degree-day factors for snow (DDFS), and delta groundwater (deltaGW). Following calibration, the optimized values were RC = 0.92, DDFG = 1.5 mm °C^{-1} day^{-1}, DDFDG = 3.0 mm °C^{-1} day^{-1}, DDFS = 1.5 mm °C^{-1} day^{-1}, alphaGW = 0.015, deltaGW = 150, GlacF = 0.6, and Tcrit = -2°C. Sensitivity of the simulated outputs was evaluated on a daily timescale using three statistical metrics: coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), and percent bias (PBIAS). During calibration, the model yielded R^2 = 0.79, NSE = 0.79, and PBIAS = 7.19%. For the validation period at Chisapani, performance improved slightly with R^2 = 0.84, NSE = 0.83, and PBIAS = -5.09%, indicating a strong representation of actual hydrological conditions. At the Bheri outlet (Samajhighat), the validation metrics showed R^2 = 0.81, NSE = 0.77, and PBIAS = -14.4%. The negative bias at this station suggests a systematic underestimation of discharge. Additionally, the model occasionally failed to reproduce high flow. The simulated long-term mean annual discharge for the Karnali Basin over the 2005–2022 period was 1,369 m^3/s, which compares closely with the observed long-term mean of 1,356 m^3/s for the same period.

Based on the statistical results and the agreement between observed and simulated hydrographs (FIGURE 3), the SPHY model is considered to perform satisfactorily for the Karnali River Basin and suitable for subsequent analyses. A two-year warm-up phase (2005–2007) was included to establish realistic initial conditions for soil moisture and groundwater storage. Nevertheless, several limitations should

be acknowledged, discrepancies between observed and simulated flows may stem either from structural constraints within the model or from inaccuracies in the meteorological forcing data, especially under extreme events.

The SPHY model relies on a simplified flow routing scheme, wherein discharge is calculated using a recession coefficient combined with one-directional grid-to-grid water transfer. Baseflow is modeled using a temporally and spatially constant recession coefficient, which does not account for variability across the basin. Although more advanced hydraulic routing methods—such as diffusive wave or fully dynamic routing—could enhance peak flow simulations, they demand more extensive input datasets and substantially higher computational power, making them impractical for the scale and objectives of this study.

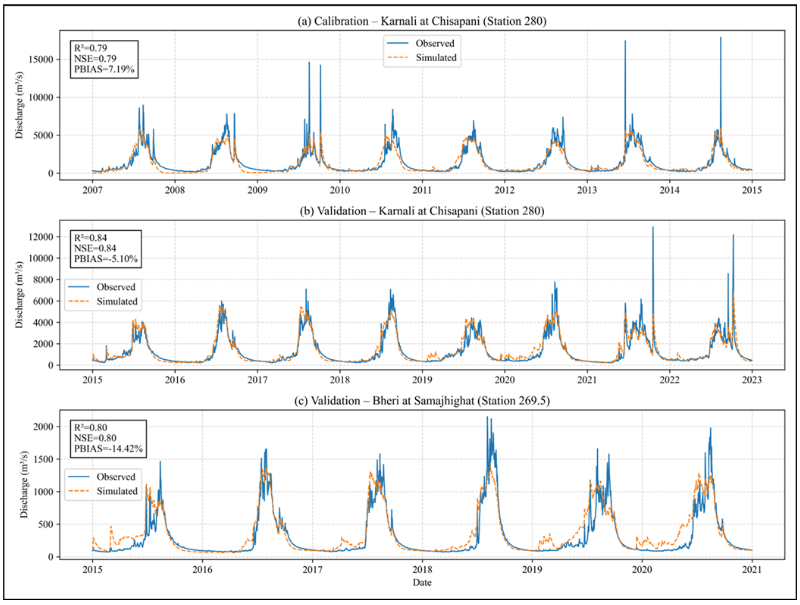

FIGURE 3. Hydrograph of the Karnali River Basin (a) for calibration at Chisapani (280), (b) for validation at Chisapani and (c) for validation at Bheri River at Samajhighat

4.2. **TOTAL RUNOFF AND RUNOFF COMPONENTS.** Total runoff in the Karnali River Basin (KRB) consists of four primary components: runoff from rainfall, meltwater from glaciers, base flow (groundwater contribution), and snowmelt. The simulated average annual total discharge across the basin ranged between 1,239 m^3/s and 1,680 m^3/s.

When examining individual components, the annual average contribution from rainfall varied from 527 to 770 m^3/s, while base flow ranged between 193 and 317 m^3/s. Glacier melt contributed an annual average of 10 to 80 m^3/s, and snowmelt contributed between 238 and 606 m^3/s. Peak values for different components occurred in different years. Rain runoff, glaciers melt, and base flow all reached their highest simulated annual averages in 2019. In contrast, total runoff peaked in 2014, and snowmelt runoff was highest in 2015. At the basin scale, rainfall runoff dominates the hydrological regime of the KRB, accounting for approximately 52.6% of the total runoff. The remaining contributions are split among base flow (16.4%), snowmelt (27.7%), and glacier melt (3.3%). Notably, the snowmelt share of 27.7% in this study is higher than the 15% previously reported by [5]. This discrepancy is likely due to the SPHY model's ability to compute melt on a grid-by-grid basis and to account for fractional snow and glacier coverage within individual grid cell features that provide a more detailed representation of high-altitude hydrological processes. Seasonally, surface runoff components—namely rainfall runoff, glacier melt, and snowmelt—are all increased during the monsoon period. Conversely, base flow reaches its highest level during the winter season. These seasonal trends are explained by the basin's dominant climatic control: the Indian monsoon system. During the monsoon, higher temperatures and abundant precipitation lead to increased surface runoff. A substantial portion of this water infiltrates and recharges shallow aquifers, which then sustain higher base flow during the subsequent dry winter months. Rainfall runoff remains the primary water source for the KRB, with nearly 71% of total annual runoff being generated within the four-month monsoon season (June through September). Overall, the water balance clearly indicates that monsoon precipitation is the principal hydrological driver in the Karnali basin— a finding consistent with earlier work by [25].

4.3. **SUB-BASIN VARIATION OF RUNOFF COMPONENTS.** The varying climatic conditions and availability of glacier mass across the different sub basins of the KRB are likely to influence the total discharge of rivers. The estimated average annual discharge of the Bheri River

(largest tributary of the KRB) was 391 m3/s, with the highest and lowest discharge observed during monsoon (1117 m3/s) and winter (111 m3/s) seasons, respectively. The annual average discharge of West Seti, Humla Karnali, Mugu Karnali, Tila, Budhiganga and Kuwadi River were 253, 199, 149, 129, 59 and 38 m3/s, respectively. The order of tributaries based on the average annual discharge was Bheri ¿Humla Karnali ¿ West Seti ¿ Tila ¿ Mugu Karnali ¿ Budhiganga ¿ Kuwadi. In the sub basins scale, the contribution of glacier melt ranged from 0.1% (Budhiganga) to 8% (Kuwadi). The contribution of snowmelt ranged from 9% (Budhiganga) to 54% (Mugu Karnali). Likewise, the contribution of base flow ranged from 16% (Bheri, West Seti and Humla Karnali) to 20% (Tila), and the contribution of rainfall ranged from 28% (Mugu Karnali) to 72% (Budhiganga). In the basin and sub- basin scales, more than half of the total annual discharge was contributed by rainfall runoff in the KRB. A significantly higher contribution (¿60%) of rainfall runoff was observed in the West Seti and Budhiganga sub-basin.
The seasonal and spatial comparison of total discharge and the contribution of its contributors was carried out. This study considered the four major seasons as winter, pre- monsoon, monsoon, and post- monsoon for all sub-basins distributed across the basins. The results suggested a substantial seasonal variation in the contribution of major contributors to total discharge. During the winter season, all tributaries were dominated mainly by base flow, more than 60% of the total runoff was contributed by base flow in all sub-basins. During the pre-monsoon season, all the tributaries were dominated mainly by snowmelt runoff except for the West Seti and Budhiganga indicating less snowmelt contribution by the western part of the Basin regions. The Budhiganga and West Seti had comparatively lesser glacier area ratio coverage, and rainfall was dominant in this sub-basin during the pre- monsoon season. With the dominancy of the Indian monsoon, the rainfall runoff is the most profound component during both the monsoon and post- monsoon in all sub-basins. Most of the snowmelt was generated in higher reaches of Upper basins Mugu Karnali, Humla Karnali, Kuwadi and Tila. These basins receive higher snowfall during winter and lead to higher snowmelt during pre-monsoon seasons.

4.4. **FUTURE WATER AVAILABILITY.**

4.5. **INTER ANNUAL CHANGES.** Figure 4 shows annual cycles of historical and future discharges generated from snowmelt under two SSP Scenarios and for two 21st century climates. For the mid future climate, SSP245 projects a substantial increase in the snowmelt runoff during the latter half of the snowmelt season particularly during the months of May instead of June and July as seen in historical periods. Likewise, Peak snowmelt runoff is projected to shift early from July to the month of May indicating early in melt out timings. On the other hand, the start of snowmelt has been projected earlier in late February. But for the far future all SSPs project a substantial decline in the snowmelt runoff with more prominent decline in SSP585 scenario. We notice an increase of flow during monsoon and pre-monsoon season as compared with the baseline. Overall, total water availability is projected to rise throughout the 21st century. Monsoon discharges for the month June, July, August and September substantially increase SSP245 and SSP585 scenarios by 25.92% and 46.2% respectively with highest discharge in the month of July and August. Such findings are also highlighted in [19]study done for the same region.
The intermodal ensemble means annual discharges shows above throughout the 21st century for all SSPs and all considered hydrological components. Interestingly, snowmelt runoff features a declining trend throughout the 21st century under all SSPs scenarios. In sum, historical mean annual
discharges are projected to increase by 24.2% and 58.3% for mid-future climate and by 28.4% and 62.1% for far future climate under SSP245 and SSP585 Scenarios respectively, where such an increase will be higher for relatively high-end warming scenarios (FIGURE 5). These findings suggest that overall discharge from the Karnali Basin will increase throughout the 21st century.

4.6. **CHANGES IN FLOW DURATION CURVE.** The flow duration curve (FDC) represents the percentage of time for which the flow in a river channel is equaled or exceeded to some quantified values of interest. To analyze the integrated effect of hydro-climatic changes within the Karnali Basin, we plot FDC for Mid and Far future scenarios. The probability of occurrence and

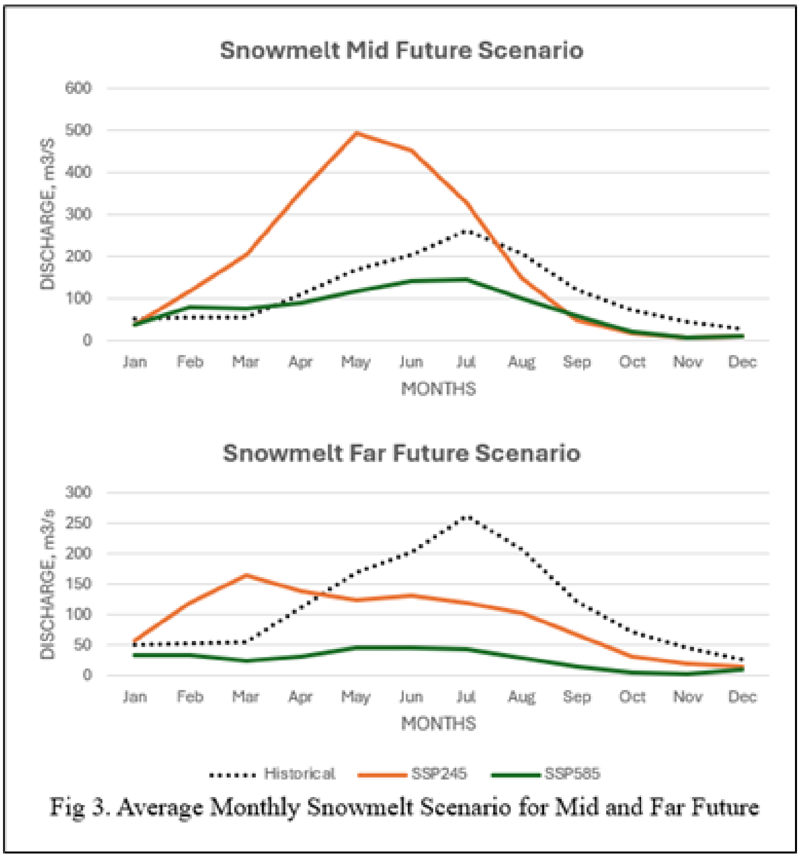

Figure 4. Intra Average Annual Snowmelt Scenario for Mid and Far Future under SSP245 and SSP585

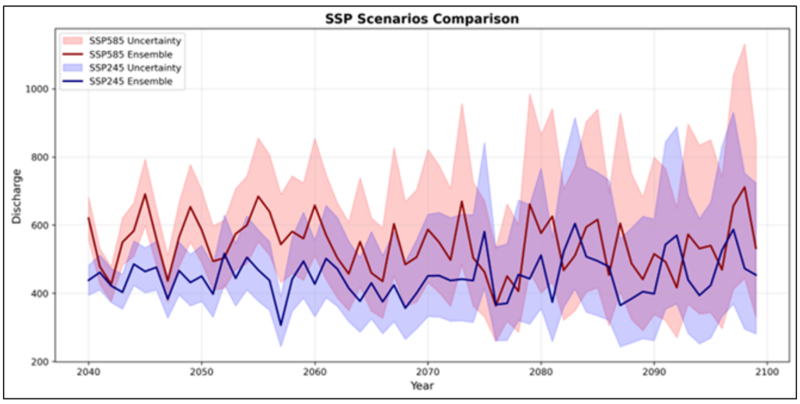

Figure 5. Ensemble Mean Annual Discharge and uncertainty band for SSP245 and SSP585 Scenarios.

magnitude of the low, medium and high flows are projected to increase for mid and far future climates under all SSPs scenarios. These changes are particularly prominent for SSP585 for the mid- and end-of-century climates. However, there is a noticeable decrease in Q95 discharge i.e. low flow for far-end future climate scenarios in both SSP245 and SSP585 as compared with mid-century climate and similar decreasing trends were observed for median(Q50) and high(Q5) flow (FIGURE 6). The historical median flows are projected to increase by 25.9 to 28.3% under SSP245 and 49.5

to 61.4% under SSP585. The historic high flow was increased by 4.95 to 16.53% under SSP245 and 20.35 to 22.19% under SSP585 respectively for mid-future and far-future. The strong positive changes in the median flows could suggest that the Karnali Basin will confront frequent and heavy flooding in the mid future, however it will be less increasing for far future as compared to mid.
The changes in the high flow also suggest that the frequency of flooding will reduce by the end of the 21st century under all SSP Scenarios.

5. CONCLUSION

This study applied the Spatial Processes in Hydrology (SPHY) model to simulate hydrological processes and to assess future water availability under climate change scenarios in the Karnali River Basin. The model demonstrated satisfactory performance, with NSE values ranging from approximately 0.79 to 0.83 during calibration and validation, indicating reliable simulation of streamflow at the basin scale.
The analysis of runoff components showed that rainfall runoff is the dominant contributor, accounting for approximately 53% of total discharge, followed by baseflow (16.4%). Snowmelt and glacier melt contributed around 27% and 3%, respectively, and play an important role during specific seasons, particularly in sustaining pre-monsoon flows. Further analysis reveals pronounced spatial variability in river discharge and the relative contribution of different runoff components across the Karnali River Basin. The order of tributaries based on the average annual discharge was found as Bheri ¿Humla Karnali ¿ West Seti ¿ Tila ¿ Mugu Karnali ¿ Budhiganga ¿ Kuwadi. The western sub-basins, West Seti and Budhiganga, are found comparatively wetter as rainfall-driven runoff plays a dominant role in these areas, while the contribution from snowmelt remains relatively limited. In contrast, the Upper Karnali regions—including Mugu Karnali, Tila, and Humla Karnali—are characterized by higher elevations and colder climatic conditions, where snow accumulation and subsequent melting processes significantly influence streamflow. In these sub-basins, snowmelt constitutes a major component of total discharge, making them more sensitive to temperature variations in the future. Overall, this contrast highlights a clear spatial heterogeneity across the basin, largely governed by elevation gradients and climatic differences.
Future projections based on CMIP6 climate scenarios indicate an overall increase in annual streamflow (FIGURE 5). Mean annual discharge is projected to increase by approximately 24.2% and 58.3% for mid-future climate and by 28.4% and 62.1% for far-future climate under SSP245 and SSP585 respectively, with a noticeable increase in peak flows during the monsoon season (up to 46.2% increase in higher emission pathway). These changes suggest increased variability in flow regimes, which may have significant implications for flood risk and hydropower operations.
However, the results are subject to uncertainties arising from climate model variability, bias correction methods, and hydrological model assumptions. The limited availability of high-altitude hydro-meteorological data also affects the accuracy of snow and glacier melt simulations. Overall, the study provides a quantitative understanding of hydrological processes and future water availability in the Karnali Basin, which can support informed decision-making for water resources management and hydropower development under changing climatic conditions.

6. RECOMMENDATION

Based on the findings and conclusions the following recommendations are made for further study and implementation.
The future work would be preferable, including an ensemble of hydrological models with latest CMIP scenarios.
More detailed representation of cryosphere processes is recommended, including dynamic glacier evolution and improved snowmelt parameterization, to reduce uncertainty in streamflow projections under rising temperatures.
This study evaluates the impacts of climate change on the availability of water in the Karnali Basin using only 4 GCMs, although it is advisable to use more than 4 GCMs to overcome the uncertainties associated with its outputs.

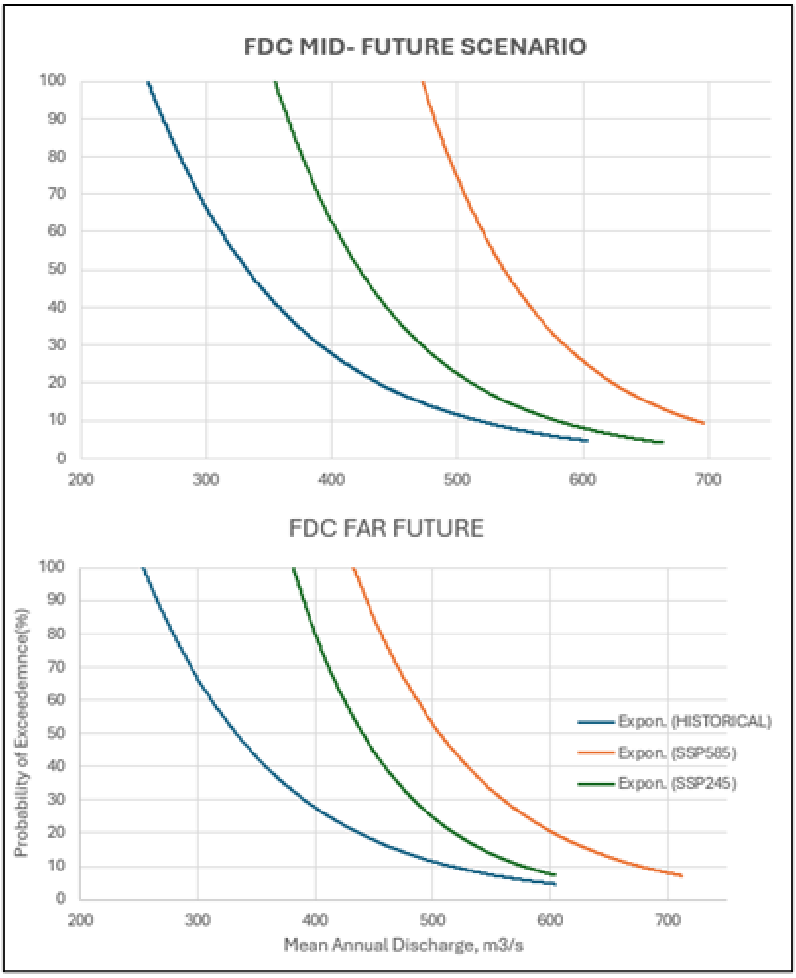

FIGURE 6. Flow Duration Curve for Mid and Far Future under SSP245 and SSP585 Scenarios.

Further research should explore advanced bias correction techniques (machine learning-based approaches) and high-resolution downscaling methods to enhance the reliability of climate inputs for hydrological modeling.
Expanding the use of satellite datasets (snow cover, evapotranspiration, soil moisture) and big data analytics can improve spatial representation and validation of hydrological processes.
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