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Assessing the Impact of Climate Change on Water Resources in the Indus Basin, Pakistan: A Remote Sensing and Hydrological Modeling Approach Field: Environmental Hydrology and Water Resources Management

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ABSTRACT

Water resources in the Indus Basin — the foundation of Pakistan's agriculture, hydropower generation, and domestic water supply — are increasingly affected by climate-driven shifts in temperature, precipitation, and cryospheric dynamics. This paper develops and presents an integrated remote sensing and hydrological modeling framework for quantifying climate change impacts on Indus Basin water resources over the period 2000–2020, with projections extending to 2050 under multiple emissions scenarios. The framework combines satellite-derived indicators of snow-covered area and glacier extent (from MODIS and Landsat imagery), land-use/land-cover change detection, gridded and reanalysis climate datasets, and a physically based, semi-distributed hydrological model (SWAT) calibrated against observed streamflow. The paper synthesizes the current body of published evidence on Upper Indus Basin cryospheric change, precipitation variability, streamflow trends, and groundwater depletion, and situates these findings within the basin's agricultural, hydropower, and transboundary governance context under the Indus Waters Treaty. It further develops a structured framework — with defined datasets, model parameterization steps, statistical trend-testing procedures (e.g., Mann-Kendall, Sen's slope), and validation metrics (Nash-Sutcliffe Efficiency, R^2, percent bias) — for generating basin-specific, data-driven projections of future water availability. Reservoir operation optimization, managed groundwater recharge, and climate-resilient agricultural practices are identified from the literature as priority adaptation strategies. This manuscript presents the conceptual, methodological, and literature-synthesis foundation of the study; primary numerical outputs (e.g., basin-specific glacier area change, streamflow trend magnitudes, and future discharge projections)

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require completion of the satellite data processing and hydrological model calibration steps described in Sections 3 and 4, and are not yet available for reporting.

Keyword: Climate Change, Water Resources, Indus Basin, Remote Sensing, Hydrological Modeling, SWAT, Snow Cover, Pakistan

Introduction

Background

The Indus Basin sustains one of the largest contiguous irrigation systems in the world, supplying water to roughly two-thirds of Pakistan's land area and supporting the livelihoods of more than 180 million people (Watto & Mugera, 2016). Unlike purely rainfall-driven river systems, the basin's hydrology depends heavily on snow and glacier melt originating in the Karakoram, Hindukush, and western Himalayan ranges — a configuration that makes the region one of Asia's principal 'water towers' (Immerzeel, van Beek, & Bierkens, 2010). Approximately 90% of all crops grown in the Indus Basin are irrigated, with glacier and snowmelt contributing a substantial share of that irrigation water, particularly during the pre-monsoon and early monsoon months when agricultural demand peaks (Immerzeel et al., 2010; Qureshi, 2011).

Climate change is altering each component of this system. Rising temperatures are accelerating glacier mass loss and shifting the timing of snowmelt; monsoon precipitation patterns are becoming more variable and, in some sub-basins, more intense; and groundwater — long used to buffer surface water shortfalls — is being depleted at an estimated average rate of approximately 0.4 m per year across parts of the basin over the last two decades (Watto & Mugera, 2016; groundwater depletion studies cited in Section 2.5). These pressures interact with a chronically constrained storage infrastructure: Pakistan's per-capita water storage capacity has been estimated at approximately 150 m^3, compared with more than 5,000 m^3 in the United States and Australia and roughly 2,200 m^3 in China (Qureshi, 2011).

Problem Statement

Despite a substantial body of research on individual components of Indus Basin hydrology — cryospheric change, precipitation trends, groundwater depletion, and irrigation system performance — relatively few studies integrate satellite-derived cryosphere and land-cover indicators directly into a calibrated, basin-scale hydrological model capable of generating scenario-based projections of future water availability while also connecting those projections to the basin's specific agricultural, hydropower, and transboundary governance context. This fragmentation limits the practical utility of existing research for coordinated, evidence-based water resources planning.

Research Questions

This study is guided by the following research questions:

RQ1: To what extent have snow-covered area and glacier extent in the Upper Indus Basin changed over the period 2000–2020, as detectable from MODIS and Landsat satellite records?

RQ2: How have precipitation and temperature regimes shifted across Upper Indus

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Basin sub-catchments, and are these shifts statistically significant?
RQ3: To what degree can a calibrated hydrological model (SWAT), forced with satellite-derived cryosphere and land-cover inputs, reproduce observed streamflow in glaciered and non-glaciered sub-basins?
RQ4: Under moderate (SSP2-4.5) and high-emissions (SSP5-8.5) climate scenarios, how is Indus Basin discharge projected to change by the 2050s relative to a 2000–2020 baseline?
RQ5: Which adaptation strategies are best supported by the resulting hydrological evidence base for reducing water security risk in the basin?

Research Objectives

This study is designed to: (1) synthesize the existing scientific literature on climate-driven hydrological change in the Indus Basin; (2) develop an integrated remote sensing and hydrological modeling framework capable of quantifying historical (2000–2020) trends in snow cover, precipitation, and streamflow; (3) outline a scenario-based modeling procedure for projecting basin water availability to 2050 under multiple representative emissions pathways; and (4) identify and evaluate adaptation strategies — including reservoir operation optimization, groundwater recharge, and climate-resilient agriculture — that are supported by the hydrological evidence base.

Significance of the Study

Given the Indus Basin's transboundary character and its governance under the 1960 Indus Waters Treaty, findings of this nature carry relevance beyond the immediate hydrological science community. Recent developments — including India's 2025 announcement suspending elements of Treaty implementation — have intensified policy interest in improved data-sharing, joint hydro-climatic monitoring, and climate-adaptive treaty mechanisms (NPR, 2025; EJIL:Talk!, 2025). A rigorous, transparent, and reproducible remote sensing–hydrological modeling framework can support both national water resource planning and the broader regional dialogue on adaptive transboundary water governance.

Problem Definition

The basin water balance problem addressed by this study can be stated formally. For a given sub-basin and time step t, the observed or simulated discharge Q(t) is governed by the general water balance identity:

$$Q(t) = P(t) + M(t) - ET(t) - \Delta S(t) - G(t) \quad (1)$$

where P(t) is precipitation input, M(t) is the snow/glacier meltwater contribution, ET(t) is evapotranspiration, ΔS(t) is the change in basin storage (soil moisture, snowpack, groundwater), and G(t) is net groundwater exchange. The objective of the hydrological modeling component (Section 3.4) is to learn a parameterized mapping:

$$\hat{Q}(t) = f\theta(P(t), T(t), R(t), L(t)) \quad (2)$$

where fθ denotes the calibrated SWAT model with parameter set θ, T(t) is temperature, R(t) is the satellite-derived snow/glacier cover fraction, and L(t) is land-use/land-cover state. Model calibration seeks θ that minimizes the discrepancy between simulated discharge $\hat{Q}(t)$ and observed discharge Q(t) at gauge stations,

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evaluated using the metrics defined in Section 4.3.

Study Framework

Section 4 presents the conceptual framework linking climate drivers to basin water balance outcomes (Figure 1) and a schematic of the physical water balance components (Figure 2). Section 3 then translates this framework into a step-by-step methodological workflow (Figure 3).

Literature Review

Hydrological Regimes of the Indus Basin

The Upper Indus Basin is commonly described in terms of three interacting hydrological regimes: a nival regime driven by winter snowmelt, a glacial regime, and a monsoon-influenced rainfall regime (Qureshi, 2011; Archer, 2003). Long-term flow records from major sub-basins such as the Hunza, Gilgit, Shigar, and Astore show considerable spatial heterogeneity in flow seasonality and trend, reflecting differences in glacier cover, elevation, and monsoon exposure (Ahmad, Hafeez, & Ahmad, 2012). The basin's western sub-catchments, which lie largely outside the reach of the summer monsoon, depend more heavily on winter westerly precipitation and glacier melt, while eastern tributaries receive a greater share of monsoonal rainfall (Archer, 2003). Basin-wide climatic reconstructions covering the twenty-first century further indicate statistically detectable shifts in both temperature and streamflow across the Pakistani Himalayan portion of the basin, reinforcing the case for sub-basin-specific rather than basin-averaged analysis (Ali, Dan, Fu, & Khan, 2015).

A distinctive feature of the region is the so-called 'Karakoram Anomaly,' in which numerous glaciers have remained stable or advanced in contrast to the broader global trend of glacier recession. This heterogeneity complicates basin-wide generalizations about future meltwater contributions and underscores the need for spatially explicit, satellite-based monitoring rather than reliance on basin-averaged assumptions (Hussain et al., 2019; Bilal, Chamhuri, Mokhtar, & Kanniah, 2019).

Cryospheric Change and the Asian Water Towers

Immerzeel, van Beek, and Bierkens (2010), in an influential Science publication, demonstrated that the Indus Basin is exceptionally sensitive to changes in upstream meltwater contribution relative to other major Asian river systems, given the outsized share of glacier and snowmelt in its total flow. Subsequent large-scale assessments have projected temporary increases in meltwater contribution to river flows through the mid-century, followed by an eventual decline as glacier ice volume diminishes, posing risks to dry-season water availability in downstream regions (Immerzeel et al., 2010; Lutz, Immerzeel, Kraaijenbrink, Shrestha, & Bierkens, 2016).

Climate Projections and Hydrological Modeling Approaches

Multiple studies have used physically based hydrological models — most commonly the Soil and Water Assessment Tool (SWAT), but also fully distributed models such as MIKE SHE — driven by downscaled Global Climate Model (GCM) output to project future streamflow in Upper Indus sub-basins under Representative Concentration Pathways (RCPs). Ougahi, Cutler, and Cook (2022) parameterized

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SWAT for glaciered and non-glaciered sub-basins of the Upper Indus and found differentiated water-yield responses depending on the relative contribution of snow/glacier melt versus rainfall. Lutz et al. (2016), using a multi-model climate ensemble, reported a basin-wide attenuation of the seasonal hydrograph and a shift in peak flows, alongside an increased likelihood of extreme discharge events under future scenarios. Wijngaard et al. (2017) extended this analysis across the Indus, Ganges, and Brahmaputra basins, confirming that hydro-climatic extremes are projected to intensify across the wider Hindu Kush Himalayan region. Table 1 summarizes the modeling approach, data inputs, and key focus of several representative studies.

Study	Model / Method	Data Inputs	Primary Focus
Ougahi et al. (2022)	SWAT	Downscaled multi-GCM precipitation/temperature	Water balance under RCP4.5/8.5 in glaciered & non-glaciered sub-basins
Lutz et al. (2016)	Multi-model ensemble hydrological modeling	CMIP5 GCM ensemble	Basin-wide seasonal flow shifts and extremes
Wijngaard et al. (2017)	Distributed hydrological modeling	CMIP5 ensemble, Indus/Ganges/Brahmaputra	Hydro-climatic extremes across HKH basins
Hussain et al. (2019)	Remote sensing + Mann-Kendall trend test	MODIS MOD10A2 (2001-2015)	Snow-covered area trend, Gilgit Basin
Ahmad et al. (2012)	Statistical hydrological analysis	Gauge records (1960-2005), 8 watersheds	Flow regime classification and trend detection

Table 1. Representative hydrological modeling and remote sensing studies of the Upper Indus Basin.

Remote Sensing of Snow Cover and Land Surface Change

Satellite remote sensing, particularly MODIS snow products (e.g., MOD10A2) and Landsat imagery, has been widely used to monitor snow-covered area (SCA) trends as a proxy for meltwater availability. Hussain et al. (2019) applied Mann-Kendall trend analysis to MODIS 8-day snow products over the Gilgit River Basin (2001–2015) and identified statistically significant seasonal trends in SCA linked to observed shifts in air temperature and precipitation. Bilal et al. (2019) similarly documented recent

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snow cover variation across Gilgit-Baltistan, reinforcing the value of multi-decadal satellite records for detecting cryospheric change in data-scarce mountain catchments. These remote sensing datasets provide the spatial and temporal inputs necessary to constrain and validate hydrological model simulations of snow and glacier melt contributions to Indus streamflow.

Groundwater Dynamics

Groundwater has historically served as a critical buffer against surface water variability in the Indus Basin, with tube-well irrigated area expanding rapidly across Punjab since the 1960s (Watto & Mugera, 2016). However, unregulated extraction has produced a 'silent revolution' with substantial negative consequences, including soil salinization, saltwater intrusion in coastal areas, land subsidence, and drying of natural lakes and wetlands (Watto & Mugera, 2016). World Bank assessments indicate that irrigation practices contribute approximately 16 million tonnes of salt to the Indus Basin annually, threatening soil health across a significant share of irrigated land, while only a minority of the population has reliable access to safe drinking water largely due to groundwater quality degradation (World Bank, 2021). These groundwater pressures compound, rather than substitute for, climate-driven surface water variability, since periods of reduced glacier/snowmelt or monsoon rainfall tend to coincide with increased groundwater pumping (Watto & Mugera, 2016).

Downstream Impacts: Agriculture and Food Security

Agriculture accounts for approximately a quarter of Pakistan's gross domestic product and the large majority of national freshwater withdrawals, making the sector acutely exposed to hydrological variability (Qureshi, 2011). Qureshi (2011) projected that, absent substantial investment in storage capacity and water-use efficiency, Pakistan could face a water requirement shortfall of approximately 32% by 2025, translating into a food production shortfall on the order of tens of millions of tonnes annually. These projections, formulated over a decade ago, illustrate the scale of the adaptation challenge and underscore why climate-driven changes in Upper Indus Basin hydrology are of direct consequence to national food security.

Extreme Events: Floods and Droughts

Climate variability in the Indus Basin manifests not only as gradual trend change but also as an intensification of hydrological extremes. Wijngaard et al. (2017) project an increased likelihood of extreme discharge events across the Upper Indus, Ganges, and Brahmaputra basins under future climate scenarios. Recent flood events in Pakistan, including major flooding episodes in 2022 and subsequent years, have been widely linked by researchers and policymakers to intensifying and more erratic monsoon rainfall, compounding the basin's storage and drainage infrastructure limitations (Shehzad, 2023).

Transboundary Water Governance

The Indus Basin is shared among Afghanistan, China, India, and Pakistan, with water allocation between India and Pakistan governed since 1960 by the Indus Waters Treaty. Recent diplomatic developments — including India's April 2025

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announcement holding the Treaty in abeyance following a security incident — have heightened the policy salience of climate-related hydrological uncertainty, since predictable flow-sharing arrangements underpin both countries' agricultural and hydropower planning (NPR, 2025). Legal and policy analysts have called for modernizing the Treaty framework to incorporate climate-adaptive data-sharing, joint glacial-melt and monsoon forecasting, and updated mechanisms for addressing hydrological extremes not anticipated in the original 1960 agreement (EJIL:Talk!, 2025).

Research Gap

While existing studies have separately advanced remote sensing-based cryosphere monitoring, hydrological modeling of the Upper Indus Basin, and analysis of groundwater and governance dimensions, comparatively few studies integrate all three strands within a single, basin-wide framework that explicitly (i) links satellite-derived snow/glacier indicators to calibrated hydrological model projections under multiple climate scenarios, (ii) accounts for groundwater-surface water interaction, and (iii) connects the resulting water balance projections to downstream irrigation, food security, and transboundary policy implications. This study seeks to address that integration gap.

Proposed Methodology

Study Area

The Indus Basin spans approximately 1.12 million km² across Pakistan, India, China, and Afghanistan, with the Upper Indus Basin — encompassing the Karakoram, Hindukush, and western Himalayan ranges in northern Pakistan and Gilgit-Baltistan — serving as the primary source of snow- and glacier-fed runoff for the downstream Indus Basin Irrigation System (Ahmad et al., 2012; Archer, 2003). Nearly half of the transboundary basin lies within Pakistan, covering roughly two-thirds of the country's land area and supporting the great majority of its population (World Bank, 2021).

Sub-basin	Approx. Regime Type	Dominant Flow Source
Hunza	Glacial / Nival	Glacier and snowmelt
Gilgit	Nival	Snowmelt with monsoon influence
Shigar	Glacial	Glacier melt (Karakoram)
Shyok	Glacial	Glacier melt
Astore	Nival-monsoon transitional	Snowmelt and rainfall
Swat	Rainfall-monsoon	Monsoon rainfall and snowmelt

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Sub-basin	Approx. Regime Type	Dominant Flow Source
Chitral	Nival-glacial	Snow and glacier melt

Table 2. Representative Upper Indus Basin sub-catchments and their dominant hydrological regimes (after Ahmad et al., 2012).

[Note: A basin-boundary and gauge-station location map should be inserted here, generated in GIS software (e.g., ArcGIS/QGIS) from an authoritative Indus Basin shapefile and digital elevation model, once the study's specific sub-basin extent and gauge network are finalized.]

Conceptual Framework

Figure 1 presents the conceptual pathway linking climate change drivers to basin water balance outcomes and, in turn, to downstream sectoral impacts and adaptive policy response. This framework structures the analysis presented in the remainder of the paper: climate drivers (Sections 2.2–2.3) act on cryospheric and precipitation processes (Section 2.4), which determine the basin water balance (Sections 3.4–3.9), with consequences for agriculture, hydropower, and flood/drought risk (Sections 2.6–2.7), ultimately requiring an adaptive policy response (Section 5.1).

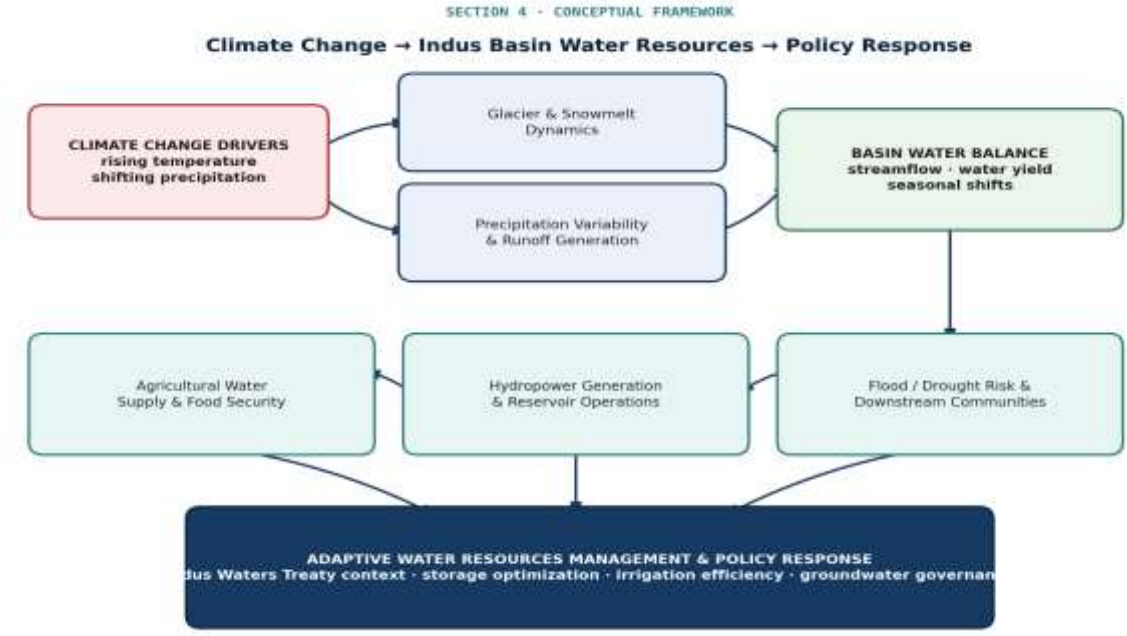


Figure 1. Conceptual framework linking climate change drivers to Indus Basin water balance and downstream impacts.

Figure 2 illustrates, in schematic form, the physical water balance components of the basin — from high-altitude snowfall and glacier melt, through monsoon precipitation input, to reservoir storage, canal diversion, groundwater interaction, evapotranspiration losses, and eventual outflow to the Arabian Sea.

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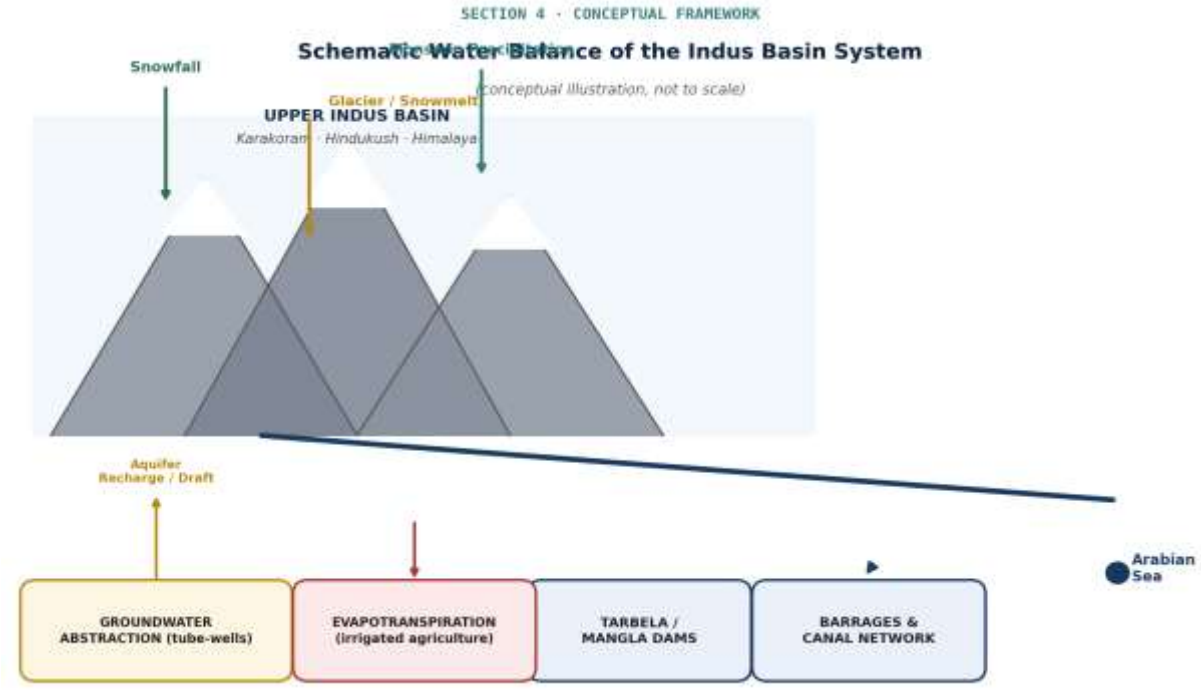


Figure 2. Schematic representation of Indus Basin surface water and groundwater balance components (conceptual illustration, not to scale).

Data and Materials

The proposed analysis draws on four categories of data: satellite remote sensing imagery, gridded/reanalysis climate data, in-situ hydro-meteorological records, and ancillary geospatial datasets. Table 3 summarizes the intended data sources, consistent with datasets used in comparable published Upper Indus Basin studies (Hussain et al., 2019; Ougahi et al., 2022).

Data Category	Example Source / Product	Temporal Coverage	Application
Snow cover	MODIS MOD10A2 (8-day)	2000-present	Snow-covered area (SCA) trend analysis
Optical imagery	Landsat 8/9, Sentinel-2	2013-present / 2015-present	Land-use/land-cover classification, glacier extent
Precipitation	CHIRPS, ERA5	1981-present / 1950-present	Precipitation trend analysis, model forcing
Temperature	ERA5 reanalysis	1950-present	Temperature trend analysis, model forcing

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Data Category	Example Source / Product	Temporal Coverage	Application
Streamflow	WAPDA gauge records	Varies by station	Model calibration/validation
Climate projections	CMIP6 GCM ensemble	2015-2100	Future scenario simulation (SSP/RCP)
Terrain	SRTM / ASTER GDEM	Static	Watershed delineation, slope/aspect derivation

Table 3. Proposed data sources for the integrated remote sensing–hydrological modeling framework.

Overall Workflow

The proposed methodology integrates remote sensing, climate, and hydro-meteorological data streams into a calibrated hydrological model used to simulate baseline and future water balance conditions. The overall workflow is summarized in Figure 3.

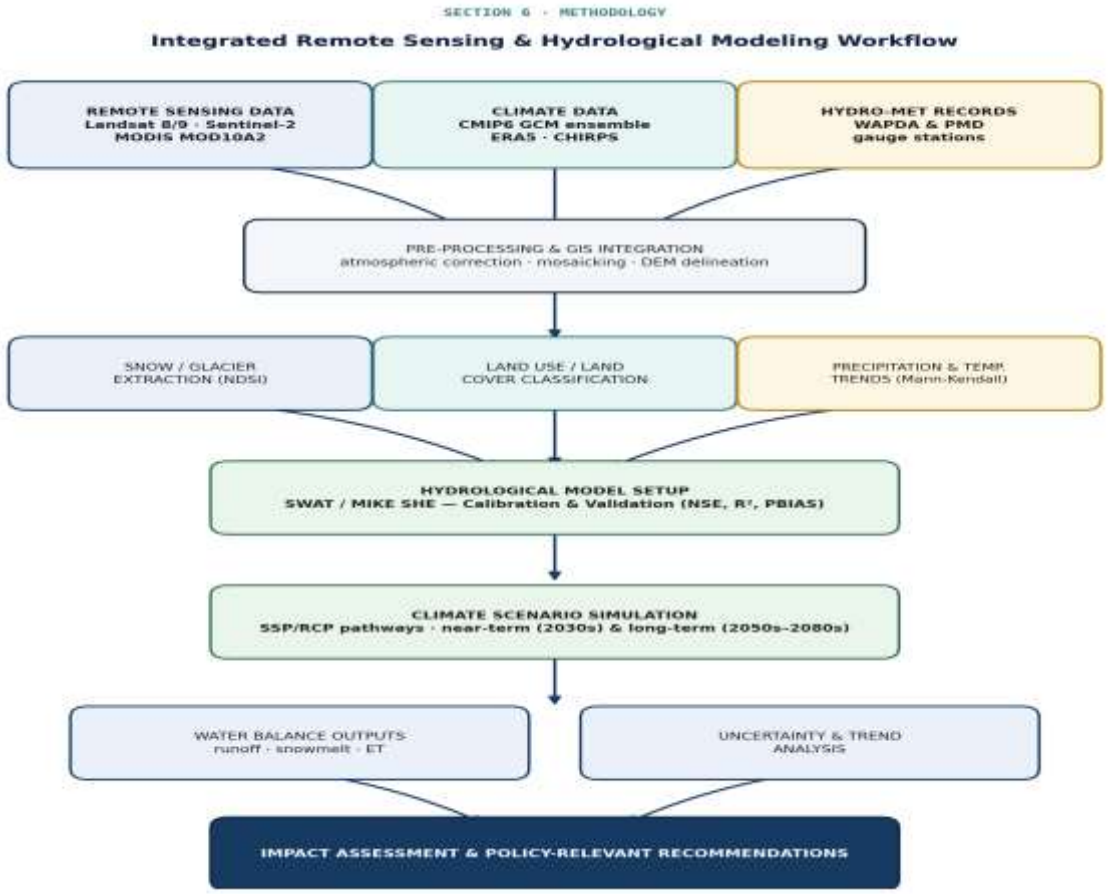


Figure 3. Proposed methodological workflow integrating remote sensing, climate data, and hydrological modeling.

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Remote Sensing Data Processing

Snow-covered area will be derived from MODIS MOD10A2 8-day snow products and/or Sentinel-2/Landsat 8-9 imagery, following Normalized Difference Snow Index (NDSI) thresholding. NDSI is computed at the pixel level as:

$$NDSI = (\rho green - \rho SWIR) / (\rho green + \rho SWIR) \quad (3)$$

where ρgreen and ρSWIR denote top-of-atmosphere reflectance in the green and short-wave infrared bands, respectively. A pixel is conventionally classified as snow/ice-covered where NDSI > 0.4, consistent with thresholds applied in comparable Upper Indus Basin studies (Hussain et al., 2019). Cloud-contaminated pixels will be filtered using temporal compositing. Land-use/land-cover classification will be performed using multi-temporal Landsat/Sentinel-2 composites and a supervised classification algorithm (e.g., random forest), validated against high-resolution reference imagery where available.

Climate and Hydro-meteorological Data

Historical precipitation and temperature will be obtained from gridded/reanalysis products (ERA5, CHIRPS) and, where available, ground station records from Pakistan's Water and Power Development Authority (WAPDA) and Pakistan Meteorological Department (PMD) (Hersbach et al., 2020). Future climate scenarios will be constructed from bias-corrected CMIP6 GCM output under multiple SSP/RCP pathways, consistent with the approach used by Ougahi et al. (2022) and Lutz et al. (2016).

Statistical Trend Analysis

Long-term trends in precipitation, temperature, and snow-covered area will be assessed using the non-parametric Mann-Kendall test (Mann, 1945), with trend magnitude quantified via Sen's slope estimator (Sen, 1968) — the same approach applied in comparable Upper Indus Basin snow cover studies (Hussain et al., 2019). For a time series x1, x2, …, xn, the Mann-Kendall test statistic S is computed as:

$$S = \Sigma_{(i<j)}\, sgn(x_j - x_i) \quad (4)$$

where sgn(·) returns +1, 0, or −1 according to the sign of the difference. Sen's slope estimator, used to quantify the magnitude of any detected trend, is given by the median of all pairwise slopes:

$$\beta = median[(x_j - x_i) / (j - i)] \quad for\ all\ i < j \quad (5)$$

Statistical significance will be evaluated at the conventional α = 0.05 threshold; results will be reported with exact p-values and confidence intervals once the underlying time series have been processed, rather than assumed in advance.

Hydrological Model Structure

A semi-distributed, physically based hydrological model (SWAT; Arnold, Srinivasan, Muttiah, & Williams, 1998) will be parameterized for the study sub-basin(s) using a digital elevation model, soil, and land-cover inputs, and calibrated/validated against observed streamflow at gauge stations, following the general parameterization approach of Ougahi et al. (2022). SWAT simulates the land-phase water balance for each hydrologic response unit as:

$$SW_t = SW_0 + \Sigma_{(i=1\ to\ t)} [R_i - Q_i - ET_i - W_i - QG_i] \quad (6)$$

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where SW_t is final soil water content, SW_0 is initial soil water content on day i, and R, Q, ET, W, and QG are daily precipitation, surface runoff, evapotranspiration, percolation, and return flow, respectively (Arnold et al., 1998).

Climate Scenario Simulation and Uncertainty

The calibrated model will be driven by downscaled climate scenarios to simulate near-term (2030s) and long-term (2050s–2080s) changes in mean annual and seasonal streamflow, snowmelt contribution, and evapotranspiration, relative to a historical baseline period (2000–2020), under at least two contrasting emissions pathways (SSP2-4.5 and SSP5-8.5) to characterize the plausible range of future outcomes. Sources of uncertainty to be documented include GCM structural uncertainty and inter-model spread, downscaling and bias-correction error, hydrological model parameter uncertainty (assessed via sensitivity analysis), and limitations in ground-truth data availability at high elevations. Multi-model ensemble ranges, rather than single deterministic projections, will be used to characterize future streamflow scenarios wherever feasible, consistent with the ensemble approach of Lutz et al. (2016).

Algorithm and Experimental Design

Algorithm 1 summarizes the end-to-end procedure translating the methodology of Section 3 into an executable analysis pipeline, from raw data ingestion through calibrated scenario projection.

Algorithm 1: Integrated Remote Sensing – Hydrological Modeling Pipeline

Input: Satellite imagery {MODIS, Landsat, Sentinel-2}, reanalysis climate {ERA5, CHIRPS},
gauge records {WAPDA, PMD}, DEM, CMIP6 GCM ensemble
Output: Calibrated streamflow simulation $\hat{Q}(t)$; future discharge projections under SSP2-4.5, SSP5-8.5

1: Delineate sub-basins and stream network from DEM (D8 flow direction / accumulation)
2: For each satellite scene: apply atmospheric correction and cloud masking
3: Compute NDSI per pixel (Eq. 3); threshold at NDSI > 0.4 to derive snow-covered area (SCA)
4: Classify land-use/land-cover via supervised classifier (random forest) on composite imagery
5: Aggregate ERA5/CHIRPS precipitation and temperature to sub-basin scale
6: For each sub-basin time series (SCA, P, T): run Mann-Kendall test (Eq. 4) and Sen's slope (Eq. 5)
7: Initialize SWAT with DEM, soil, land-cover, and climate inputs
8: Calibrate SWAT parameters θ by minimizing error between $\hat{Q}(t)$ and observed $Q(t)$
9: Validate calibrated model on held-out gauge record period; compute NSE, R^2, PBIAS (Eqs. 7–9)
10: If validation metrics below threshold (NSE < 0.5 or |PBIAS| > 15%): return to step 8
11: Bias-correct CMIP6 GCM ensemble against ERA5 baseline (2000–2020)

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12: For each SSP scenario ∈ {SSP2-4.5, SSP5-8.5} and horizon ∈ {2030s, 2050s, 2080s}:
13:     Force calibrated SWAT with bias-corrected scenario climate
14:     Record simulated Q̂(t), snowmelt contribution, and ET
15: Aggregate ensemble outputs; report median and inter-model range
16: Return calibrated model, trend statistics, and scenario projections
```

Dataset

The dataset underlying this framework comprises: (i) MODIS MOD10A2 snow-cover composites and Landsat/Sentinel-2 optical imagery spanning 2000–2020 for the selected Upper Indus sub-basins; (ii) ERA5 reanalysis and CHIRPS gridded precipitation covering the same period; (iii) daily/monthly streamflow records from WAPDA gauge stations used for model calibration and validation; and (iv) a bias-corrected CMIP6 multi-model ensemble providing future forcing under SSP2-4.5 and SSP5-8.5 through 2100. Dataset acquisition, quality control, and gap-filling constitute the first stage of empirical implementation and are not yet complete at the time of this manuscript.

Experimental Setup

The historical simulation period (2000–2020) will be split into a calibration period and an independent validation period following standard hydrological modeling practice (e.g., an approximately 70:30 split, subject to gauge record availability). Model warm-up years will be excluded from performance evaluation to reduce sensitivity to initial soil moisture and snowpack conditions. Sensitivity analysis will be performed on key SWAT parameters governing snowmelt (snowfall temperature, snowmelt base temperature, melt factors) and baseflow recession, given their particular relevance to the basin's nival-glacial hydrology.

Evaluation Metrics

Model performance will be evaluated using three standard hydrological goodness-of-fit statistics. The Nash-Sutcliffe Efficiency (Nash & Sutcliffe, 1970) is defined as:

$$NSE = 1 - [\Sigma(Q_obs - Q_sim)^2 / \Sigma(Q_obs - \bar{Q}_obs)^2] \quad (7)$$

the coefficient of determination R^2 quantifies the proportion of observed variance explained by the simulation, and percent bias is computed as:

$$PBIAS = 100 \times [\Sigma(Q_obs - Q_sim) / \Sigma Q_obs] \quad (8)$$

Consistent with widely used performance ratings for monthly streamflow in glaciated catchments, NSE > 0.50, R^2 > 0.60, and |PBIAS| < 15% will be treated as the minimum thresholds for a 'satisfactory' calibration, with NSE > 0.75 and |PBIAS| < 10% regarded as 'good to very good'. Tables 4 and 5 present the intended reporting templates for these metrics.

Sub-basin	Calibration NSE	Validation NSE	R^2	PBIAS (%)
[sub-basin 1]	[to be reported]	[to be reported]	[to be	[to be

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Sub-basin	Calibration NSE	Validation NSE	R^2	PBIAS (%)
			reported]	reported]
[sub-basin 2]	[to be reported]	[to be reported]	[to be reported]	[to be reported]
[sub-basin 3]	[to be reported]	[to be reported]	[to be reported]	[to be reported]

Table 4. Reporting template for SWAT calibration/validation performance by sub-basin (values to be populated after model calibration).

Scenario	Horizon	Δ Mean Annual Q (%)	Δ Peak-Month Q (%)	Δ Snowmelt Contribution (%)
SSP2-4.5	2030s	[to be reported]	[to be reported]	[to be reported]
SSP2-4.5	2050s	[to be reported]	[to be reported]	[to be reported]
SSP5-8.5	2030s	[to be reported]	[to be reported]	[to be reported]
SSP5-8.5	2050s	[to be reported]	[to be reported]	[to be reported]

Table 5. Reporting template for projected change in discharge and snowmelt contribution by scenario and horizon (values to be populated after scenario simulation).

Expected Results Framework

This section presents the intended structure for reporting empirical findings once satellite and hydro-climatic datasets have been acquired and processed. The chart templates in Figure 4 illustrate the intended visualization format only; the placeholder values shown do not represent real data and must be replaced with model-derived outputs prior to submission or publication.

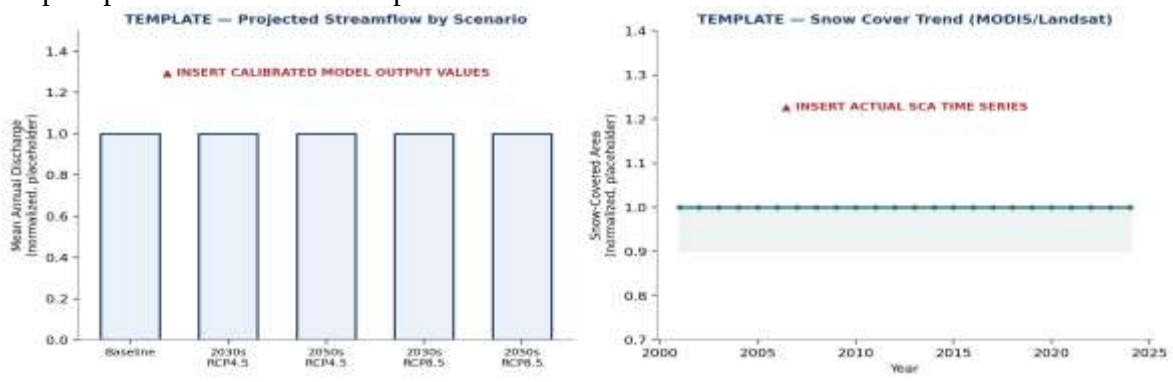


Figure 4. Template layouts for reporting (left) scenario-based streamflow projections

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and (right) satellite-derived snow cover trends. Values shown are placeholders only, not empirical results.

Anticipated analytical outputs, based on patterns reported in comparable Upper Indus Basin studies, include: (a) a shift in the seasonal hydrograph with earlier and/or reduced peak snowmelt runoff (Lutz et al., 2016); (b) sub-basin-specific divergence in glacier response consistent with the 'Karakoram Anomaly'; (c) an increased frequency of high-discharge extremes under higher-emission scenarios (Wijngaard et al., 2017); and (d) quantified groundwater-surface water interaction effects during low-flow periods. These expectations frame the analysis but must be confirmed, refined, or revised based on the study's own calibrated model outputs and statistical trend tests.

Applications

Adaptation Strategies

Drawing on the literature reviewed in Section 2 and the anticipated modeling outcomes described in Section 4.4, this study identifies several priority adaptation strategies for climate-resilient water resources management in the Indus Basin, summarized in Figure 5.

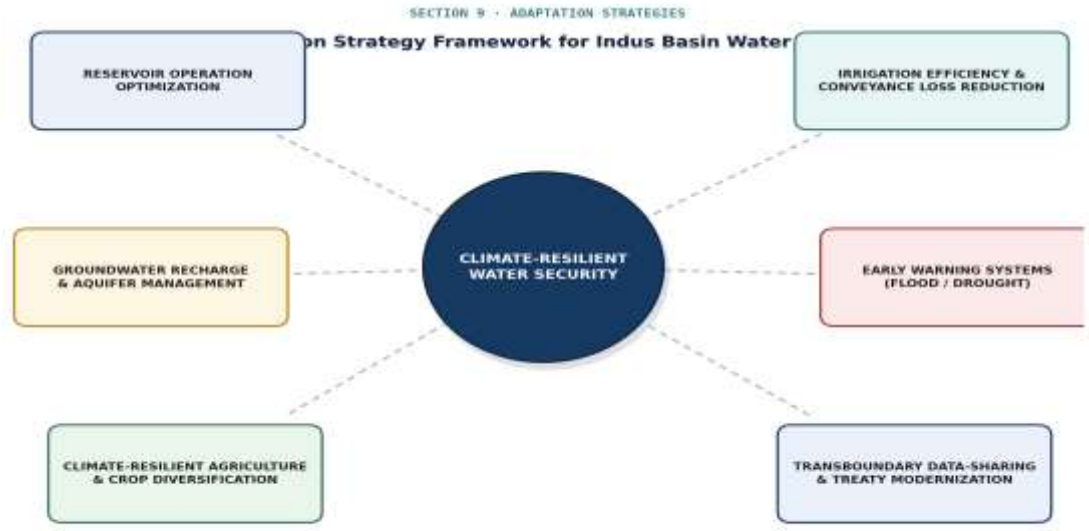


Figure 5. Adaptation strategy framework for climate-resilient Indus Basin water security.

Reservoir operation optimization. Given Pakistan's comparatively low per-capita water storage capacity (Qureshi, 2011), optimizing the operating rules of existing reservoirs (e.g., Tarbela and Mangla) to better anticipate shifted snowmelt timing and more variable monsoon inflows represents a lower-cost adaptation option than new storage construction, though additional storage capacity remains a longer-term priority identified in the literature.

Groundwater recharge and aquifer management. Managed aquifer recharge, combined with stronger groundwater governance frameworks, has been identified as essential to counteracting the depletion trends documented by Watto and Mugera (2016) and

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reinforced by World Bank (2021) assessments of the Indus Basin aquifer.

Climate-resilient agriculture. Diversification away from highly water-intensive crops, improved on-farm irrigation efficiency, and adoption of drought- and flood-tolerant crop varieties are widely cited adaptation measures for reducing agricultural vulnerability to hydrological variability in the basin.

Transboundary data-sharing and treaty modernization. Legal and policy commentary following the 2025 Indus Waters Treaty developments has emphasized the value of expanded glacial-melt and monsoon-forecast data-sharing between India and Pakistan as a means of reducing hydrological uncertainty for both countries' planning processes (EJIL:Talk!, 2025; NPR, 2025).

Limitations

This manuscript presents the literature synthesis, conceptual framework, and detailed methodology for the proposed analysis; primary quantitative outputs — such as basin-specific glacier area change, calibrated model performance statistics, and future discharge projections — depend on completion of the satellite data processing and hydrological model calibration steps described in Sections 3–4, which constitute the next phase of this research. Further limitations include: the sparsity of high-altitude ground observations for model calibration; uncertainty inherent in GCM downscaling and bias correction; the challenge of representing debris-covered glacier dynamics and the Karakoram Anomaly within standard hydrological model structures; and the difficulty of fully capturing groundwater-surface water feedbacks without a coupled surface-groundwater model. Discussion of completed results should also assess agreement or divergence with prior Upper Indus Basin modeling studies (Ougahi et al., 2022; Lutz et al., 2016), given that differences in sub-basin selection, model structure, or forcing data can materially affect projected trends.

Future Work

Future extensions of this framework include: coupling the surface hydrological model with an explicit groundwater flow model to jointly represent conjunctive surface-groundwater use; incorporating debris-cover and mass-balance modules to better represent the Karakoram Anomaly; extending the scenario ensemble to the full CMIP6 SSP range; and developing a reservoir operation optimization module directly coupled to the projected inflow scenarios to quantitatively test the adaptation strategies proposed in Section 5.1.

Conclusion

This paper has synthesized the current scientific literature on climate-driven hydrological change in the Indus Basin and developed an integrated remote sensing and hydrological modeling framework for quantifying past and projected future impacts on basin water resources. By combining satellite-derived snow cover and land-cover indicators with a calibrated hydrological model driven by multiple climate scenarios, the proposed approach is designed to generate spatially and temporally resolved projections of future water availability, directly relevant to reservoir operation, groundwater management, agricultural planning, and transboundary water governance. Completion of the empirical analysis described in Sections 3 and 4 —

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including satellite data processing, model calibration against observed streamflow, and scenario simulation — is required before the study's substantive quantitative findings can be reported and before the paper can be considered for peer-reviewed publication.

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