Discussion Paper

High Altitude Wetlands of Sikkim:
Status, Emerging Scenarios and Conservation Pathways

G. B. Pant National Institute of Himalayan Environment (NIHE)
Sikkim Regional Centre, Pangthang, Gangtok 737 101, Sikkim
(An Autonomous Institute of Ministry of Environment, Forest and Climate Change, Govt. of India)

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ISBN

Published by
G. B. Pant National Institute of Himalayan Environment (NIHE)
Sikkim Regional Centre, Pangthang, Gangtok, 737 101, Sikkim, India

Cover Photo: Hanspokhari Lake, East Sikkim (By Rajesh Joshi)
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Citation:
Joshi R, Chhetri P, Sharma A, Tamang L, Gaira K S (2025). High Altitude Wetland of Sikkim: Status, Emerging Scenarios & Conservation Pathways. NIHE, pp: 56.

Acknowledgements: This document has been prepared as a part of the HKN project "Himalayan Knowledge Network- Bridging science, policy and practice" and "Multidimensional Assessment of Ecological Dynamics and Ecosystem Health of Selected High-Altitude Wetlands of Indian Himalayan Region (IHR) for Effective Conservation and Management planning". The authors greatly acknowledge the support received from NMHS, Ministry of Environment, Forest and Climate Change, Government of India for both the projects. We thank Director, GBPNIHE for encouragement, support and constant support in implementation of the project and preparation of this document. Support received from DST, Govt. of Sikkim in implementation of HKN Project is duly acknowledged. We would like to thank our reviewers, Dr. Pankaj Saini, Dr. Rajib Gogoi, Dr. Sarala Khaling, Dr. B K Acharya for their constructive and insightful suggestions that helped in refining the content of the document.

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Preface

High altitude wetlands and glaciers of Sikkim represent critical components of the Eastern Himalaya, functioning as reservoirs of biodiversity, regulators of hydrological regimes, and providers of ecosystem services essential for regional and downstream sustenance. These ecosystems, situated in climatically sensitive zones, are increasingly threatened by rapid glacier retreat, altered hydrological processes, land use change, and anthropogenic pressures. Their degradation poses serious implications not only for ecological stability but also for water security, disaster risk, and the socio-economic well-being of dependent communities. This discussion papere on "High Altitude Wetlands of Sikkim: Status, Emerging Scenarios and Cnservation pathways" is an effort to compile, synthesize, and analyze existing knowledge, field observations, and gaps related to these unique ecosystems. This paper seeks to document their current status, identify emerging threats, and highlight conservation challenges while exploring the policy frameworks that govern their protection and management.

The preparation of this paper has been guided by the pressing need to bring out the synthesized knowledge that may guide policymakers, researchers, conservation practitioners, and other stakeholders about the need of protecting and managing Sikkim's high altitude wetlands and glaciers through in-depth research and policy intervention. It emphasizes an integrated approach that combines scientific research, and participatory governance to ensure the longterm conservation of these ecosystems and mitigation of risks like Glacial Lake outburst Flood (GLOF).

We hope that this paper will contribute to strengthen the evidence base for decision making, guide research priorities, and inform adaptive management strategies in line with both national and global commitments to biodiversity conservation and climate action. The findings and perspectives presented herein are intended to support policymakers, scientific institutions, and civil society stakeholders in evolving an integrated approach towards the conservation and sustainable governance of high altitude wetlands of Sikkim.

Authors

Foreword

Sikkim, part of Eastern Himalaya is draped in lakes and glaciers in upper reaches of its altitudinal gradient. These landscapes are not only physically mesmerizing but also among the most fragile yet vital ecosystems of the Himalaya. In Sikkim, lakes and glaciers not only sustain rich biodiversity but also serve as critical sources of water, influencing livelihoods, agriculture, and hydropower downstream. Their role in regulating hydrological cycles and buffering against climate variability has made them indispensable for both ecological security and human well-being. In recent decades, however, these ecosystems have come under increasing pressure from climate change, anthropogenic activities, and developmental challenges.

The present Discussion Paper on High Altitude Wetlands of Sikkim: Status, Emerging Scenarios and Conservation Pathways is both timely and significant. It synthesizes the current scientific understanding, highlights emerging issues, and provides valuable insights into policy frameworks that can guide sustainable management of high altitude wetlands. It offers a comprehensive knowledge base on ecological, hydrological dimensions of these ecosystems. It lays out perspectives that can inform evidence based decision making, ensuring that conservation priorities are aligned with developmental needs.

I believe this discussion paper will help all stakeholders committed to management and conservation of high altitude landscapes. By fostering dialogue between science and policy, it can contribute meaningfully to the conservation of these irreplaceable ecosystems for generations to come.

Prof. Sunil Nautiyal
Director, NIHE

List of Acronyms and Abbreviations

amsl: Above Mean Sea Level
ATREE: Ashoka Trust for Research in Ecology and the Environment
BSI: Botanical Survey of India
CBCM: Centre for Biodiversity Conservation and Management
CEA&CC: Centre for Environment Assessment and Climate Change
CITES: Convention on International Trade in Endangered Species
CLWRM: Centre for Land and Water Resource Management
GHC: Greater Himalayan Crystalline
GLOF: Glacial Lake Outburst Flood
GoI: Government of India
ha: Hectare
HAL: High Altitude Lakes
HAW: High Altitude Wetlands
HKH: Hindu Kush Himalaya
HCC: Higher Himalayan Crystalline
ICIMOD: International Centre for Integrated Mountain Development
IHR: Indian Himalayan Region
IUCN: International Union for Conservation of Nature
km: Kilometre
m: Metre
mm: Millimetre
MBT: Main Boundary Thrust
MCT: Main Central Thrust
MoEF&CC: Ministry of Environment, Forest and Climate Change
MPCA: Medicinal Plant Conservation Area
NMHS: National Mission on Himalayan Studies
NWCP: National Wetland Conservation Programmes
PA: Protected Areas
TII: The (Economics of Ecosystems and Biodiversity) India Initiative
TPSS: Tsomgo Pokhari Sanrakshan Samiti
UNDP: United Nations Development Programme
WII: Wildlife Institute of India
WQI: Water Quality Index
WWF: World Wide Fund for Nature

Executive Summary

The High Altitude Wetlands (HAWs) of Sikkim form one of the most ecologically fragile yet indispensable ecosystems of the Eastern Himalaya. Spread over more than 60,000 acres and comprising over 534 lakes, they play a pivotal role as natural reservoirs of water, regulators of hydrological regimes, and providers of ecosystem services essential to human well-being. Rich in biodiversity, these wetlands sustain both local livelihoods and downstream populations. At the same time, they hold profound cultural and spiritual value, with sites such as Gurudongmar, Tsomgo, and Khecheopalri revered in religious traditions and integrated deeply into Sikkim's socio-cultural landscape.

Despite their immense importance, these ecosystems are increasingly under stress. Climate change and glacial retreat are altering the delicate balance of hydrological systems, increasing the risks of glacial lake outburst floods (GLOFs) and destabilizing water security. Land-use changes, unregulated tourism, and infrastructure expansion are adding layers of pressure, leading to fragmentation of habitats, biodiversity loss, and pollution. Together, these drivers have begun to erode the ecological resilience of wetlands, placing biodiversity, ecosystem services, and local livelihoods at risk.

This discussion paper situates Sikkim's wetlands within their physiographic, climatic, and geological context, highlighting the processes that shaped their formation. It further provides a detailed account of wetland definitions and classifications, with specific attention to the Indian Himalayan Region, before moving into an inventory of Sikkim's wetlands. Their district-wise distribution, hydrological significance, and cultural importance are presented as evidence of both their ecological and socio-economic relevance. The paper also synthesizes available knowledge on glaciers, biodiversity, limnology, and wetland–climate interactions, and discusses how anthropogenic drivers are compounding the impacts of climate change.

Legal and policy frameworks form another important strand of this discussion. From India's national wetland rules to global conventions and biodiversity treaties, the paper examines the relevance and adequacy of these instruments in relation to the conservation of Sikkim's HAWs. It identifies gaps in the implementation of these frameworks, noting that while laws exist on paper, effective enforcement and contextual adaptation to fragile mountain environments remain limited.

The analysis reveals significant knowledge gaps that hamper effective management. Biodiversity documentation is still fragmented and largely limited to certain flagship species, with little attention to ecological interactions. Long-term monitoring data on wetland dynamics, glacial meltwater contributions, and climate variability are conspicuously absent. Equally underexplored are the socio-ecological linkages between local communities and wetlands, which are essential to designing participatory and culturally sensitive management strategies. Without a holistic understanding of these dimensions, conservation interventions risk being piecemeal and ineffective.

Against this backdrop, the paper calls for an integrated approach to conservation, rooted in science, local participation, and adaptive governance. Long-term ecological monitoring, systematic biodiversity documentation, and climate impact assessments must be prioritized to generate reliable data for decision-making. At the same time, the role of communities must be recognized not just as beneficiaries but as active custodians of wetlands, given their traditional knowledge and cultural ties to these ecosystems. Sustainable tourism frameworks, disaster risk reduction strategies that integrate wetland management and robust legal enforcement are also critical. Together, these measures can create a governance model that is not only ecologically sound but also socially inclusive.

The discussion note concludes that Sikkim's HAWs should be understood as socio-ecological systems rather than isolated natural entities. Their conservation is central to safeguarding water resources, biodiversity, cultural values, and livelihoods in the face of mounting climatic and developmental pressures. The way forward lies in fostering collaboration among scientists, policymakers, communities, and civil society, ensuring that these ecosystems are managed with resilience and foresight. In doing so, Sikkim can also contribute to India's broader commitments on biodiversity conservation, climate adaptation, water security, and disaster risk reduction.

Chapter 1

1. Sikkim: State at a Glance

Sikkim, the second smallest state of India, covers an area of 7,096 km^2 and is located in the eastern Himalaya between 27°05′–28°09′ N latitudes and 87°59′–88°56′ E longitudes (Fig. 1) (Chettri et al., 2021). Geologically, the state forms part of the young, highly folded Himalayan mountain belts, characterized by active tectonics, steep slopes, and complex lithological formations. Sikkim exhibits a pronounced altitudinal climatic gradient, ranging from subtropical conditions in the lower southern valleys (<1,500 m) to temperate (1,500–2,500 m), subalpine (2,500–3,500 m), alpine (3,500–4,500 m), and tundra climates (>4,500 m) in the northern highlands. Snow and glacial cover dominate much of the northern region for four to six months annually, with temperatures frequently falling below 0°C. In the high-elevation tundra zones of northern Sikkim, winter temperatures may decline below –40°C. The mean annual temperature of the state is approximately 18°C. Precipitation is highly seasonal and strongly influenced by the southwest monsoon, with the highest rainfall occurring during July and August (National Wetland Atlas: Sikkim, 2011). The diverse altitudinal zones support distinct bioclimatic regions, influencing both ecosystem types and the distribution of flora and fauna across the state.

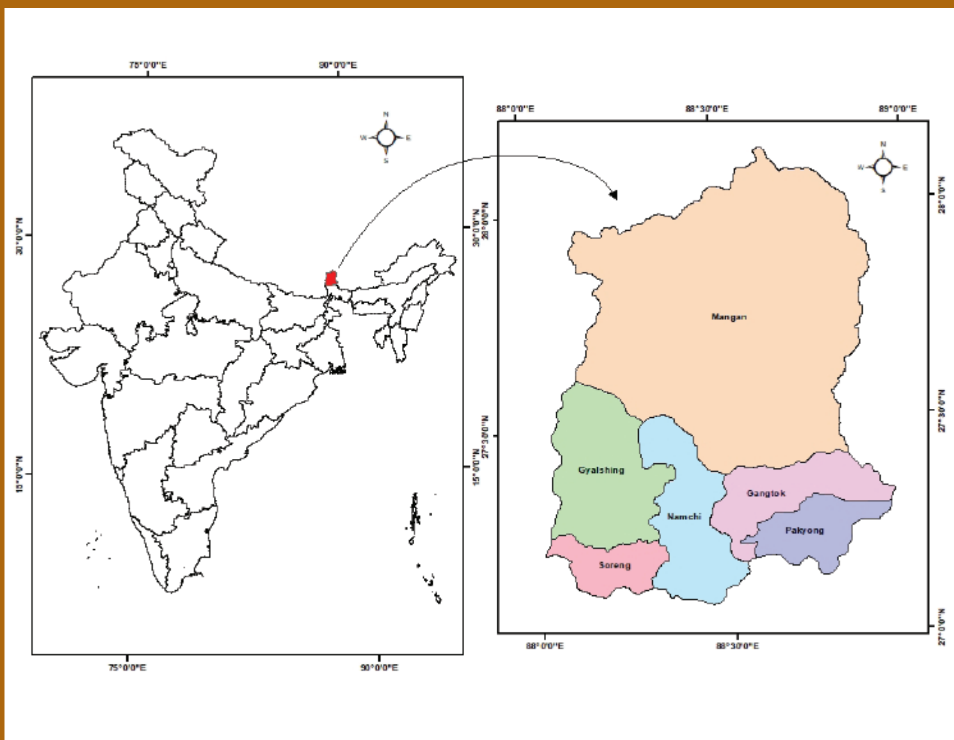

Figure 1: Map of Sikkim state

The Teesta and Rangeet rivers constitute the two major perennial water sources in Sikkim. The state also hosts numerous lakes and high-altitude wetlands of diverse sizes and morphologies (Hussain et al., 2018). Among these, Gurudongmar Lake, a sacred high-altitude lake located in Mangan (formerly North Sikkim) district at 5,243 m elevation, is well known for its ecological and cultural significance. Chholhamu Lake, situated near Donkiala Pass in the same district at 5,300 m elevation, is the highest lake in India and serves as a source of the Teesta River. The Sikkim Himalaya supports a variety of lakes across different altitudinal zones, which are primarily snow-fed, rain-fed, or both. Some of the most notable lakes in the state include Changu (Tsomgo), Khechodpalri, Gurudongmar, Chholamu, Memencho, Lampokhari, and Samiti, among others (Chatterjee et al., 2010). These water bodies play a critical role in maintaining regional hydrology, supporting biodiversity, and sustaining local livelihoods.

Based on elevation and size, wetlands in Sikkim can be classified into three categories: (i) major rivers and streams, (ii) high-altitude lakes located above 3,000 m elevation, and (iii) small wetlands occupying an area of less than 2.25 ha, as well as low-altitude lakes (Fig. 2) (Sharma et al., 2010). Most lakes in the state are monsoon-fed and are highly sensitive to climatic variations. Rising temperatures have led to substantial glacial retreat, which in turn has contributed to the expansion of several high-altitude lakes (Shukla et al., 2018). These changes have important implications for regional hydrology, biodiversity, and downstream water resources.

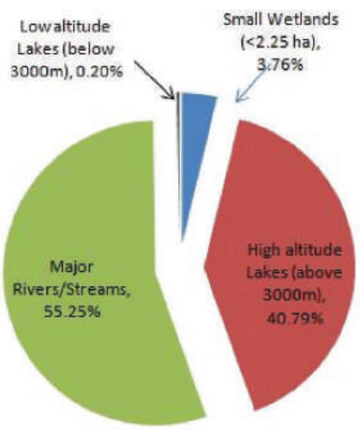

Figure 2: Distribution of wetlands in Sikkim Himalaya (Source: Sharma et al., 2010)

The Sikkim Himalaya forms part of the Himalayan biodiversity hotspot and harbors over 5000 species of vascular plants. This rich biodiversity is embedded within a geographically complex terrain shaped by a monsoonal climate. During the Pliocene, tectonic uplift significantly transformed the region's topography, influencing habitat heterogeneity and ecological niches (O'Neill, 2019; Qu et al., 2014). Prolonged periods of geographical isolation further shaped evolutionary trajectories in the region. Notably, Pleistocene glaciations created periods of isolation for local biota, resulting in population bottlenecks during glacial maxima and facilitating gene flow during interglacial periods (O'Neill, 2019). Consequently, these glacial dynamics have strongly influenced the formation of high-altitude wetlands in the Sikkim Himalaya and adjacent regions, which now serve as critical reservoirs of rich biodiversity.

1.1. Physiographic features

Physiographically, the state of Sikkim lies within the Central Himalayan Zone and forms part of the Eastern Himalaya. The region is characterized by rugged topography, comprising a series of ridges and valleys generally oriented in a northeast–southwest direction. Elevation in the state ranges from 230 to 8,598 m

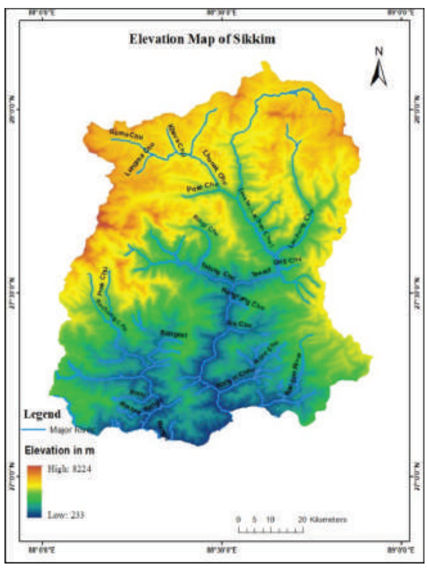

Figure 3: Elevation map of Sikkim Himalaya

amsl(Fig.3). Based on physiographic characteristics, Sikkim can be classified into nine distinct divisions: (i) summits and ridges, (ii) escarpments, (iii) very steep slopes (>50%), (iv) steep slopes (30–50%), (v) moderately steep slopes (20–30%), (vi) valleys, (vii) cliffs and precipitous slopes (>20–30%), (viii) glacial drifts, moraines, and boulder fields, and (ix) high mountains with perennial snow.

1.2. Geology

The Himalaya are traditionally divided into linear geotectonic belts, each characterized by distinct geological features. From south to north, these belts are: Sub-Himalaya, Lesser Himalaya, Higher Himalaya, and Trans-Himalaya. In the Sikkim–Darjeeling Himalaya, the Sub-Himalayan domain primarily consists of molasse-type deposits of the Siwaliks. Moving northward, it is succeeded by the Lesser Himalayan Belt, which comprises a thin strip of sandstone, carbonaceous shale, and coal (Gondwana), followed by stromatolitic dolomite and variegated slate of the Buxa and Reyang Formations (Daling Group), and a thick metasedimentary sequence dominated by pelites with subordinate psammite and wacke (Gorubathan Formation, Daling Group). Further north, the Daling sequence is overlain by the Higher Himalayan rocks, characterized by medium- to high-grade pelitic schists with minor interbeds of quartzite, calc-silicate rocks, and metabasites (commonly referred to as the Chungthang/Paro Formation), along with small intrusive bodies of granite (Lingtse Gneiss).

This sequence, in turn, is overlain to the north by a migmatitic terrain known as the Darjeeling Gneiss or Kanchenjunga Gneiss, which is considered equivalent to what has been variously described as the Central Crystalline, Greater Himalayan Crystalline, or Higher Himalayan Crystalline (GHC/HHC). Farther north, a thick succession of fossiliferous Cambrian to Eocene sediments, belonging to the Tethyan Belt (Tethyan Sedimentary Sequence), overlies the HHC.

The Main Boundary Thrust (MBT) separates the Siwalik deposits of the Sub-Himalayan domain from the overlying rocks of the Lesser Himalayan Belt, while the Main Central Thrust (MCT) demarcates the boundary between the Lesser Himalaya and the Higher Himalaya. In both the western and eastern sectors of the Sikkim–Darjeeling Himalaya, the Lesser Himalayan sequence is exposed as a thin strip between the MBT and MCT. However, in the central sector, a domal structure known as the Teesta/Daling Dome has uplifted and exposed a broad expanse of Lesser Himalayan rocks. The MBT, characterized by Mio-Pliocene synorogenic Siwalik Group in the footwall and Permo-Carboniferous Gondwana rocks in the hanging wall, remains largely unaffected by this domal culmination and exhibits an approximately east–west trend. Gondwana rocks, along with the Buxa and Rangit pebble slate, are exposed in the Rangit Window, where they are surrounded by the Daling Group of rocks (Gansser, 1964; Acharyya, 1989, 1992). The Tethyan Belt is exposed on the hanging-wall side of a series of north-dipping normal faults constituting the South Tibetan Detachment System (STDS), with the Higher Himalayan Crystallines forming the footwall (GSI, 2012).

1.3. Climate profile

Sikkim exhibits a strong altitudinal climatic gradient and can be broadly classified into tropical, temperate, and alpine zones (Fig. 4). For most of the year, the state experiences cold and humid conditions, with substantial precipitation in most regions. The extreme northern areas adjoining Tibet, however, receive very low rainfall. The mean annual precipitation ranges from a minimum of 82 mm at Thangu to a maximum of 3,494 mm at Gangtok. Isohyetal analysis reveals two primary rainfall maxima: (i) the southeastern quadrant, including Mangan, Singhik, Dikchu, Gangtok, Rongli, and adjacent areas, and (ii) the southwestern hilly terrain. Between

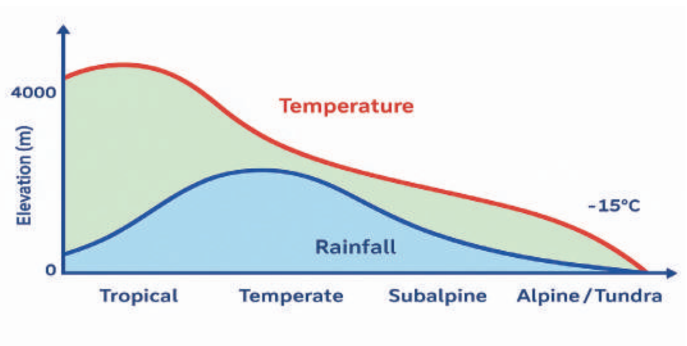

Figure 4: Climate gradient of Sikkim

these regions lies a low-rainfall zone around Namchi, while certain parts of northwestern Sikkim receive less than 5 mm annually.

The rainfall and temperature patterns of Sikkim are highly variable (Table 1). The monsoon season, from May to early October, is marked by heavy and well-distributed rainfall, with July being the wettest month. Post-monsoon and winter seasons (October–March) are comparatively dry (GSI, 2012). Temperature varies significantly with elevation. In the Lesser Himalayan regions, temperatures range between 4°C and 30°C, whereas areas around 1,800 m typically experience 1°C to 25°C. High-altitude regions above 4,000 m experience maximum summer temperatures up to 15°C, while winter, early spring, and late autumn temperatures generally remain below freezing (Basu, 2013).

Table 1. Approximate ttemperature and rainfall ranges in Sikkim by elevation zone

Elevation Zone (m)	Climatic Type	Temperature Range (°C)	Mean Annual Rainfall (mm)	Remarks
<1,500	Tropical	4 – 30	1,500 – 3,000	Humid, heavy monsoon rainfall
1,500 – 2,500	Temperate	1 – 25	1,000 – 3,000	Moderate rainfall, cooler
2,500 – 4,000	Subalpine	0 – 20	500 – 2,500	Snow possible in winter
>4,000	Alpine/Tundra	-15 – 15	50 – 500	Perennial snow, sparse rainfall

Chapter 2

Definitions, Status, and Scenarios

2.1. Wetlands

Article 1.1 of the Ramsar Convention defines wetlands as areas encompassing marshes, peatlands, fens, or water bodies that may be either natural or artificial, permanent or temporary, static or flowing, and may contain freshwater, saline, or brackish water (Ramsar Convention Secretariat, 2013). This definition also includes marine waters at low tide that do not exceed six meters in depth. Wetlands typically occur where the water table is at or near the land surface or where the land is periodically or permanently inundated. These ecosystems are characterized by areas that are partially or fully submerged, making them functionally aquatic, terrestrial, or a combination thereof depending on seasonal hydrological variability.

Wetlands support exceptionally high biodiversity due to their geological origin, geographic location, hydrological regimes, and the availability of diverse sediments and mineral resources. Functioning as ecotonal zones, wetlands often exhibit transitional characteristics, which can complicate their precise demarcation. The persistent presence of water is a primary determinant in the formation and maintenance of wetland ecosystems. Based on hydrological, geological, and ecological criteria wetlands are classification into different categories (Cowardin et al. (1979).

Wetlands hold immense ecological significance, serving as critical habitats for a wide range of plant and animal species, regulating hydrological cycles,

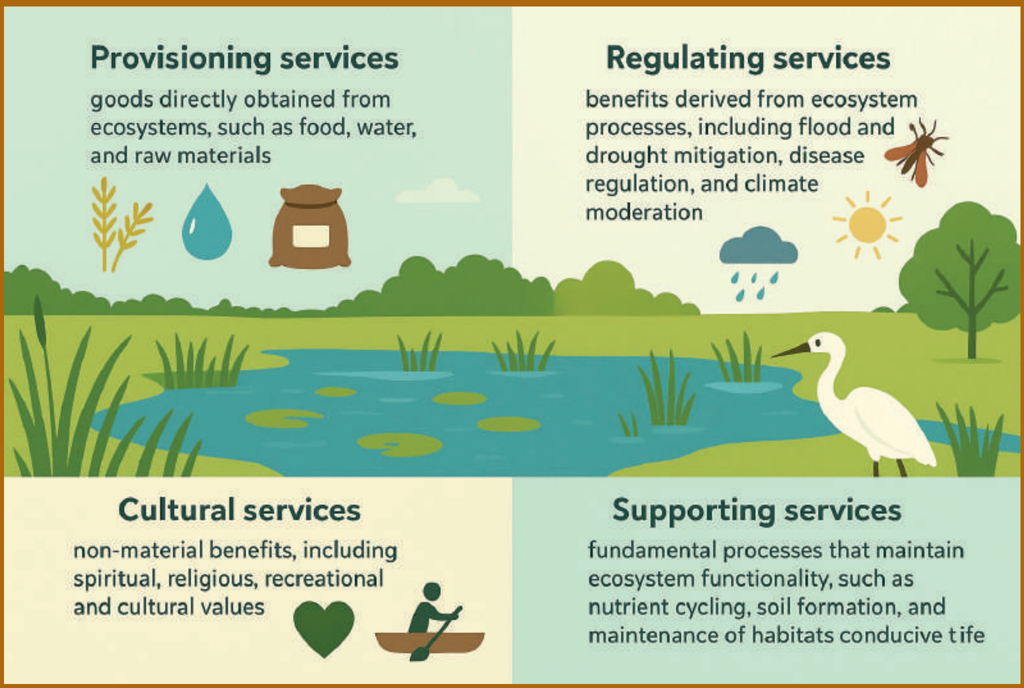

Figure 5: Ecosystem services of wetlands

and providing essential ecosystem services including nutrient cycling, carbon sequestration, and flood mitigation. Wetlands provide a wide range of ecosystem services (Fig.5), encompassing both direct and indirect use values. These services include provisioning of food and fiber, regulation of storm surges and floods, nutrient cycling, temperature moderation, and more. According to the Millennium Ecosystem Assessment (2003), wetlands cover approximately 7% of the Earth's surface yet contribute nearly 45% of global ecosystem productivity and services, with an estimated annual economic value of up to $30 trillion. The Millennium Ecosystem Assessment (2003) defines ecosystem services as the benefits that people obtain from ecosystems, categorized into four major types; (i) Provisioning services, (ii) Regulating services, (iii) Cultural services, (iv) Supporting services (Fig. 5). Wetlands, by delivering these multiple services, are critical not only for biodiversity conservation but also for sustaining human well-being and socio-economic development.

2.2. High Altitude Wetlands

High-altitude wetlands (HAWs) are generally defined as marshes, fens, peatlands, swamps, or other water bodies—whether stagnant or flowing, natural or artificial, freshwater, brackish, or saline—occurring at elevations above 3000 meters (Khan and Baig, 2017). These ecosystems are predominantly located in transitional zones between the treeline and the permanent snowline. A defining feature of HAWs is the presence of a permafrost layer, which may be seasonal or diurnal. Vegetation within these wetlands is typically dominated by grasses and shrubs, reflecting the constraints of low temperatures and elevated solar radiation. HAWs play a critical role in regional hydrology and support human populations across South and Central Asia (Milner et al., 2017). Functioning as natural water storage basins, they receive runoff from snowmelt and provide essential habitats for species endemic to the Himalayan and trans-Himalayan regions (Ragettli, 2016).

2.3. Wetland Distribution Scenario: Indian Himalayan Region

According to the National Wetland Inventory and Assessment (NWIA), wetlands cover approximately 5% of India's total geographical area. Of these, around 69.2% are inland wetlands, 27.15% are coastal wetlands, and the remaining 4% comprise other wetland types (Panigrahy et al., 2012) (Fig. 6 & 7). Wetlands in India provide a diverse array of ecosystem services, including regulation of riverine water flow, maintenance of ecological productivity, and provision of critical habitats that support biodiversity.

Indian wetlands harbor approximately 1,200 floral species and 18,000 faunal species. Remarkably, India

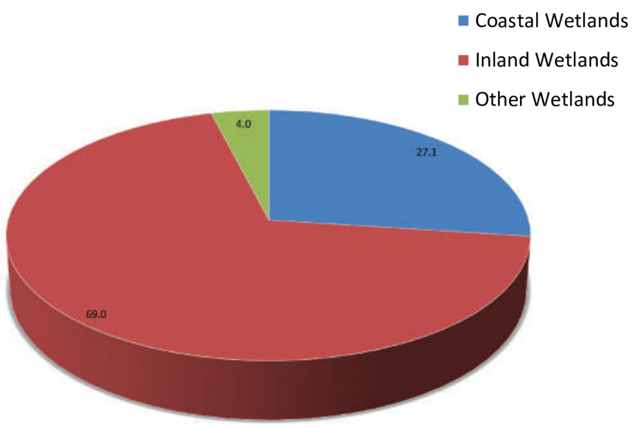

Figure 6: Wetland type distribution in India

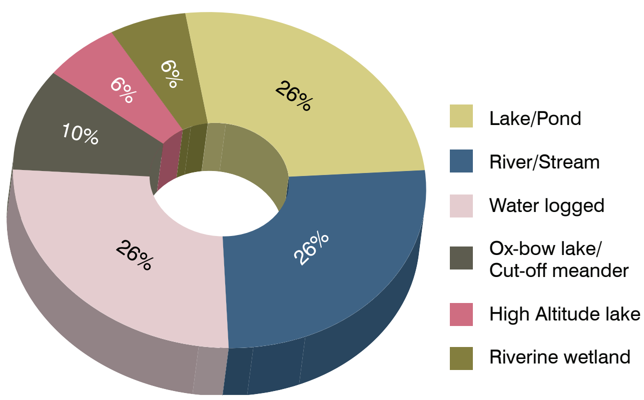

Figure 7: Natural Inland Wetlands (by number) in India (Total number > 45600; Source: EnviStats-India 2020

supports nearly 60% of the world's mangrove species. The Sundarbans, spanning India and Bangladesh, are home to two endangered mangrove species, *Sonneratia griffithii* and *Heritiera fomes* (Bhatt and Kathiresan, 2011). Additionally, Indian wetlands host 81 extralimital seasonal migrant species from the Palearctic region—encompassing Central and Northern Asia, as well as Eastern and Northern Europe. Notable endangered migratory birds include Baer's Pochard (*Aythya baeri*), Spoon-billed Sandpiper (*Calidris* pygmaea), and Sociable Lapwing (*Vanellus gregarius*) (Kumar et al., 2017).

Within the Indian Himalayan Region (IHR), the National Wetland Atlas documented 8,536 wetlands across 55 administrative districts (NWA, 2011). Of these, 5,271 wetlands are located in the western Himalayan states of Uttarakhand, Himachal Pradesh, and Jammu & Kashmir, while 3,265 wetlands occur in the eastern Himalayan states of Arunachal Pradesh and Sikkim (Hussain et al., 2018). Jammu & Kashmir accounts for the largest wetland area, followed by Arunachal Pradesh, whereas Sikkim contains the smallest wetland extent (NWA, 2011).

In Arunachal Pradesh, approximately 28.3% of the total geographical area is classified as high-altitude terrain, whereas Jammu and Kashmir, along with the Union Territory of Ladakh, comprises about 78.8% of its area at high elevations (Sharma, 2020). The average size of high-altitude wetlands (HAWs) is considerably larger in the northwestern Himalaya, with Jammu and Kashmir exhibiting an average wetland area of approximately 52.4 ha. The number and average size of HAWs is significantly higher in the eastern Himalaya, (6.2 ha in Sikkim and 7 ha in Arunachal Pradesh—compared to 1.9 ha in Uttarakhand and 2.1 ha in Himachal Pradesh) than in the western Himalaya (Fig. 8).

The highest density of high-altitude wetlands (HAWs) is observed in Sikkim, with approximately 12.6 lakes per km^2, whereas Uttarakhand exhibits the lowest density at 0.7 lakes per km^2. However, these estimates are limited, as they often exclude smaller wetlands. The Himalayan region is generally data-deficient, with restricted availability of ecological, hydrological, and climate-related information. Additionally, administrative divisions and overlapping ownership of high-altitude areas often constrain research activities in these regions.

Biodiversity assessments indicate that Ladakh exhibits the highest plant endemism, with approximately 700 plant species, of which around 280 are utilized in traditional Tibetan medicine. The region also serves as a prime breeding ground for the Black-necked Crane (*Grus nigricollis*) (Gopi et al., 2014). Research on HAWs in the Indian Himalayan Region has predominantly focused on inventory and assessment (48.63%), followed by biodiversity studies (34.93%), with comparatively fewer studies addressing climate change impacts (8.9%) and ecosystem services (7.54) (Figure 9).

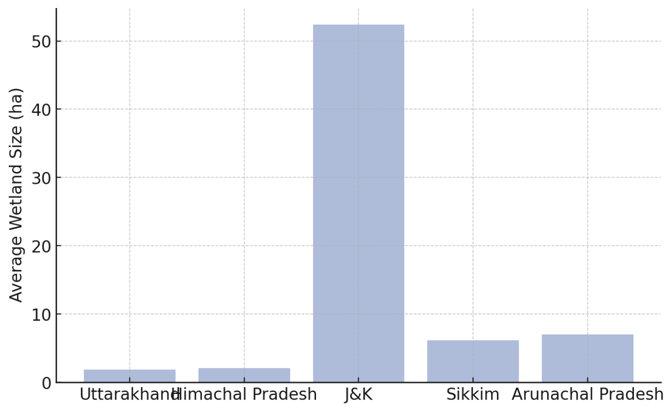

Figure 8: Average size of HAWs in Himalayan states

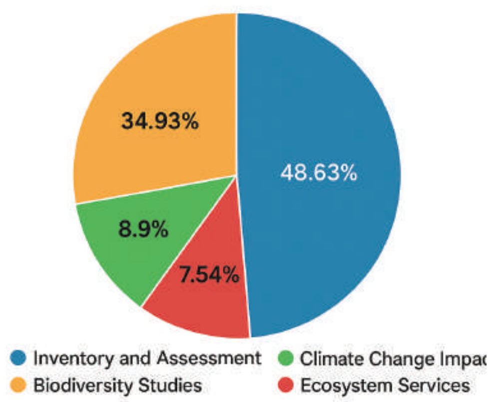

Figure 9: Analysis of research focus on HAWs in Indian Himalaya region

2.4 High Altitude Wetlands Scenario in Sikkim

Wetlands in Sikkim have historically served as critical sources of diverse ecosystem services. Ranging from Gurudongmar Lake in the north to Khecheopalri Lake in the west, these wetlands represent ecologically significant landscapes of the state. Numerous studies and institutional reports have documented the distribution, typology, and ecological characteristics of these wetland habitats. High-altitude wetlands in Sikkim are predominantly fed by glacial meltwater and seasonal snow from the surrounding mountain ranges. Sikkim encompasses a total geographical area of 7,096 km^2, of which approximately 40.79% is constituted by wetland ecosystems. To date, a total of 534 lakes covering an area of 3,325 hectares have been recorded (Khan and Baig, 2017). The permanent snowline in the state occurs between 4,877 and 6,096 meters above sea level (Basnett et al., 2013).

Over the past several years, the Government of Sikkim has undertaken extensive geo-referencing of 526 lacustrine wetlands within the state's geopolitical boundaries. The highest density of wetland systems has been reported within the Chombo Chu watershed along the Tibetan Plateau (O'Neill, 2019; GoS, 2015). Approximately 215 high-altitude lakes are located within protected areas. Prominent lakes of Sikkim include Tsomgo, Khecheopalri, Gurudongmar, Lampokhari, Samiti, Cholamu, and Memcho, among others. According to the National Wetlands Inventory and Assessment (NWIA), a total of 534 high-altitude wetlands in Sikkim have been georeferenced. Of these, 205 wetlands are situated above 5,000 m elevation, 323 wetlands occur between 4,000 and 5,000 m, and six wetlands are recorded within the 3,000–4,000 m elevation range (Table 2). The cumulative wetland area of Sikkim is estimated at 33.24 km^2. The majority of wetlands in the state fall within the size range of 2.25–10 ha, collectively accounting for a total area of 852 ha.

2.5 Ecological, Cultural, and Limnological Significance of HAWs in Sikkim

High-Altitude Wetlands (HAWs) are biodiversity hotspots, exhibiting elevated rates of endemism and

Table 2: Areas wise distribution of wetlands in Sikkim

Sl no	High Altitude Lakes of Sikkim	
1	Total (number)	534
2	Density (per 100 km^2)	12.6
Altitudinal Distribution		
3	Above 5000 m (Number)	205
4	4000-5000 m (Number)	323
5	3000-4000 m (Number)	6
Area		
6	Total Area (km^2)	33.24
7	>500 ha size (ha)	-
8	100-500 ha size(ha)	497
9	25-100 ha size (ha)	874
10	10-25 ha size (ha)	826
11	2.25-10 ha size (ha)	852

(Source: Sharma et al., 2020)

playing a crucial role in regulating hydrological cycles (Dorador, 2010). They are integral components of the global climate system, contributing to regional and potentially global climate regulation (Buytaert, 2011). Beyond their ecological functions, HAWs provide substantial cultural and livelihood value to indigenous agro-pastoralist communities inhabiting adjacent and downstream regions (García-San et al., 2021; Uruttia and Vuille, 2011). Despite their critical role in climate regulation and provision of multiple ecosystem services, HAWs are highly vulnerable to anthropogenic pressures and climate-induced disturbances, which threaten their structural integrity and functional capacity (Uruttia and Vuille, 2011).

Limnology, the multidisciplinary study of inland water bodies, offers a comprehensive framework for understanding these ecosystems (Cole and Weihe, 2015). Limnological approaches integrate geology, chemistry, physics, and biology within a holistic ecosystem perspective, addressing both academic and applied management objectives (Dodson, 2004). These approaches include direct field experiments, laboratory-based studies, observational surveys, and theoretically supported analyses. Modern disciplines such as aquatic science, hydro-ecology, freshwater ecology, and geo-hydrology often overlap with limnological studies. Limnological tools facilitate the assessment of both positive and negative impacts on water bodies, supporting restoration, pollution control, hydraulic management, and the evaluation of threats such as resource depletion, invasive species, and contamination.

The HAWs of the Sikkim Himalayas represent highly diverse habitats spanning over 4,000 hectares (NWIA, 2011), hosting more than 800 recorded species. These wetlands provide critical habitats for avifaunal species of international significance under the Ramsar Convention, including the Ruddy Shelduck, Eurasian Wigeon, and Black-necked Crane, serving as breeding and staging grounds. While many HAWs in Sikkim are located within protected areas, those with the highest conservation value are frequently situated outside formal protection zones, particularly along India's Himalayan frontiers. Conservation of these wetlands often follows Ramsar principles, emphasizing both socio-cultural and ecological importance, highlighting the need for integrated approaches that combine biodiversity protection, community engagement, and ecosystem management.

2.6 HAWs Susceptibility to GLOFs and Climate Change

The assessment of Glacial Lake Outburst Floods (GLOFs) is inherently challenging due to the rapid dynamics of glacial systems, the infrequency of such events, and the complex interplay of geomorphological and hydrological processes (Wang et al., 2015). In Sikkim, numerous studies have documented a predominantly retreating trend among glaciers. For instance, between 1980 and 2012, the East Rathong Glacier in West Sikkim retreated by approximately 460 m, corresponding to an average annual retreat rate of 13.9 m/year. Recent inventories of glacial lakes in the region have provided updated insights into GLOF hazards. Luitel et al. (2012) and Aggarwal et al. (2016) mapped 143 glacial lakes using IRS-LISS III and Landsat TM satellite imagery from 2009 and 2011, identifying 18 lakes with significant potential for GLOF occurrence. A subsequent study by Aggarwal et al. (2017) evaluated the sensitivity of 472 lakes using a set of predefined susceptibility traits based on the WIOA approach, identifying 21 lakes as potential GLOF sources. Comparative analysis across these studies indicates an increasing number of high-altitude lakes exhibiting GLOF susceptibility over time. This trend underscores the growing vulnerability of Sikkim's glacial water bodies including HAWs to hydrological hazards, highlighting the need for continuous monitoring and risk mitigation strategies for these fragile high-altitude ecosystems.

2.7 HAWs and Threats to Water Security

Globally, population growth has led to a corresponding exponential increase in water demand. By 2030, the demand for food is projected to increase by approximately 50%, directly translating into heightened water requirements for agriculture (Kallenborn, 2006). Climate change represents a critical factor influencing water security, as it alters both the temporal and spatial distribution of freshwater resources. Anthropogenic pressures combined with changing climatic patterns have rendered some previously perennial rivers seasonal, thereby increasing their vulnerability. Reductions in rainfall have been shown to decrease river discharge by up to 50%, promoting the seasonality of formerly perennial rivers and contributing to the emergence of intermittent flow regimes (Silberstein et al., 2012). Such hydrological variability poses significant challenges for sustainable water management, agricultural productivity, and ecosystem resilience.

The Himalayan glaciers serve as the primary source for several major rivers of the Indian subcontinent, including the Ganges, Brahmaputra, and Indus. Meltwater from these glaciers contributes approximately 45% of the total river flow, sustaining the livelihoods and agricultural practices of nearly 500 million people (Water Resources Institute, 2003; Cruz et al., 2007). Regions dependent on glacial meltwater are particularly vulnerable to the adverse effects of global warming (Barnett et al., 2005). Climate-induced glacial retreat is expected to result in several hydrological disruptions, including shifts in seasonal flow patterns, erratic rainfall distribution, and increased flood risks due to sudden surges in glacial runoff (Cruz et al., 2007). Among all terrestrial surfaces, snowpacks and glaciers are especially sensitive to climate change, making them critical indicators of environmental transformations. Consequently, there is increasing scientific focus on glacial dynamics, as these studies provide early warning signals of potential water scarcity and hydrological stress in Central and South Asia (Cruz et al., 2007).

2.8 Conservation Status and Research Gaps in High-Altitude Wetlands of Sikkim

Although protected areas encompass approximately one-third of Sikkim's High-Altitude Wetlands (HAWs), those with the greatest conservation potential are primarily located outside these zones, particularly along India's trans-Himalayan border. Current legislation and state notifications support the protection of HAWs and recognize their socio-ecological significance, in alignment with the Ramsar Convention's principle of "wise use." For practical implementation, the concept of "wise use" requires further clarification to ensure that India fulfills its international commitments under the Convention. Engaging international experts and fostering collaborative research can enhance Ramsar-related initiatives and address institutional and programmatic gaps within the Forest and Environment Department.

Despite their ecological importance, HAWs remain a neglected category in wetland research. While some pioneering studies have focused on mapping these wetlands and documenting selected aspects of biodiversity, there is limited long-term data capturing changes over time. Furthermore, few studies have systematically explored the interdependence of biotic communities and HAWs, particularly in relation to natural processes and anthropogenic pressures. The impacts of climate change on these sensitive ecosystems remain poorly understood, and current management and conservation efforts have been insufficient to address emerging ecological threats.

Chapter 3

Conservation, Management and Policy Perspectives

3.1 Conservation and management of wetlands- efforts & initiatives

Wetland ecosystems in the Himalayan region demand urgent attention due to escalating anthropogenic and climatic pressures. Key threats include landscape fragmentation driven by developmental activities, excessive tourism exceeding the ecological carrying capacity of these fragile habitats, and intensified impacts of climate change. Although a substantial portion of existing research has focused on biodiversity inventories and spatial mapping of these wetlands, there remains a significant knowledge gap regarding their ecological functioning and ecosystem service provision. Conservation measures are critically needed to safeguard the hydrological, ecological, and socio-economic services these wetlands provide, which are increasingly vulnerable under changing climatic conditions.

In India, wetlands are frequently considered in isolation, often excluded from integrated water resource management and development plans. The primary responsibility for wetland management rests with ecologically oriented institutions, particularly the Ministry of Environment, Forests, and Climate Change (MoEFCC). While India is a signatory to international agreements such as the Ramsar Convention on Wetlands and the Convention on Biological Diversity, there is an absence of a dedicated legal and regulatory framework specifically addressing wetland conservation. This regulatory gap underscores the urgent need for strengthened policies, governance mechanisms, and implementation strategies to ensure the long-term protection and sustainable management of Himalayan wetlands.

3.2 Legal and Policy Context for Wetland Conservation in India

India currently lacks a dedicated policy or legislative framework specifically targeting the conservation and management of wetlands. Nonetheless, these ecosystems are indirectly governed and influenced by multiple existing legal instruments (MoEFCC, 2007). Key statutes include: Indian Forest Act, 1927; Indian Fisheries Act, 1857; Wildlife Protection Act, 1972; Water (Prevention and Control of Pollution) Act, 1974; Territorial Waters, Continental Shelf, Exclusive Economic Zone and Other Marine Zones Act, 1976; Forest Conservation Act, 1980; Environment Protection Act, 1986; Biological Diversity Act, 2002; Scheduled Tribes and Other Traditional Forest Dwellers (Recognition of Forest Rights) Act, 2006 (Prasad et al., 2002).

Collectively, these statutes address critical aspects such as the conservation of water quality, protection of ecologically sensitive areas, and maintenance of biodiversity, including flora, fauna, and avifauna within India's aquatic ecosystems. Despite their overarching relevance, the explicit recognition and definition of "wetlands" within these legal frameworks remains ambiguous. This lack of specificity limits the enforceability and effectiveness of conservation measures, highlighting the urgent need for a dedicated legal and policy framework to safeguard wetlands as integral components of India's ecological and hydrological landscapes.

3.3 Evolution of Wetland Conservation Policies in India

Until the early 2000s, India lacked policies explicitly focused on wetland conservation and management. Existing management frameworks were largely shaped by the Ramsar Convention and indirectly guided by broader environmental and forest conservation laws. India became a signatory to the Ramsar Convention on Wetlands in 1981, with initial attention primarily directed toward the designated Ramsar sites.

To address the degradation and shrinkage of these critical wetlands, the National Wetland Conservation Programme (NWCP) was launched in 1985–1986 in collaboration with respective state governments. This program implemented a range of interventions aimed at preserving and restoring Ramsar sites. Subsequently, in 1993, the National Lake Conservation Plan (NLCP) was carved out from the NWCP to specifically focus on the conservation of lakes in urban and suburban areas threatened by rapid urbanization and anthropogenic pressures. Under the NLCP, ten priority lakes were identified for targeted interventions.

In parallel, the National River Conservation Plan (NRCP), initiated in 1995, aimed to improve river water quality through comprehensive pollution abatement measures and sustainable management practices. The National Water Policy, 2012, further reinforced the importance of conserving river corridors, wetlands, and other critical water bodies, explicitly emphasizing the inclusion of embanked floodplains in conservation strategies.

Collectively, these policy instruments represent a gradual evolution from site-specific wetland protection toward a more integrated approach encompassing rivers, lakes, and floodplains, reflecting India's growing recognition of wetlands as vital components of its ecological and hydrological systems.

3.4 Expansion and Policy Recognition of Wetlands in India

Over the past decade, India has witnessed a substantial increase in the number of designated Ramsar sites, growing from 26 sites in 2012 to 91 sites by 2025. Simultaneously, rivers incorporated under the National River Conservation Plan (NRCP) have increased to 39, and wetland ecosystems protected under the National Wetland Conservation Programme (NWCP) have expanded to 115 sites. Despite the broad ecological and functional definition of wetlands, conservation efforts to date have predominantly focused on lakes and their degradation status, often overlooking the full spectrum of wetland types and their ecosystem functions.

The National Environmental Policy (NEP), 2006 acknowledged the critical ecosystem services provided by wetlands, including hydrological regulation, biodiversity support, and carbon sequestration. The policy emphasized the necessity of establishing a robust national regulatory framework to prevent wetland degradation and to enhance their conservation, extending beyond international commitments such as the Ramsar Convention. This marked a significant shift toward recognizing wetlands as integral components of India's ecological infrastructure and water resource management.

3.5 Wetland Conservation and Management Rules in India

In response to the National Environmental Policy (NEP), 2006 and recommendations from the National Forest Commission, the Government of India promulgated the Wetland (Conservation and Management) Rules, 2010. Under these rules, the Central Wetland Regulatory Authority (CWRA), operating under the Ministry of Environment, Forests, and Climate Change (MoEF&CC), was empowered to regulate activities in the vicinity of wetlands. Restrictions included prohibitions on establishing industrial units, dumping solid waste, and discharging untreated effluents. The rules also granted states the authority to regulate activities such as hydraulic alterations, agriculture, aquaculture, unsustainable grazing, and extraction of wetland resources.

However, the 2010 rules applied only to selected wetlands, based on their ecological significance. These included: Wetlands designated under the Ramsar Convention, Wetlands recognized as UNESCO Heritage sites, Wetlands located in ecologically sensitive areas, High-altitude wetlands, Wetlands at elevations ≥2,500 m or ≥500 hectares in area, Wetlands specifically identified by the Authority.

A key limitation of the 2010 rules was the exclusion of wetlands situated at elevations ≥2,500 m outside urban areas, leaving several ecologically important high-altitude wetlands unregulated. To address these gaps, the Wetlands (Conservation and Management) Rules, 2017 expanded regulatory coverage and strengthened conservation mechanisms. The 2017 rules emphasized:

- Designation of wetlands, wetland complexes, and zones of influence
- Regulation of activities that may adversely impact wetland ecosystems
- Development of integrated management plans for wetlands, particularly those that are biodiversity-rich

As part of these initiatives, the MoEFCC established the Centre for Wetland Conservation and Management (CWCM) under the National Centre for Sustainable Coastal Management (NCSCM) to facilitate research, policy implementation, and capacity building. The 2017 rules represent a significant step toward comprehensive wetland conservation in India, combining regulatory oversight with integrated ecological management.

3.6 Legal and Institutional Framework for Wetland Conservation in India

Water being a state subject in India has historically resulted in a fragmented legal and regulatory framework for wetland protection. Consequently, both state and central legislation contribute to wetland conservation. Following India's accession to the Ramsar Convention, the National Wetland Conservation Programme (NWCP) was launched in 1985, fostering coordinated efforts between the central and state governments to safeguard wetlands. Subsequent initiatives include the National Lake Conservation Plan (NLCP, 1993) and the National River Conservation Plan (NRCP, 1995), focusing on the protection and restoration of lakes and rivers, respectively.

The Wetlands (Conservation and Management) Rules, 2017 provide the current legal framework. Notably, the rules exempt certain man-made water bodies from regulatory oversight, including tanks designed for drinking water supply, as well as facilities constructed for aquaculture, salt production, recreation, and irrigation. Under these rules, a wetland must meet at least one of the following criteria to be protected:

i. Recognition as a site of international importance under the Ramsar Convention

ii. Notification as a wetland by a state or union territory government

iii. Notification by the central government for transboundary wetlands

While these guidelines have strengthened the protection of ecologically significant wetlands, gaps remain in coverage, particularly for smaller or unlisted wetlands, highlighting the ongoing need for comprehensive and integrated wetland governance.

Chapter 4

Significance and Distribution of HAW in Sikkim

4.1 Hydrological Significance of High-Altitude Wetlands in Sikkim

High-Altitude Wetlands (HAWs) in Sikkim face multiple anthropogenic and natural threats, including climate change, glacial lake outburst floods (GLOFs), earthquakes, and unregulated tourism. Many HAWs are located on steep slopes (~30°), which increases their vulnerability to these hazards (Baig et al., 2017). Glaciers feeding these wetlands are highly sensitive to global warming, and their accelerated melting significantly influences the stability and hydrology of glacial lakes.

In addition to climatic and geophysical threats, HAWs are increasingly impacted by land use and land cover changes, rapid urbanization, infrastructure development, tourism pressures, and the establishment of army installations, particularly in high-altitude zones. A total of 534 HAWs have been recorded in Sikkim (Table 2). Surveys at national, state, and regional levels reveal that data

Table 2: Estimates of High-Altitude Wetland area in the Sikkim Himalaya

Type	Methods	Classification	Assessors/ Surveyors	Survey Year	Wetland Count	Estimated HAW Area (ha)
Remote Sensing	Normalized Difference Indices	High-altitude Wetlands	SAC (2013)	2008	534	3324
		Glacial Lakes	Govindha Raj et al. (2013)	2010	320	>757
			Aggarwal et al. (2016)	2011	143	>1020
			Aggarwal et al. (2017)	2013	1104	3050
		Glacial & High-altitude Lakes	CWC (2016)	2016	34	>842
			Shukla et al. (2018)	2017	463	2930
Compilation	Compiling Feature Datasets		ICIMOD (2003a, 2003b, 2005)	2003	266	2020
Field	GPS	Lakes	Government of Sikkim (2015)	2015	521	2294

(Source: O'Neill, 2019)

collection methods and methodologies vary, often emphasizing larger water bodies that are detectable via remote sensing imagery, while smaller, inaccessible lakes are frequently underrepresented. Most research relies on satellite imagery acquired during winter months, focusing predominantly on lacustrine systems.

Hydrologically, Sikkim's HAWs are critical for spring recharge, sustaining water supplies for approximately 80% of the state's population. Spatial distribution shows that HAWs are most abundant in the Mangan district (North), followed by Gyalshing (West), Gangtok (East), and Namchi (South). Many of these wetlands also possess religious and cultural significance, providing vital cultural ecosystem services in addition to their ecological and hydrological functions, as recognized by the Millennium Ecosystem Assessment. Collectively, these wetlands act as natural reservoirs, sustaining downstream water availability within Sikkim and neighboring regions, and are crucial for maintaining both human livelihoods and ecological integrity.

4.2 Wetland Inventory and Hydrological Dynamics in Sikkim

The National Wetland Inventory and Assessment (NWIA) of India utilized GIS-based analyses incorporating water spread, aquatic vegetation, wetland boundaries, and turbidity to systematically map wetlands in Sikkim. A total of 451 wetlands were mapped at a 1:25,000 scale, complemented by the identification of 245 smaller wetlands (<0.5 ha in size). Collectively, these wetlands cover approximately 8,463 hectares, representing 1.19% of the state's total geographical area.

The dominant wetland types include high-altitude lakes, which account for 35.48% of the total wetland area, followed by rivers and other lake systems (Table 3). The formation and persistence of these wetlands are primarily controlled by a combination of snowmelt, glacial meltwater, and rainfall-induced runoff, with the relative contribution of glaciers and snowmelt being particularly pronounced at higher altitudes. These hydrological processes are critical for maintaining wetland hydrodynamics, water balance, and associated ecological functions in the Sikkim Himalaya.

4.3 District-wise distribution of wetlands of Sikkim

Analysis of wetland distribution across Sikkim's districts indicates that three districts—Mangan (formerly North), Gangtok (formerly East), and Gyalshing (formerly West)—host the majority of the state's wetlands. The North district exhibits the highest wetland concentration, accounting for approximately 60.40% of Sikkim's total wetland area, representing 1.21% of the district's geographical area. This prominence is largely attributable to the presence of the renowned Gurudongmar Lake.

The East and West districts contribute 14.43% and

Table 3: Distribution of different types of wetlands in Sikkim

Sl. No.	Wetland Category	Number of Wetlands	Total Wetland Area (ha)	% of Wetland area
1	Lakes Ponds	45	118	1.4
2	High Altitude Wetland	405	3003	35.48
3	River/Streams	1	5097	60.22
	Sub-Total	451	8212	97.11
	Wetlands <0.5 ha	245	245	2.89
	Total	**696**	**8463**	**100**

Source: NWIA, 2011

14.23%, respectively, to the state's total wetland area (Table 4). The Namchi district (formerly South) has the smallest wetland coverage, comprising 10.94% of the total wetland area. Notably, high-altitude wetlands (HAWs) are found exclusively within the North, East, and West districts, emphasizing the spatially restricted distribution of these ecologically sensitive ecosystems in Sikkim.

Turbidity was assessed for lakes, high-altitude wetlands, rivers, and streams. During the post-monsoon period of 2005, open water covered 863 ha, with 51 ha exhibiting low turbidity and 812 ha exhibiting moderate turbidity. In the pre-monsoon period of 2005, open water coverage was 750 ha, with 52 ha of low turbidity and 698 ha of moderate turbidity, indicating seasonal variation in water quality and sedimentation patterns.

Table 4: Distribution of High Altitude Wetlands in different districts of Sikkim

District	Area (sq. km)	Wetland area (ha)	% of total wetland area	% of total geographic area
East	954	1221	14.43	1.28
West	1166	1204	14.23	1.03
North	4226	5112	60.4	1.21
South	750	926	10.94	1.23
	7096	8463	100	1.19

Source: NWIA, 2011

4.3.1 Wetlands of the East District, Sikkim

The undivided East district lies in the southeastern part of Sikkim, with Gangtok as its administrative headquarters, spanning coordinates 88°26'00" E to 88°55'00" E and 27°08'00" N to 27°25'00" N, covering an area of 954 km2. The district is divided into three revenue subdivisions: Gangtok, Pakyong, and Rongli. Hydrologically, the region is predominantly drained by tributaries of the Teesta River, including Rangpo-chu and Ronghi-chu (ENVIS, 2015). Tsomgo Lake, located within the district, is a major wetland attracting significant tourism. The total wetland area in the East district is estimated at 1,221 hectares, which includes 30 smaller wetlands below the minimum mappable unit (MMU).

Using the Normalized Difference Water Index (NDWI) to assess water bodies and open water features, qualitative turbidity was evaluated via signature statistics. Open water wetlands not detected in satellite imagery were likely below the resolution threshold.

4.3.2 Wetlands of the West District, Sikkim

The West district of Sikkim is geographically located between 88°01'00" E and 88°21'00" E longitudes and 27°06'00" N and 27°36'00" N latitudes. It shares international and inter-state borders with Nepal to the west, Namchi (South) district to the east, West Bengal to the south, and Mangan (North) district to the north. The district encompasses several notable landmarks, including Khecheopalri Lake, Yuksom (the first capital of Sikkim), and Rabdentse (the second capital). The total geographical area of the district is 1,166 km2, administratively divided into two subdivisions: Gyalshing and Soreng. Recently, the district has been formally bifurcated into Gyalshing and Soreng districts.

The total wetland area in the district is estimated at 1,204 hectares, including 41 small wetlands below the minimum mappable unit (MMU). Rivers and streams are the predominant wetland type, accounting for 81.83%, followed by lakes and ponds at 8.08%, with only a single lake/pond covering 97 hectares (ENVIS, 2015).

Seasonal turbidity analysis of open water revealed that during the post-monsoon period of 2005, open water covered 949 ha, with 158 ha exhibiting low turbidity and 791 ha exhibiting moderate turbidity. In the pre-monsoon period of 2005, turbidity distribution shifted slightly, with 235 ha of low turbidity and 714 ha of moderate turbidity out of the same 949 ha of open water, reflecting seasonal variations in sediment load and water quality.

4.3.3 Wetlands of Mangan (North) District, Sikkim

The Mangan District, formerly known as the North district, has its administrative headquarters at Mangan and lies between 88°07'00" E and 88°31'48" E longitudes and 27°04'12" N and 27°33'00" N latitudes, encompassing a total geographical area of 4,226 km^2. The district shares international borders with China to the north and east, and domestic borders with South and East districts to the south. Administratively, the district is divided into two subdivisions: Mangan Sub-Division, headquartered at Mangan, and Chungthang Sub-Division, headquartered at Chungthang.

Mangan District contains the largest wetland area in Sikkim, totaling 5,112 hectares, which represents 1.21% of the district's geographic area. Among these, 171 small wetlands are below the minimum mappable unit (MMU). High-altitude lakes (HAWs) dominate the district, comprising 52.70% of the total wetland area, and include major water bodies such as the Gurudongmar Lake (ENVIS, 2015).

The district's marshes are fully submerged, and aquatic vegetation is largely absent. Turbidity assessments indicate predominantly moderate levels, with a fraction showing low turbidity. During the post-monsoon period of 2006, 4,543 ha of open water were recorded, including 2,171 ha of low turbidity and 2,372 ha of moderate turbidity. In the pre-monsoon period of 2005, open water coverage totaled 2,585 ha, with 598 ha exhibiting low turbidity and 1,987 ha exhibiting moderate turbidity, reflecting pronounced seasonal variations in sedimentation and water quality across the district's wetlands.

4.3.4 Wetlands of Namchi (South) District, Sikkim

The Namchi District, formerly known as the South district, has its headquarters at Namchi and covers a total area of 750 km^2. Geographically, it lies between 88°15'00" E and 88°32'00" E longitudes and 27°04'00" N and 27°32'00" N latitudes. The district is bordered by the Teesta River to the east, the Rangeet River to the south and west, and the Dzongu region of North (Mangan) district to the north. Administratively, it comprises Namchi and Ravongla subdivisions.

Agriculture is the primary source of livelihood, and Namchi is recognized as the driest district of Sikkim, receiving the least rainfall in the state. Wetlands in the district are extremely limited, primarily restricted to rivers and streams (ENVIS, 2015). The total wetland area is estimated at 926 hectares, including three small wetlands below the minimum mappable unit (MMU). The open water extent of the perennial river/stream, totaling 737 hectares, remains relatively stable across seasons, reflecting minimal seasonal variability in water availability. Some of the High Altitude Wetlands of Sikkim are discussed below in Table 5.

Table 5: Details of High Altitude Wetlands of Sikkim

Wetland Name	Location (District)	Coordinates	Elevation (m)	Area (ha)	Type	Hydrology / Source	Ecological Significance	Cultural / Religious Significance
Gurudongmar Lake	North (Mangan)	28°02'07.88" N, 88°42'44.36" E	5,148	118	Moraine-dammed glacial lake	Fed by Gurudongmar Glacier; tributary of Teesta River	High-altitude desolate environment; low flora; freezes Nov–May	Sacred to Buddhists and Hindus; source of Teesta River
Tsomgo Lake (Changu Lake)	East (Gangtok)	27°21'28.36" N, 88°46'00.40" E	3,780	~100	Glacier-fed lake	Fed by tributary glaciers of Zemu Glacier; icefalls and waterfalls	Habitat for brahminy ducks; important hydrological hotspot	Name in Bhutia: "Tso" = lake, "Mgo" = head; considered water source for downstream communities
Khecheopalri Lake	West (Gyalshing/ Soreng)	27°18' N, 88°17' E	1,524	38	Sacred high-altitude lake	Rain-fed with small inflow streams	Habitat for migratory birds; rich riparian biodiversity	Revered by Lepcha community; "Wish fulfilling Lake" with ritual significance
Samiti Lake	North (Mangan)	27°42' N, 88°35' E	4,200	12	Alpine glacial lake	Fed by snowmelt and seasonal streams	High-altitude aquatic flora and fauna	Tibetan Buddhist significance; trekking destination
Lampokhari Lake	South (Namchi)	27°10' N, 88°22' E	1,000	21	Natural pond/lake	Rain-fed with small streams	Supports local freshwater biodiversity	Used in local rituals and recreation
Cholamu Lake	North (Mangan)	27°45' N, 88°40' E	4,500	9	Glacial lake	Fed by glacier and snowmelt	Alpine aquatic species; breeding ground for waterfowl	Culturally important to local Buddhist communities
Memcho Lake	North (Mangan)	27°46' N, 88°38' E	4,300	15	High-altitude glacial lake	Glacier-fed; seasonal runoff	Supports endemic alpine flora and fauna	Associated with local folklore and rituals

- Elevation ranges highlight vulnerability to climate change and glacial retreat.
- Glacial-fed lakes are sensitive to GLOF events.
- Cultural and religious associations indicate the need for integrated conservation approaches combining ecology and community values.

Chapter 5

State-of-Art knowledge on HAWs in Sikkim

5.1 Physical setting of HAWs of Sikkim Himalaya

Sikkim lies almost entirely within the Teesta River catchment, characterized by a rugged, steep, and mountainous topography ranging from 300 to 8,598 m above sea level (Krishna, 2005). Seasonal snow accumulation at higher elevations melts during spring, contributing significantly to river flow, groundwater recharge, and wetland hydrology in specific areas (Bandyopadhyay et al., 1997). Despite its small geographic extent, the state encompasses a wide array of eco-climatic zones, spanning from subtropical through temperate to subalpine and alpine regions.

The Teesta River and its tributaries are primarily fed by snowmelt and glacial runoff from the high mountains, supporting both hydrological and ecological processes across the region (Krishna, 2015). Vegetation in these high-altitude areas includes alpine thickets, alpine scrub, and alpine meadows (Champion and Seth, 1968; ENVIS, 2016). Recent studies indicate a gradual decline in glacier area, ice cover, and associated water volumes within the state, reflecting the impacts of climate change (Dubey et al., 2019).

Sikkim occupies a transitional zone between the sub-humid, wet Himalayas to the south and the arid trans-Himalayan steppe and Tibetan Plateau to the north. This unique positioning, combined with its high-altitude glacial lakes and steep terrain, renders many water bodies highly susceptible to glacial lake outburst floods (GLOFs). The region thus necessitates targeted adaptation and mitigation strategies to safeguard hydrological resources and dependent ecosystems.

5.2 Geology of HAWs of Sikkim Himalaya

The lithology of the Sikkim Himalaya is dominated by the Kanchenjunga/ Darjeeling Gneiss, primarily composed of quartz, feldspar, and biotite (GSI, 2012). The region is largely underlain by Precambrian metapelites, with four major rock formations recognized: Everest Pelitic Formation, Sikkim Group, Chungthang Formation, and Kanchenjunga Gneiss Group of the Precambrian era (Bhasin et al., 2020).

The lithostratigraphic succession, from youngest to oldest, includes: Sesela Formation, Gondwana Supergroup, Daling Group, Kanchenjunga/Darjeeling Gneiss, and Chungthang Formation.

Most of the high-altitude wetlands (HAWs) in Sikkim are located above 3,000 m, typically on terrains associated with the Main Central Thrust (MCT). In the south-central part of Sikkim, the MCT exposes Kanchenjunga Gneiss and Paro Gneiss, which constitute the predominant lithology supporting the majority of HAWs. The distribution of these wetlands is strongly influenced by the underlying rock type, tectonic setting, and glacial geomorphology.

5.3 History of Glaciation

The planet has endured alternating cycles of warm and cold temperatures throughout its geological history. Glaciers and ice sheets developed on the earth's surface during frigid climates. According to geological evidence, glaciations existed on earth during the Permo-Carboniferous and Pleistocene epochs (Embleton and King, 1975). Numerous locations around the world, including Scotland and the United States, have also reported finding Precambrian tillites and boulder-beds. There is clear evidence of the Permo Carboniferous ice age in South Africa and India as well. Following the Permo-Carboniferous glaciation was the Mesozoic era, when global temperatures were greater than they are now and no glaciation-related geological formations have been found. Large-scale glaciations, including those during the Pleistocene and Quaternary periods, occurred during the Cenozoic era (Smith et al., 2005). The current distribution of glaciers on the earth's surface has also been altered by glaciation. The earth's surface repeatedly witnessed glaciation over a sizable land mass throughout the Pleistocene. The area that the glaciers covered at their greatest extent was 46 million Km^2. (Embleton and King, 1975). The regular monitoring of Himalayan glaciers is of paramount importance in light of their vast number and area covered, as they are the source of many enormous North and Eastern Indian rivers and their tributaries.

5.4 Glaciers of Sikkim

A glacial lake is described as a body of water that is sufficiently abundant, extends with a free surface within, beside, in front of, or beneath a glacier, and was produced by glacier activities (Campbell et al., 2004). The glaciers are melting faster than they used to, expanding the lakes' surface area and water storage capacity (Pandey et al., 2021). Glacial lake outburst flood is the name given to the sudden release of large amounts of water and debris from these lakes (GLOF). GLOF has the potential to rapidly drain, resulting in dramatic floods downstream, which can seriously harm the environment and human property. GLOF is a natural risk that is associated with a geomorphological hazard, so it can be regarded as a geomorphological risk. According to several studies (Kumar et al., 2019) the continued glacier retreat in high mountain regions around the world, particularly in the Himalaya and its neighbouring Tibetan regions, has resulted in the formation and expansion (dramatic increase) of glacial lakes.

Glaciers in the Sikkim Himalayas are only found in the state's western and northern regions. The glaciers are commonly referred to as Teesta Basin glaciers because their water flows into the Teesta River (Puri et al. (1999). The Sikkim Himalayas has four glacierized basins covering an area of 7172.21 sq km. East Rathong, Talung, Changme Khangpu, and Zemu basins which are fifth order basins.

5.4.1 Changme Khangpu basin

This basin lies in between the Zemu basin in the west and Chumbi valley (Tibet) in the east, this is the Sikkim Himalayas' most eastern glacier-bearing basin. The basin contains 102 glaciers and covers an area of 1158.75 sq km. Only the region to the north of Lachung is glacierized. Three glacial terraces can be seen in the longitudinal profile of the valley from Khadom to Yomesomdong. There have been a few cascades as a result of the subsequent fluvial action. Glacier-smoothed valley walls can be seen all the way along the valley up to Khandom. On the southern, south-eastern, and south-western aspects, large-sized glaciers make up about 73% of the total area, with an average slope of <20°.

The annual Snow Cover Area has decreased over the last 18 years in Changme Khangpu Basin (Singh et al., 2021). The maximum rate of area loss in the most recent ten years is between 2001 and 2016, while the slower rate of glacier area loss between 1988 and 2001 (Debnath et al., 2019). Maximum snowfall was recorded in February and March, while minimum accumulation occurred in June and July. The study suggests that the Snow Cover Area has seen a massive decline in accumulation and increase in ablation season.

5.4.2 East Rathong basin

The East Rathong basin is the southernmost basin in the Sikkim Himalayas (Fig. 10). It covers an area of

2351.12 sq km, is situated west of the Teesta River, and extends in that direction toward the Nepal border. It supports 36 glaciers, almost all of which are confined to the basin's northern region. Rathong Chhu, the main channel, joins the Rajal River at Legship (GSI, 2012). The multi-cyclic geomorphic history of the East Rathong basin, which includes both proglacial and periglacial regimes, has been preserved. From Bakhim northward, epigenetic gorges are very frequent (Luitel et al., 2012). From south of Dzongri, a distinct U-shaped valley profile is visible.

The peak ablation is recorded in the month of July and August in East Rathong Basin contributing to maximum Suspended Sediment Concentration (SSC) which

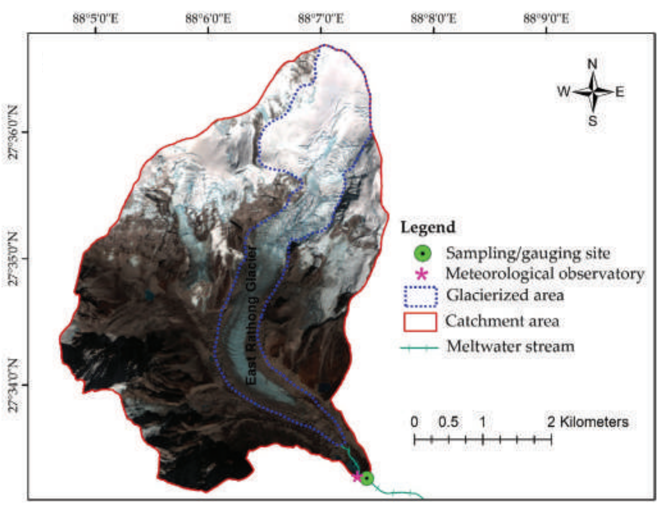

Figure 10: East Rathong glacier catchment Source: (Sharma et al., 2021)

gets transported along with glacier water melt in the months of June and September (Sharma et al, 2021). The Glacial basin is subjected to soil erosion at a rate of 1.0–1.1 mm/yr.

5.4.3 Talung Basin

The basin is located at the west of the Teesta River, north of the East-Rathong basin, and extends to Nepal's eastern border. It has 61 glaciers and a surface area of 1270.74 Km^2. The basin's northwest is where the majority of the glaciers can be found. A significant portion of the basin's northwest is covered by the Talung glacier, which is the largest glacier in this basin (GSI, 2012). Additionally, this basin has preserved a multi-cycle geomorphic history with recognisable proglacial and periglacial environments. The distinctive U-shaped valley profile and colonized moraine debris are found west of the confluence of Umrang Chhu and Rukal Chhu, and they appear to mark the lower limit of the paleoglaciation in the valley region of the basin.

5.4.4 Zemu basin

It is supported by 250 glaciers and covers an area of 2391.60 sq km (Fig. 11). The Zema Chhu and Hema Chhu, two significant tributaries, drain the basin. The Zema Chhu sector covers 1358.88 Km^2. Zemu Glacier, which is also the largest glacier in the Sikkim Himalaya, is the largest glacier in this area. Different cycles of glacial and periglacial regime cycles are still existent. The distinctive U-shaped valley profile, which can be seen close to Telim, indicates the lowest limit of glaciation in the Zemu basin (GSI, 2012). East of Zemu Chhu, the Hema Chhu sector spans 1032.72 km^2. Teesta Khangse glacier, the source of the Teesta River, is the biggest glacier in the Hema Chhu sector. This area has preserved remnants of numerous geomorphic phases, and 2 km south of Thangu, signs of past glaciation can be seen.

As per a research carried out by Rashid and Majeed (2020), one of the glaciers (Zemu glacier) of Zemu basin lost its snow cover of 102.3 m from1931 to 2012 with average loss of 1.3 m/annum. The glacier lost 30.67% of area and disintegrated into 7 parts in between 1931 to 2018.

5.4.5 Status of Glaciers

In Sikkim, glaciers have generally been retreating at varying rates over the past few decades. While many glaciers are rapidly receding, some have also shown a very slight advancement. The Teesta basin in Sikkim Himalaya has about 84 glaciers (Bahuguna et al., 2001). A study that focussed on 20 glaciers suggests an annual loss from 1990 to 1997 and from 1997 to 2004 was 0.28 and 0.89%, respectively while monitoring the glaciers in the Teesta basin. According to Raina (2009), who examined the 26 glaciers in Sikkim, 25 of the glaciers retreated on an average rate of 13 meters per year between 1976 and 2005, with the exception of one glacier that exhibited a small advance of 1.3

meters. From 1909 to 2005, the Zemu glacier receded about 863 meters (Raina, 2009), Zemu glaciers lost its snow cover of 102.3 m from 1931 to 2012 (Rashid and Majeed., 2020).

Monitoring of the East Rathong glacier's snout position in west Sikkim found a retreat of 460 meters (13.9 acres) between 1980 and 2012 (Luitel et al., 2012). Between 1962 and 2008, South Lhonak glacier significantly shrank by 1.9 km, causing the deglaciated proglacial region to produce a cemented moraine dammed lake (Raj et al., 2013). 39 glaciers, or about 75% of the state's entire ice reserve, were mapped in a recent study by Basnett et al. (2013), who discovered that Sikkim's glaciers lost about 3.3 % of their area between 1989/90 and 2010. Additionally, they reported that throughout this time, the area covered with debris increased by 6.5±1.4 km^2.

For the previous 40 years, or from 1975 to 2017, the temporal change in lakes has been estimated. Since 1975, there has been a consistent growth in the number and size of the lakes. A growth of roughly 9% can be seen in the number of lakes, which went from 425 in 1975 to 466 in 2017 (Shukla et al., 2018).

5.4.6 Research gaps

There has been significant research in terms of mapping of glacial bodies and the High Altitude Wetlands in Sikkim Himalaya with an emphasis on glacial retreat in the purview of climate change. About 6 studies delve into the geology and geomorphology of glaciers while 23 studies indirectly delve into the geological aspects of Glaciers and glacial lakes. The research mostly encompasses the associated risks of HAWs to various hazards. However, there is no significant research connecting the role of geology and ecosystem services of High Altitude Wetlands. These wetlands bodies play a significant role in water provisioning in the

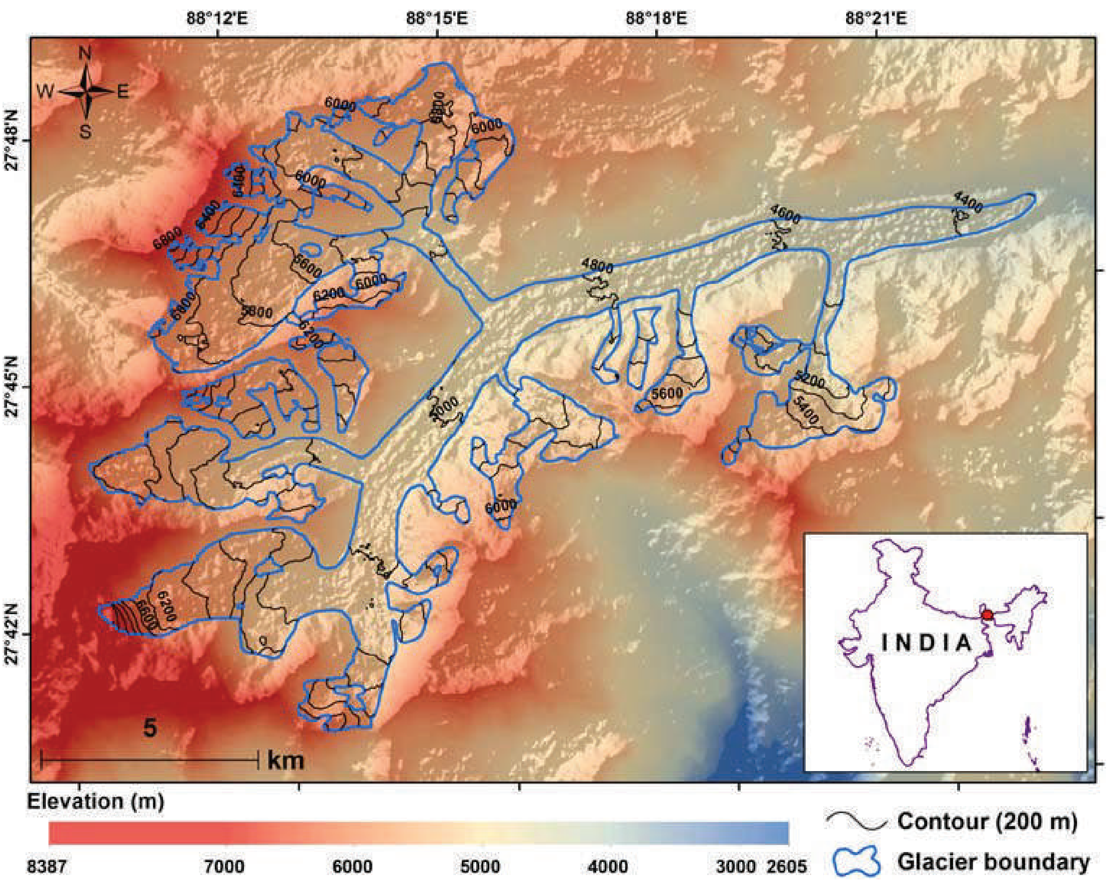

Figure 11: Zemu Basin Catchment Source: Rashid and Majeed (2020)

downstream region and maintenance of biodiversity in various service provisioning areas and service benefitting areas. There has been no research in terms of direct correlation between the region's geology and history of glaciation for Sikkim Himalaya. It becomes important to characterize the spatial heterogeneity of environmental conditions with the varying hydrology of HAWs. A sediment study carried out in Andean Altiplano in regards to Limnological response from high-altitude wetlands to the water supply (Sanz et al., 2021) demonstrated the spatial and temporal heterogeneity between and within the sample which are likely to be affected by changes in hydrology and precipitation. The limited high-altitude observatories and insufficient local glacier research capabilities in the Sikkim Himalayan region increase the glacio-hydrological uncertainties.

Another such research carried out in the same region emphasized on the relationship between the geology and the occurrence and variation of biota of the HAWs of Andean region (Otto et al., 2011). It shows the variation in the presence of various peatland plants along with the change in sediment concentration and the amount of water in the pool, puddles and rivulets (Fig. 12). In order to comprehend landform genesis more fully and to identify patterns and relationships among glacial landforms at different scales, it is crucial to evaluate and analyze the spatial distribution and temporal evolution of glacial landforms.

The Limnological or mineralogical response of High Altitude Wetlands of Sikkim Himalaya has been understudied and thus, raise an urgency to take up such studies to build a better understanding of various other aspects (biological, conservation and social).

The majority of the researches in terms of geology, geomorphological studies have been carried out in the Northern region of Sikkim followed by the research focussing on the entire state followed by west Sikkim. However, the majority of research in the Northern part has been focussed on South Lhonak Lake in North Sikkim due to its high susceptibility to GLOFs. Oftentimes, due to the coarser resolution of datasets while mapping the entire state leads to the discrepancy in data as smaller wetland bodies are not taken into consideration.

5.5 Biodiversity and Ecological Significance

Sikkim, situated within the Eastern Himalaya Biodiversity Hotspot, harbors exceptionally diverse flora and fauna, earning recognition as a region of global biodiversity significance. Approximately 83% of the state's territory is managed by the Forest Department with 47% forest cover, and distributed across five major eco-regions: tropical, subtropical, temperate, alpine forest and scrub, and trans-Himalayan (Table

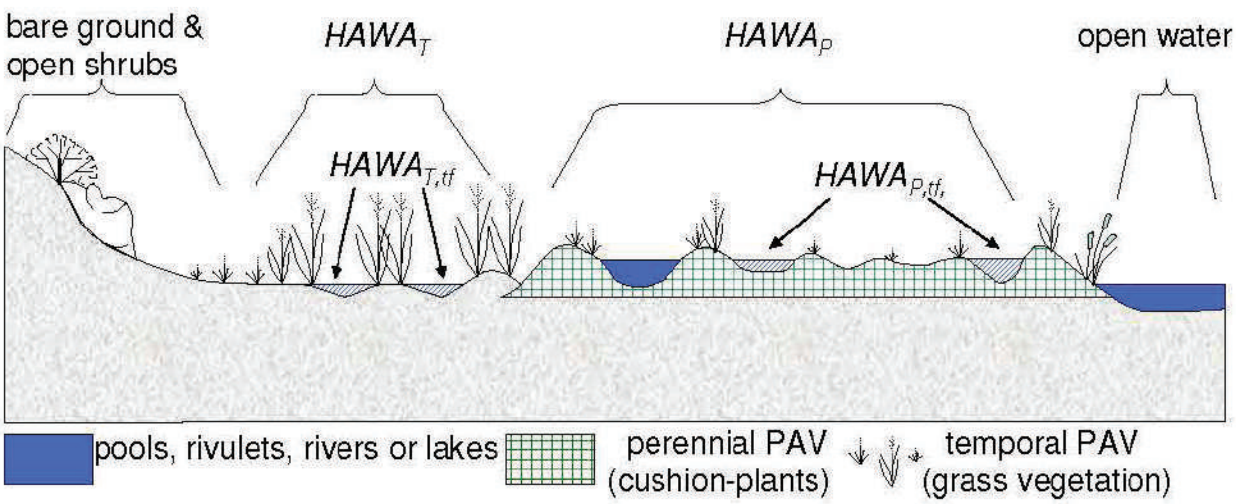

Figure 12: Schematic cross-cut through an ideal High Altitude Wetlands (Source: Otto et al., 2011)

6). The state hosts 11 Important Bird Areas (IBAs), designated by BirdLife International, and 8 protected areas, collectively covering 47% of Sikkim's geographic area (ISFR, 2019).

The Sikkim Himalaya, a subregion of the broader Himalayan Biodiversity Hotspot, supports over 5000 vascular plant species, reflecting the region's complex topography and monsoonal climate. The tectonic uplift during the Pliocene and subsequent Pleistocene glacial cycles shaped both the physical landscape and evolutionary processes, including genetic bottlenecks during glacial periods and gene flow during interglacial periods (O'Neill, 2019; Qu et al., 2014; BSI, 2024). These historical processes contributed significantly to the formation of High Altitude Wetlands (HAWs) in Sikkim and adjoining regions, which act as critical biodiversity reservoirs.

The trans-Himalayan zone, characterized by glaciated terrain, plays a central role in generating and recharging HAWs through glacial and snowmelt. HAWs, located above 3,000 m between the tree line and permanent snowline, occupy approximately 5% of the state's geographical area and function as ecotones, providing vital ecosystem services. These wetlands support a diverse array of birds, aquatic fauna, and amphibians, including migratory species of Ramsar significance such as the Eurasian Wigeon, Ruddy Shelduck, and Black-necked Crane, which rely on these habitats for both breeding and stopover sites. Sikkim's altitudinal vegetation is stratified into five major zones, with several forming transitional habitats that underpin the ecological complexity of HAWs. Collectively, the HAWs of the Sikkim Himalayas cover over 60,000 acres and support 803 recorded species (O'Neill, 2019), emphasizing their critical role in regional biodiversity conservation and hydrological stability.

The high-altitude flora and fauna of the Sikkim Himalaya are primarily confined to temperate ecoregions, alpine forests and scrublands, and trans-Himalayan ecosystems. High-altitude wetlands are critical for the establishment, sustenance, and seasonal dynamics of these biotic communities. These eco-regions harbor numerous globally threatened and endangered species,

Table 6: Five ecoregions or altitudinal zones of vegetation in Sikkim

Ecoregions	Altitude	Floral diversity	Faunal diversity
Tropical eco-region	300 m–900 m	Aroid (*Rhaphidophora decursiva*), wild banana (*Musa sikkimensis, M. Balbisiana*), Himalayan screwpine (*Pandanus nepalensis*), Date palm (*Phoenix sylvestris* and rare *P. rupicola*), Sal (*Shorea robusta*) associates uniquely with chir pine (*Pinus roxburghii*), Bamboo (*Dendrocalamus hamiltonii, Dendrocalamus sikkimensis*), etc.	Rufous-necked hornbill (*Aceros nipalensis*), great pied hornbill (*Buceros bicornis*), chestnut-breasted partridge (*Arborophila mandelli)* and rare red jungle fowl (*Gallus gallus*) peafowl, Burmese python (*Python bivittatus*), house geckos, Himalayan crestless porcupine (*Hystrix rachyuran*), Assamese macaque (*Macaca assamensis*), Chinese pangolin (*Manis crassicaudata*) and barking deer (*Muntiacus muntjak*).

Sub tropical eco-region	900 m- 1800 m	*Alnus nepalensis, Bischofia javanica, Castanopsis indica, Castanopsis tribuloides, Ficus semicordata, Macaranga denticulata, Buddleja asiatica, Himalayacalamus hookerianus,* Bamboo (*Bambusa nutans, Bambusa tulda, Phylostachys manii*) etc.	Common leopard (*Panthera pardus*), flying squirrel (*Petaurista magnificus*), Himalayan black (*Selenarctos himalayanus*)bear, Palm civet (*Paguma larvata*), wild boar (*Sus scrofa*), Red Jungle fowl (*Gallus gallus*), Mountain pit viper (*Ovophis monticola*), etc are the key faunal element of this eco-region
Temperate eco-region	1,800 m–3,500 m	Temperate broadleaved forest: *Castanopsis hystrix, Machilus edulis., Rhododendron arboreum., Symplocos spicata, S. theifolia, Magnolia doltopsa, Quercus lamellosa, Q. lineata, Lithocarpus pachyphylla, Engelhardia spicata and Leucoceptrum Canum, Eurya japonica, Rhododendron grande* and *Viburnum erubescens, Yushania maling* Temperate Coniferous Forest: *Abies densa, Tsuga dumosa, Rhododendron falconerii, Taxus wallichiana, Acer caudatum, Magnolia campbelii*	Red panda (*Ailurus fulgens*), red fox (*Vulpes vulpes*), golden jackal (*Canis aureus*), leopard cat (*Prionailurus bengalensis*), spotted linsang (*Prionodon pardicolor*), common leopard (*Panthera pardus*), asiatic black bear (*Selenarctos himalayanus*), palm civet (*Paguma larvata*), flying squirrel (*Petaurista magnificus*), wild boar (*Sus scrofa*) and barking deer (*Muntiacus muntjac*),
Alpine forest and Scrublands	3,500 m – 4,500 m	*Rhododendron lepidotum, R. setosum, R. anthopogon, R. Wightii, Salix calyculata, Juniperus squamata, Cotoneaster microphylla, Berberis concinna, B. macrosepala, Rosa sericea, Lonicera tomentella,* etc	Alpine musk deer (*Moschus chrysogaster*), threatened Himalayan tahr (*Hemitragus jemlahicus*), blue sheep (*Pseudois nayaur*), blood pheasant (*Ithaginis cruentus*) and ibisbill (*Ibidorhyncha struthersii*), Caterpillar-fungus (*Cordyceps sinensis*), common redshank (*Tringa totanus*)

Trans-himalayan ecoregion	4,500 m – >5,500 m	Dwarf rhododendron and Junipers are found in screes. Grasses and sedges like *Carex*, *Elymus*, *Festuca*, *Poa* etc are seen, other species like *Berberis*, *Delphenium*, *Saussurea*, *Anemone*, *Primula*, etc are found in scattered patches.	Snow leopard (*Panthera uncia*), black-necked crane (*Grus nigricollis*), Tibetan fox (*Vulpes ferrilata*), Tibetan wild ass (*Equus kiang*), Tibetan argali (*Ovis ammon*), Tibetan gazelle (*Procapra picticaudata*), Tibetan wolf (*Canis lupus chanco*), Eurasian lynx (*Lynx lynx*), brown bear (*Ursus arctos*), (*Otocolobus manul*), Tibetan snowcock (*Tetraogallus tibetanus*), lammergeier (*Gypaetus barbatus*), golden eagle (*Aquila chrysaetos*) and ruddy shelduck (*Tadorna ferruginea*), Tibetan-horned larks (*Eremophila elwesi*), Himalayan marmots (*Marmota himalayana*), Tibetan sandgrouse (*Syrrhaptes tibetanus*), black and guldenstadt's redstarts, red-billed and yellow-billed choughs, pipits, wagtails and mountain and snow finches.

(Source: Modified from Agro-biodiversity of Sikkim, 2011; Flora of Sikkim, 2024)

including the Black-necked Crane (Grus nigricollis), Kiang (Equus kiang), Tibetan Wolf (Canis lupus),

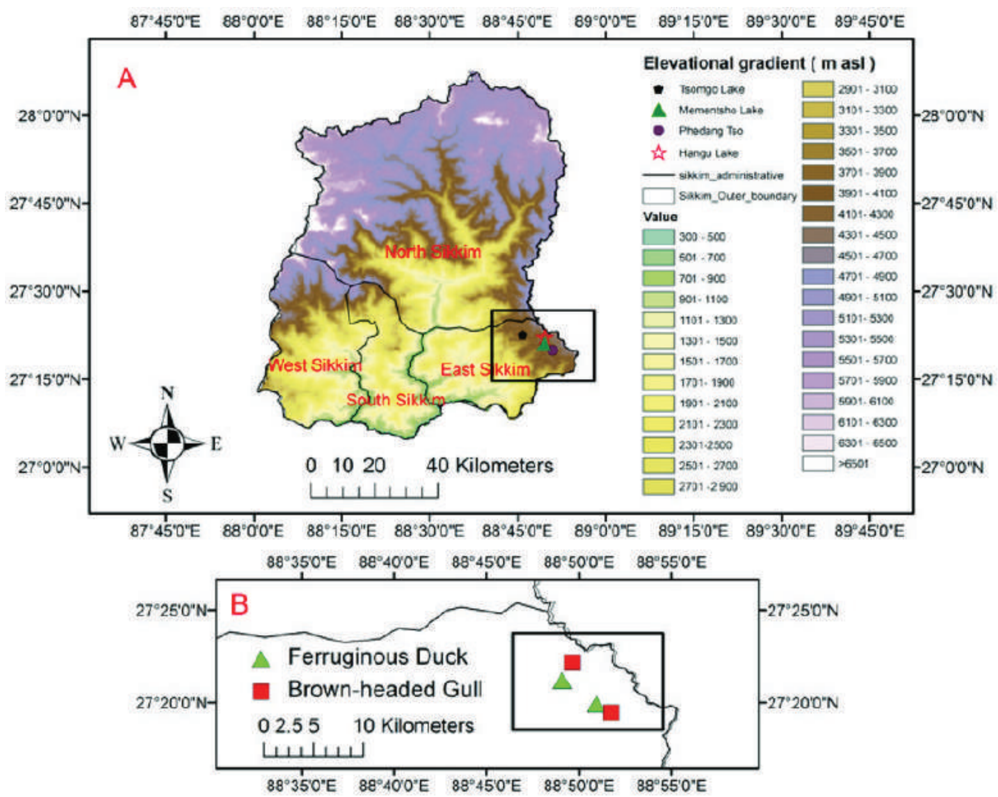

Figure 13: Distribution of Ferruginous Duck and Brown-headed gull in HAWs of Sikkim (Source: Chhetri et al., 2021)

Tibetan Snowcock (*Tetraogallus tibetanus*), Lammergeier (*Gypaetus barbatus*), Golden Eagle (*Aquila chrysaetos*), and Ruddy Shelduck (*Tadorna ferruginea*), along with diverse migratory waterfowl (Lachungpa, 1998).

Wetlands in the Sikkim Himalaya serve as essential breeding and wintering habitats for migratory birds (Ganguli and Lachungpa, 1998). Ferruginous Ducks (*Aythya nyroca*) and Brown-headed Gulls (*Chroicocephalus brunnicephalus*) are known to breed predominantly in high-altitude lakes and marshes of eastern Sikkim (Figure 13). Additional wetland-dependent avifauna reported from the region include Osprey (*Pandion haliaetus*), Pallas's Gull (*Larus ichthyaetus*), Eurasian Coot (*Fulica atra*), Common Merganser (*Mergus merganser*), Great Cormorant (*Phalacrocorax carbo*), Bar-headed Goose (*Anser indicus*), Black-necked Grebe (*Podiceps nigricollis*), and Little Grebe (*Podiceps ruficollis*), reflecting the ecological significance of these high-altitude wetland systems.

High-altitude wetlands (HAWs) also serve as important reservoirs of medicinal plant diversity. Tamze, designated as a Medicinal Plant Conservation Area (MPCA) within the Tsomgo-Hanspokhari wetland complex, harbors 114 species of medicinal plants with both local and commercial significance (Dahal et al., 2017). Ethnobotanical studies indicate that the local communities of the Tsomgo HAW utilize 23 plant species for various purposes, including edible, medicinal, and cultural applications (HAW Project, NIHE, SRC). Notable socio-culturally significant species include *Aconitum ferox*, *Dactylorhiza hatagirea*, *Cardamine macrophylla*, *Juniperus recurva*, *Nardostachys jatamansi*, *Podophyllum hexandrum*, *Polygonatum verticillatum*, *Picrorhiza kurroa*, and *Rhododendron setosum* (Fig. 14).

Earlier research by Lachungpa (1998) documented that approximately 11 wild plant species from high-altitude regions of the Sikkim Himalaya are actively used for medicinal purposes, underscoring the ecological and ethnobotanical importance of these fragile ecosystems.

A total of approximately 800 species representing five kingdoms, spanning around 170 families and 380 genera, have been documented from the high-altitude wetlands (HAWs) of Sikkim (O'Neill, 2019). Among this biodiversity, the kingdom Plantae accounts for

Figure 14: *Dactylorhiza hatagiera* (flower and root) a critically endangered medicinal herb from Tsomgo HAW catchment.

76% of the total species, followed by Animalia, Fungi, Eubacteria, and Chromista (Fig. 15). Of the documented species, 11% have been assessed under the IUCN Red List of Threatened Species (Chhettri et al., 2021). Notable critically endangered taxa include medicinal plants such as *Nardostachys jatamansi* (Jatamansi), *Dactylorhiza hatagirea* (Panchamle), and *Aconitum ferox* (Bikma), as well as avifauna including the Saker Falcon (*Falco cherrug*), Black-necked Crane (*Grus nigricollis*), Greater Spotted Eagle (*Clanga clanga*), and Wood Snipe (*Gallinago nemoricola*).

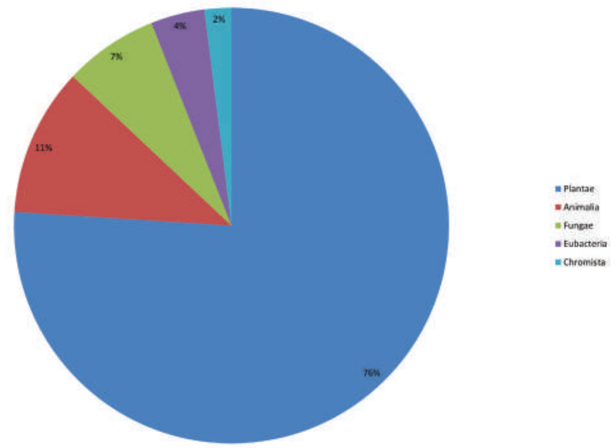

Figure 15: Percentage of biodiversity belonging to different kingdoms (Source: O'Neill, 2019)

Waterfowl diversity and abundance in high-altitude wetlands (HAWs) were systematically surveyed across four HAWs to assess species richness and population patterns (Chettri et al., 2021). The Ruddy Shelduck (*Tadorna ferruginea*) and Great Cormorant (*Phalacrocorax carbo*) were recorded in Phedang Tso Lake, Mementsho Lake, Hangu Lake, and Tsomgo Lake. The Common Coot (*Fulica atra*) and Bar-headed Goose (*Anser indicus*) were observed in Phedang Tso Lake, while the Black-necked Grebe (*Podiceps nigricollis*) was documented in Hangu Lake. These findings highlight the critical role of HAWs as habitats supporting both resident and migratory waterfowl species.

High-altitude flora and fauna are increasingly threatened by a suite of anthropogenic and environmental pressures, including habitat fragmentation, reduced food security, illegal poaching, and climate change. An emerging risk to highland

Table 7: Species richness of HAWs waterfowl birds in Sikkim Himalaya.

Common name	Scientific name	Phedang Tso	Mementsho Lake	Hangu lake	Tsomgo Lake	IUCN red List
Ruddy Shelduck	*Tadoma ferrugenea*	+	+	+	+	LC
Goosander	*Mergus merganser*	+	-	-	+	LC
Common Coot	*Fulica atra*	+	-	-	-	LC
Mallard	*Anas platyrhynchos*	+	-	+	-	LC
Eurasian Wigon	*Mareca penelope*	+	-	+	+	LC
Tufted Duck	*Aythya fuligula*	+	-	+	+	LC
Common Teal	*Anas crecca*	+	-	+	+	LC
Great Cormorant	*Phalacrocorax carbo*	+	+	+	+	LC
Northern Pintail	*Anas acuta*	+	-	+	+	LC
Black-necked Grebe	*Podiceps nigricollis*	-	-	+	-	LC
Great Crested Grebe	*Podiceps cristatus*	+	-	+	+	LC
Bar headed Goose	*Anser indicus*	+	-	-	-	LC
Gadwall	*Mareca strepera*	+	-	-	-	LC
Ferruginous Duck	*Aythya nyroca*	+	-	+	-	NT
Brownheaded Gull	*Chroicocephalus brunnicephalu*	+	-	+	-	LC

(Source: Chhettri et al., 2021).

biodiversity is the indiscriminate harvesting of medicinal and aromatic resources. Notably, the caterpillar fungus (Cordyceps sinensis) faces significant threats from the degradation of sacred habitats, largely due to unregulated tourism and other anthropogenic disturbances (Lachungpa, 1998).

A comparative survey of bird communities across different high-altitude wetlands (HAWs) in Sikkim revealed that the majority of avian species were concentrated in Phedang Tso (Elephant Lake) relative to other lakes (Chhetri et al., 2021; Table 7). This site benefits from minimal anthropogenic pressure, being both tourism-free and situated within a defense-restricted zone, whereas other wetlands are increasingly impacted by human activities, particularly tourism. These findings underscore the influence of anthropogenic disturbance on species richness and highlight the conservation value of relatively undisturbed wetlands.

5.5.1 Research Gaps on biodiversity of HAWs

High-altitude wetlands (HAWs) and surrounding ecosystems in Sikkim harbor a rich diversity of indigenous and endemic flora and fauna, many of which hold significant religious and medicinal value. These wetlands play a critical role in provisioning water to downstream ecosystems, which include Trans-Himalayan, alpine, and subalpine vegetation zones. Beyond water provisioning, HAWs sustain a wide array of biological resources, including microbial communities. For instance, microbial strains isolated from the Rathong Glacier in West Sikkim include Cryseobacterium polytrichastri, a psychrotolerant bacterium, and Arthrobacter alpinus, a yellow-pigmented, cold-tolerant bacterium. These microorganisms have notable potential for industrial enzyme applications and studies on UV-B adaptation (Kumar et al., 2015). However, research on microbial biodiversity across most other HAWs remains limited, emphasizing the need to explore microbial diversity and its ecological and biotechnological applications.

While numerous studies have cataloged species diversity in HAWs, few address the critical question of why conservation is essential. Filling this gap is necessary to inform robust policy planning and sustainable management strategies. Lachungpa (1998), in his study Indigenous Lifestyles and Biodiversity Conservation Issues in North Sikkim, highlights that recent shifts in livelihood patterns—from traditional agro-pastoralism to modern, market-oriented practices—have contributed to the threatened status of many bioresources. Declines in yak herding and increased tourism-driven economic activities have substantially altered local socio-ecological systems.

Moreover, expanding development and military infrastructure projects have accelerated habitat fragmentation, potentially increasing the risk of inbreeding depression in certain species. Conservation research must extend beyond simple species censuses to encompass population dynamics, abundance, and migratory patterns of transboundary resources. Emerging challenges, such as unregulated tourism and overharvesting of high-value medicinal resources like Cordyceps sinensis, further threaten the ecological integrity and sustainability of high-altitude ecosystems. Addressing these challenges requires integrated conservation approaches that consider ecological, socio-cultural, and economic dimensions.

5.6 Impact of Climate change on HAWs

HAWs, defined as swamps, meadows, peatlands, and other water bodies above 3000 m elevation (Chatterjee et al., 2010), function as critical "water towers" for downstream communities and biodiversity. Rivers originating from these lakes contribute significantly to water discharge and hydropower potential. Climate change threatens these wetlands by altering permafrost and peatlands, decreasing lake water levels, disrupting hydrological balance, and reducing carbon sequestration potential (WWF, 2010). Glacial retreat also modifies water inflow patterns, increases sedimentation, and accelerates desertification and soil erosion. Himalayan glaciers are increasingly affected by both climatic and anthropogenic pressures. Numerous studies document widespread glacial retreat and changes in glacial lake dynamics in response to the intensifying climate change scenario. Over the past three decades, the Himalayas have experienced warming of 0.15°C to 0.60°C per decade (Shrestha et al., 2010). Climate change manifests through rising temperatures, altered precipitation patterns, accelerated melting of glaciers and sea ice, increased risk of glacial lake outburst floods (GLOFs), sea-level rise, and heightened frequency and intensity of extreme weather events globally (Ganguly et al., 2010).

Shifts in glacier melt, irregular precipitation, and climatic variability are likely to modify the timing, magnitude, and duration of runoff from glaciers, disrupting hydrological cycles and impacting aquatic biota, physicochemical conditions, and resource availability in downstream ecosystems (Shrestha et al., 2010). Furthermore, alterations in wetland physical and chemical characteristics may lead to increased mineralization, enhanced oxygen diffusion in aquatic systems, elevated microbial activity, potential water quality degradation, and augmented methane (CH_4) emissions (Bhattacharya et al., 2012). Consequently, while anthropogenic pressures already contribute to wetland degradation, the overarching influence of climate change may exacerbate these impacts.

Sikkim hosts several glaciers, including Zemu, Rathong, and Lhonak, which serve as critical indicators of climate change impacts (SAC, 2010). The East Rathong Glacier, a key glacial system in Sikkim, has experienced pronounced retreat and thinning, resulting in the

Table 7: Statistics showing growth in the area (in sq.km) of glacial/moraine dammed lakes over

Lake Name/Year	1965	1976	1989	1997	2000	2005	2010
Gurudongmar Chho A	1.048	1.099	1.099	1.099	1.104	1.115	1.134
Gurudongmar Chho B	0.249	0.322	0.925	1.046	1.046	1.073	1.076
Gurudongmar Chho C	0.48	0.687	0.718	0.728	0.732	0.745	0.745
Chho Lhamo	0.649	0.963	1.031	1.031	1.031	1.031	1.031
Khangchung Chho	1.178	1.261	1.605	1.63	1.661	1.661	1.734
Lachen Khangse Chho	0.36	0.37	0.516	0.523	0.586	0.613	0.613
Glacial Lake feeding River - Shako Chhu	0.273	0.409	0.561	0.561	0.561	0.561	0.561
Khora Khang Chho	0.166	0.217	0.269	0.296	0.302	0.342	0.351
South Lhonak Chho	0.242	0.251	0.41	0.633	0.691	0.794	1.028
Lhonak Chho	0.231	0.282	0.418	0.46	0.494	0.652	0.656
Bhale Pokhari	0.09	0.104	0.108	0.114	0.114	0.114	0.114
Glacial Lake feeding river-Tikip Chhu	0.069	0.108	0.214	0.257	0.308	0.311	0.311

Source: (Kumar and Prabhu, 2012)

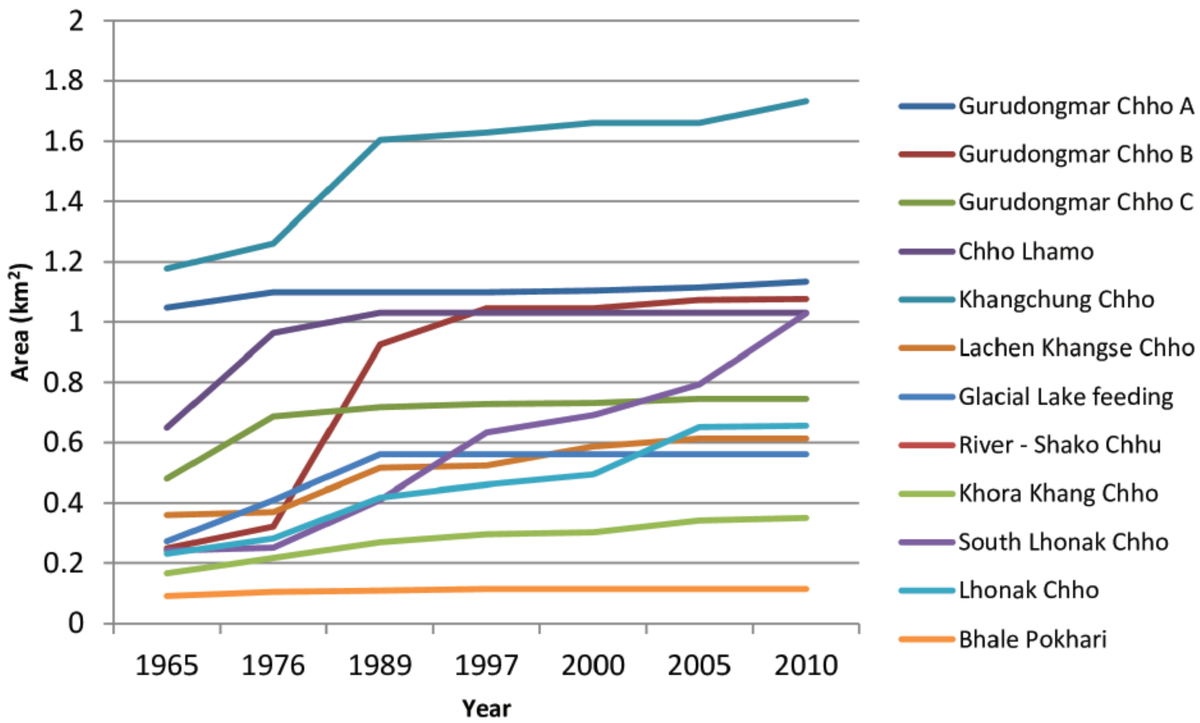

Figure 16: Expansion of different glacial lakes in between 1965-2010 (Source: Kumar and Prabhu, 2012)

formation of new glacial lakes and expansion of pre-existing ones due to the accumulation of meltwater behind loosely consolidated end-moraine dams (Kumar and Prabhu, 2012; Table 7). These glacial lakes are inherently unstable and pose substantial risks to downstream communities and infrastructure owing to their susceptibility to catastrophic outburst floods (ICIMOD, 2011). Analysis of glacier areas in the Sikkim Himalaya between 1965 and 2010 revealed a significant increase in the size of Khanchung Chho Glacier, the source of the Teesta River (Kumar and Prabhu, 2012) (Figure 16).

Glacial retreat in the Sikkim Himalaya has profound implications for adjacent lakes and wetland ecosystems. Retreating glaciers contribute to heightened vulnerability to glacial lake outburst floods (GLOFs), increased sediment load, and elevated turbidity in high-altitude wetlands (HAWs), potentially disrupting aquatic ecosystems and water quality. While numerous studies have focused on glacier mapping, comparatively few have examined the implications of glacial dynamics on downstream water availability. Himalayan glaciers remain poorly understood, particularly regarding the integrated effects of multiple climatic variables, extreme weather events, and complex topographic relief on hydrological processes and ecosystem services in downstream regions.

5.7 Effect of Anthropogenic activities on HAWs of Sikkim Himalaya

High-altitude wetlands (HAWs) and high-altitude lakes (HALs) in the Sikkim Himalaya are increasingly threatened by a combination of natural and anthropogenic pressures. These ecosystems are sensitive due to their high elevation, ecological significance, and role in water provisioning for downstream regions. Several wetlands, such as Gurudongmar and Tsomgo lakes, are considered sacred by indigenous communities and are legally protected under the Special Provisions Act, 1991 (O'Neill, 2019). Snow-covered mountains and glaciers shape the topography of these regions, and culturally significant lakes like Gurudongmar have been conserved by local communities for generations. Despite this, HAWs are subjected to multiple threats across sectors, which are summarized below:

Tourism

Tourism is one of the world's fastest-growing industries and accounted for 7% of global trade in 2019, ranking third after fuel and chemicals (WTO, 2019). In Sikkim, tourism has been a key source of livelihood for local communities, particularly women, through homestays, restaurants, souvenir shops, and garment production. While tourism has enhanced socio-economic development, it also contributes to environmental degradation around HAWs, including waste accumulation, sedimentation, erosion, water and air pollution, soil degradation, and biodiversity loss. For example, Prashar Lake in Himachal Pradesh has experienced deteriorating water quality due to tourist-generated waste (Kumari and Sharma, 2019). In Sikkim, lakes with high tourist visitation require promotion of sustainable and responsible eco-tourism practices to mitigate ecological impacts.

Waste Management

The remoteness of high-altitude areas exacerbates waste management challenges. Increasing tourist influx has led to excessive waste generation, limited by inadequate infrastructure and sanitation facilities (Islam and Rahmani, 2008). Improper disposal of human refuse, along with sedimentation from road construction, vehicular traffic, and pollution, has caused habitat fragmentation and wetland degradation. Military installations further exacerbate these pressures on HAWs.

Alteration of Natural Hydrological Regimes

Changes in precipitation patterns, evapotranspiration, snowmelt, permafrost, and runoff alter the temporal and spatial distribution of water resources, with significant implications for biogeography, geo-hydrology, and ecosystem functioning in high-altitude regions (Callaghan et al., 2004). Shifts in snow timing and duration also affect contaminant dynamics in freshwater systems. For instance, increased temperature in shallow zones can enhance methylation of mercury, leading to higher mercury uptake in aquatic food webs (Outridge et al., 2007; Wrona et al., 2016).

Deforestation

Deforestation in Sikkim, driven by dependence on forests for food, fodder, and fuel, has adversely

Table 8: The distribution of different HAWs of SIkkim according to the literature available

Sl. No.	Title of the Journal/Report	Author(s)	Elevation range	Number of High Altitude Lakes
1	Designing a Participatory Policy Framework for the Conservation of Lakes in the Sikkim Himalaya	Sandeep Tambe, Dipankar Ghose and M. L. Arrawatia	1500 - 5500m	315 (glacial lakes)
2	Evaluating High-altitude Ramsar Wetlands in the Eastern Himalayas	Alexander R. O'Neill	3000m and above	526
3	High Altitude Wetlands in the Indian Himalaya: Conservation and Management	S Sharma, V. Gosavi, K. S. Kanwal V Agnihotri, K. C Sekar S. C. Arya	3000m and above	534
4	Wetlands of Sikkim: State of Environment 2007 – Sikkim	-	3000m and above	227
5	Study on Type and Distribution of Wetlands of Sikkim Himalayas using Satellite Imagery with Remote Sensing & GIS technique	Narpati Sharma, Safal Pradhan, M. L. Arrawatia and D.G. Shrestha	Above 3000m	272 (greater than 2.25 ha); 281 (smaller than 2.25 ha) Greater than 2.25 ha + smaller than 2.25 ha
6	Evolution of Glacial and High-Altitude lakes in the Sikkim, Eastern Himalaya over the past four decades (1975–2017)	Aparna Shukla, Purushottam K. Garg, and Smriti Srivastava	3000m and above	463
7	National Wetland Atlas	Space Applications Centre, ISRO, Ahmedabad	3000m and above	451 + 245 (smaller than 0.50 ha)
8	High Altitude Lakes of India: Technical Report	Space Applications Centre, ISRO, Ahmedabad	3000m and above	677
9	National Wetland Inventory and Assessment High Altitude Himalayan Lakes	Space Applications Centre Indian Space Research Organisation Ahmedabad	3000m and above	677

10	Witnessing Change: Glaciers in the Indian Himalayas	Rajesh Kumar, G Areendran, Prakash Rao	3000m and above	449
11	Wetlands in the Himalaya: Securing Services for Livelihoods	Laxmi Dutt Bhatta, Wu Ning, Erica Udas, Nand Kishor Agrawal, Sunita Ranabhat and Deepa Basnet	3000m and above	553
12	Impacts of Climate Change: Glacial Lake Outburst Floods (Glofs)	Binay Kumar and T.S. Murugesh Prabhu	3000m and above	
13	Eleven Priority Areas for Conservation: Important Bird Areas of Sikkim	Usha Ganguli-Lachungpa, Asad R. Rahmani and M. Zafar-ul Islam	3000m and above	

affected local bio-climatic conditions, including HAWs (Bhattacharya et al., 2012). Unregulated tree felling, collection of non-timber forest products (NTFPs), and grazing reduce rainwater infiltration and increase soil erosion, further degrading wetland ecosystems.

Most research in Sikkim's HAWs has focused on biodiversity enumeration and mapping. However, integrated conservation strategies are required to protect the ecosystem services these wetlands provide, which are increasingly threatened by climate change. Wetland mapping efforts have varied depending on wetland size, satellite sensors, and elevation, with the most comprehensive mapping conducted by the Space Applications Centre (SAC), Ahmedabad, in collaboration with the Department of Science and Technology, Sikkim. According to this enumeration, Sikkim hosts a total of 677 wetlands, with an updated atlas currently under preparation. Ground validation remains challenging due to the inaccessibility of these ecosystems. There is a critical need for research on macro-fauna, vegetation dynamics, and water recharge processes to support effective conservation planning. Table 8 shows the enumerated data collected from various published research works like research articles, general articles, atlases, book chapters, etc.

The earliest documented study specifically focusing on high-altitude lakes (HALs) and wetlands (HAWs) of Sikkim was conducted by Richard Temple in 1881. Research on these wetland ecosystems gained momentum after the 2000s, coinciding with growing awareness of their critical ecosystem services. By the mid-20th century, advances in biological survey methodologies facilitated more systematic assessments of flora and fauna across different altitudinal gradients, providing a clearer understanding of species distribution and ecological patterns in these high-altitude ecosystems. The growing number of researchers studying high-altitude lakes (HALs) and wetlands (HAWs) reflects increasing awareness within the scientific community, with findings progressively reaching public and policy domains. Much of this research has focused on species enumeration and offsite analyses, highlighting the need for more collaborative, multidisciplinary studies. Such coordinated efforts are essential to generate actionable insights that can inform effective policy development and sustainable management strategies for these fragile ecosystems.

Chapter 6

Emerging Scenario and Conservation Pathways

Wetlands are among the most productive ecosystems on Earth, providing a wide range of critical ecological services (Ghermandi et al., 2008). They are highly dynamic and hydrologically sensitive systems, yet despite their importance, wetlands remain relatively underexplored in terms of their ecological, economic, and socio-cultural values. Consequently, their management and conservation have often been overlooked. Both natural and man-made wetlands support diverse biological resources and have historically been sustained through millennia of interaction with rural communities who relied on and managed them (Gopal, 1991). However, in recent decades, pressures from rapid population growth and economic expansion have led to the widespread degradation and overexploitation of these ecosystems.

Wetland degradation is primarily driven by factors such as deforestation, agricultural expansion and conversion, hydrological alterations, watershed modifications, upstream–downstream water conflicts, excessive water extraction, groundwater depletion, and the overarching impacts of climate change (Foot et al., 1996). According to the Ramsar Convention, wetlands in India encompass a wide variety of ecosystems, ranging from natural water bodies such as lakes, rivers, lagoons, peatlands, marshes, and coral reefs, to man-made systems such as ponds, reservoirs, sewage farms, canals, and salt pans.

High-altitude wetlands (HAWs), revered for their unique ecological significance, hold even deeper sacred value for the communities living in their vicinity. However, these ecosystems are often viewed in isolation and brought under rigid conservation frameworks that inadvertently exclude the very communities that have historically protected and depended on them. Given that these wetlands have long been embedded within systems of local governance, it is crucial that their management strategies emphasize community inclusion, ensuring that conservation aligns with cultural traditions, livelihoods, and sustainable practices.

Several prominent tourism sites located within the High-Altitude Wetlands (HAWs) of Sikkim are currently managed under community-based frameworks. For instance, Tsomgo Lake is overseen by the Tsomgo Pokhari Sangrakshan Samiti (TPSS), which actively engages in multiple aspects of lake management, including tourism regulation, solid waste management, and conservation activities. The committee prepares and implements Annual Lake Conservation Plans that encompass components such as garbage management, awareness campaigns, capacity-building initiatives, and tourist assistance. Similarly, Gurudongmar Lake in North Sikkim is managed under the traditional administrative institution known as the Dzumsa.

However, challenges persist. The political affiliations of local governing bodies often drive priorities towards development at the expense of sustainability. Moreover, communities tend to perceive wetlands primarily through their economic benefits rather than ecological values, creating gaps in long-term conservation outcomes. This highlights the need for greater inclusion of local community leaders and stakeholders in policy-making processes, ensuring that conservation strategies are both participatory and practical. Furthermore, there is a strong case for government agencies and research institutions to invest in capacity-building programs for local communities, particularly in technical areas such as water quality testing, biodiversity monitoring, and sustainable tourism practices. Such initiatives would strengthen community stewardship while balancing ecological preservation with socio-economic needs.

Emerging Scenarios

- **Climate-Induced Changes:**
  - o Accelerated glacier melting resulting to rise in new glacial lakes, unstable moraine dams.
  - o Reduced inflows over time resulting to shrinking lake volumes and water balance disruptions.
  - o Altered hydrological cycles affecting downstream water availability, agriculture, and hydropower.

- **Anthropogenic Pressures:**
  - o Tourism boom in sites like Tsomgo Lake has exceeded carrying capacity, leading to waste generation and habitat degradation.
  - o Road construction and infrastructure development fragment fragile landscapes.
  - o Military installations in border regions add further ecological strain.

- **Future Risks:**
  - o Increased probability of catastrophic floods due to GLOFs.
  - o Loss of biodiversity as alpine habitats shift upward beyond survival limits.
  - o Carbon release from thawing permafrost and peatlands, aggravating global warming.

- **Conservation Pathways:**
  - o Ecosystem service valuation and integration into policy.
  - o Strengthening community-driven conservation and eco-tourism.
  - o Regional and transboundary cooperation for climate adaptation strategies

Conservation Pathways for High-Altitude Wetlands

High-altitude wetlands (HAWs) in the Himalayas are critical ecosystems that regulate water flow, recharge springs, sequester carbon, and sustain unique biodiversity. They also hold deep cultural and spiritual value. However, they are increasingly threatened by climate change, tourism pressure, grazing, infrastructure development, and weak governance. A conservation approach must therefore combine ecological, cultural, and community priorities to ensure long-term resilience.

Key Conservation Pathways

High-altitude wetlands are lifelines of the Himalayas, sustaining biodiversity, water security, and cultural heritage. Their conservation requires an integrated pathway that empowers communities, safeguards ecosystems, and aligns with climate resilience strategies. By combining local stewardship, landscape management, sustainable livelihoods, and innovative financing, these fragile ecosystems can be protected for future generations. The key conservation pathways are discussed below:

1. Strengthening Community Stewardship

- Form and empower local wetland conservation committees to co-manage sites.
- Recognize and integrate sacred lake traditions, customary norms, and taboos into governance frameworks.
- Ensure gender and youth inclusion in decision-making for intergenerational stewardship.

2. Catchment and Landscape Management

- Treat entire micro-catchments with soil and water conservation works (silt traps, bunds, re-vegetation).
- Restore degraded alpine pastures to regulate grazing pressure and reduce erosion.
- Maintain natural buffer vegetation zones around wetland margins.

3. Climate Adaptation and Risk Reduction

- Map glacial-lake outburst flood (GLOF) risks and integrate into disaster preparedness plans.
- Build overflow channels and spillways for flood management.
- Monitor hydrological changes (water levels, snowmelt timing, and discharge rates) as early-warning indicators.

4. Pollution and Invasive Species Control

- Implement zero-waste tourism protocols, with strict waste collection and disposal systems.
- Establish eco-sanitation solutions for settlements and pilgrim sites.
- Control and remove invasive plants (e.g., Crofton weed), followed by reintroduction of native alpine species.

5. Biodiversity and Cultural Conservation

- Monitor indicator species (amphibians, water birds, alpine flora) to track ecosystem health.
- Protect sacred values and rituals associated with lakes through co-designed guidelines.
- Develop interpretive material linking cultural narratives with conservation education.

6. Sustainable Livelihoods and Ecotourism

- Train local youth as eco-guides and wetland monitors.
- Support community-based homestays and trekking services with conservation-linked fees.
- Develop low-impact tourism infrastructure (boardwalks, signage, visitor caps) to minimize degradation.

7. Finance and Incentives

- Establish Wetland Conservation Funds supported by eco-tourism fees, Payment for Ecosystem Services (PES), and government schemes.

- Align conservation actions with MGNREGA, CAMPA, and climate adaptation programs for funding convergence.

- Explore CSR and philanthropic partnerships for restoration and monitoring.

8. Knowledge and Monitoring Systems

- Promote community science with simple hydrological and ecological tools.

- Develop wetland health dashboards (water level, turbidity, biodiversity, visitor numbers).

- Facilitate knowledge sharing platforms between villages, districts, and Himalayan states.

Community-led wetland conservation initiatives in Sikkim

Communities residing in and around HAWs largely recognized as "Highland community", they share deep-rooted connections with these landscapes, shaped by cultural traditions, socio-economic activities, and environmental interactions. In many parts of the Indian Himalayan Region (IHR), wetlands are considered sacred, forming an integral part of local religious and cultural identity. They are closely associated with spiritual beliefs, rituals, and seasonal festivals, which strengthen community responsibility for their protection. HAWs are also vital sources of livelihood providing water, medicinal plants, fodder for livestock and opportunities for grazing, particularly yak herding.

Community-led wetland conservation in Sikkim involves active local participation through initiatives like the Tsomgo Pokhari Sanrakshan Samiti for Tsomgo Lake and the involvement of Self-Help Groups (SHGs) in initiatives like the Save Wetlands Campaign. The state emphasizes community involvement in protecting ecologically and culturally significant wetlands like Khecheopalri Lake, with strategies including strengthening Wetlands Mitra (community volunteers) under the Amrit Dharohar Initiative and promoting eco-tourism to support local communities.

The key initiatives and community roles in wetland conservation in Sikkim are described as follows:

- Tsomgo Pokhari Sanrakshan Samiti: This Community-Based Organization (CBO), notified by the Sikkim government, is responsible for the conservation of Tsomgo Lake and its surrounding areas.

- Save Wetlands Campaign: A significant campaign involving around 2,000 youth volunteers, local stakeholders, SHGs, and community members actively participates in restoring and protecting wetlands through activities like cleaning drives and awareness programs.

- Wetlands Mitra: The Amrit Dharohar Initiative aims to expand the engagement of these community volunteers to encourage active community participation in wetland preservation.

- Cultural and Sacredness values: Many lakes in Sikkim are preserved due to their cultural and spiritual importance to the local people, which fosters a strong sense of responsibility for their protection.

- Eco-tourism: The state's Ecotourism Policy encourages communities to develop eco-tourism products like bird watching, photography, and cultural tours, directly involving them in the management and protection of wetlands.

- Sustainable Practices: Communities are also involved in sustainable production of agricultural products like organic vegetables, honey, and rice, and in producing local handicrafts for sale, creating economic incentives for conservation.

- Sikkim Lake Conservation Guidelines: These guidelines were developed with support from organizations like WWF-India and helped establish new CBOs for lake conservation.

- Ramsar Site Designation: The Khecheopalri Lake was declared a Ramsar Site, a significant global recognition, highlighting the state's and communities' strong commitment to wetland conservation.

Further, community-led wetland conservation pathways (Fig. 17) offers Sikkim an opportunity to safeguard its fragile ecosystems while enhancing water security, cultural identity, and livelihood resilience. By blending traditional values with scientific management and sustainable financing, these pathways can ensure wetlands remain living assets for both local communities and the broader Himalayan region. Community-led wetland conservation in Sikkim integrates traditional knowledge, scientific inputs, and sustainable livelihoods. Strengthening Village Wetland Conservation Committees (VWCCs), backed by state collaboration, is central to this approach. Key pathways include catchment management, controlled grazing and tourism, pollution prevention, invasive species removal, and safeguarding cultural values. Livelihood linkages such as eco-guiding, homestays, and handicrafts along

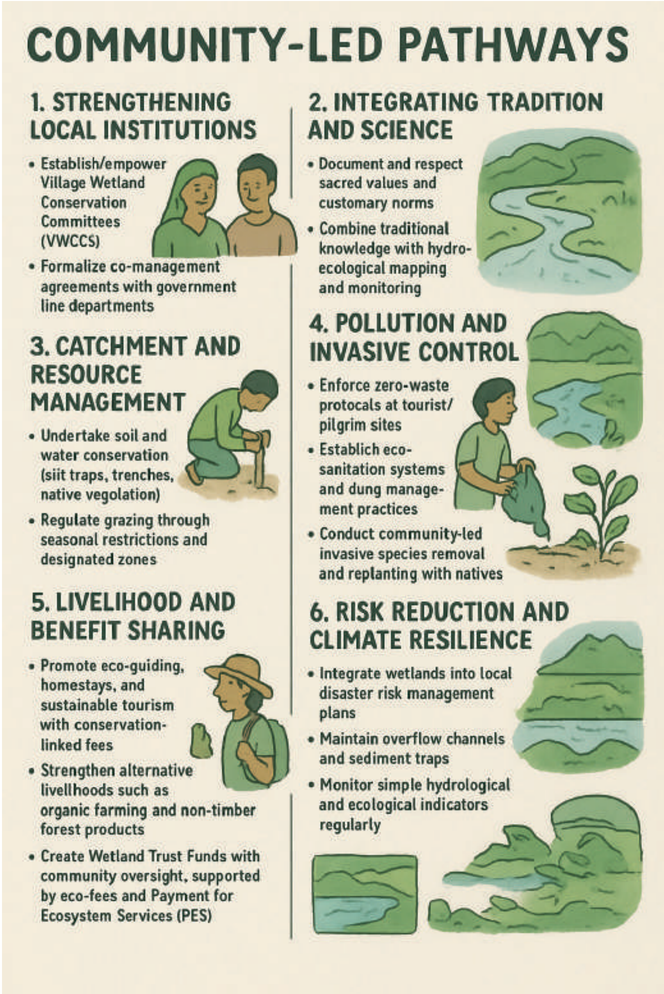

Figure 17: Community-led wetland conservation pathways

with Wetland Conservation Funds and Payment for Ecosystem Services, ensure financial sustainability. Wetlands are also vital for disaster risk reduction and climate adaptation, requiring simple, community-friendly monitoring systems and inclusive governance. By combining short-term actions (clean-ups, charters, visitor codes) with long-term strategies (management plans, ecosystem service payments), this integrated model secures wetlands for water security, biodiversity, cultural identity, and resilient community livelihoods.

Recommendations:

Sikkim is rich in glaciers and high altitude water bodies which provides ample water which makes it one of the regions with high biodiversity in the Eastern Himalayan Regions. The presence of these HAWs has ensured the water security in the region. With increase in population, there is a rampant increase in demand for water. By 2030, it is estimated that demand for food will increase by 50%, which directly points to the increased demand for water (Kallenborn, 2006). The snowpacks and the glaciers are highly susceptible to the impacts of global climate change among all the land surfaces. Thus, the increased discussion revolves around glacial retreats and becomes one of the pioneer studies with respect to global climate change. This often leads to an assumption of glacial shrinkage and possible water scarcity due to the impacts of global climate change on the water resources of central and south Asia (Cruz et al., 2007). Rising temperature and irregular precipitation may further lead to rapid melting of glacier ice and snow, exerting pressure on the moraines damming the snout. Sikkim Himalaya has 84 glaciers and 14 potentially hazardous glacial lakes. However, due to the region's limited human resources and glaciers' isolated and steep environment, in situ research on the dynamics of glaciers and glacial lakes is restricted. Thus, it increasingly poses a need for responsible or integrative research aided with strong policy imperatives for effective management of HAWs.

A policy consultation dialogue held in Sikkim—bringing together research and academic institutions, government departments, NGOs, community organizations, environmentalists, and conservationists—highlighted the urgent need for a comprehensive policy framework for the management of High-Altitude Lakes (HALs) and High-Altitude Wetlands (HAWs) in the region. The consultation also showcased successful community-based conservation practices from other parts of the Indian Himalayan Region (IHR), offering valuable lessons for Sikkim. High-altitude lakes in Sikkim are not only critical habitats for rare and endemic wildlife but also serve as sources of livelihood for local communities and hold deep religious and cultural significance. Despite their importance, these ecosystems face increasing threats from unregulated tourism, excessive waste generation, and intensified grazing by pastoral communities.

These discussions underscore the necessity of a dedicated policy framework that integrates ecological conservation, community participation, and sustainable livelihood approaches to ensure the long-term protection and resilience of these fragile ecosystems. During the consultation, the successful community-based management of Tsomgo Lake, one of Sikkim's High-Altitude Wetlands (HAWs), was highlighted. This initiative demonstrated how the active involvement of local communities in lake governance not only facilitated sustainable tourism but also ensured effective conservation outcomes.

The example underscored a key lesson: integrating local communities and traditional governing institutions into wetland management is central to achieving sustainable development in fragile mountain ecosystems. Such participatory approaches help balance ecological protection with cultural values and livelihood needs, offering a replicable model for other high-altitude wetlands across the Indian Himalayan Region.

Based on the consultation workshop conducted by GBPNIHE, Sikkim Regional Centre, in collaboration with DST, Sikkim in August 2022, several critical issues and insights emerged regarding the High-Altitude Wetlands (HAWs) of the Sikkim Himalaya. The discussions highlighted that these fragile ecosystems are highly vulnerable to natural hazards such as earthquakes and to the growing impacts of climate change. A pressing need was identified for systematic monitoring mechanisms to assess changes in lake size, water quality, and overall ecological health under shifting climatic conditions. HAWs in Sikkim play an essential role in sustaining downstream hydrology, particularly by recharging springs and water bodies that support both ecosystems and human communities. Key recommendations for the conservation and management of High-Altitude Wetlands (HAWs) in Sikkim Himalaya and address existing knowledge gaps are presented below:

- **Environmental Monitoring and Assessment**
  - o Conduct studies on the temporal changes in the size, shape, dynamics, and number of HAWs to inform conservation initiatives.
  - o Establish long-term monitoring systems to track ecological health under climate change and natural hazard pressures.
  - o Develop a standardized monitoring protocol specific to HAWs, harmonized across regions. and establish a long-term monitoring framework with standardized protocols tailored to high-altitude wetlands.
  - o Combine remote sensing (satellite/UAV) with field surveys for wetland mapping, hydrological changes, and habitat monitoring.
  - o Use GIS-based inventories and periodic updates to track trends (ice cover, shoreline erosion, GLOF risks).
  - o Integrate continuous sensors and automated data systems where feasible.

- **Limnological, Hydrological & Geomorphological Monitoring**
  - o Conduct regular limnological studies to assess physicochemical, mineralogical, and biological characteristics of HAWs.
  - o Establish hydrological monitoring systems (water balance, inflow–outflow, seasonal changes) to track climate change impacts on wetland dynamics.
  - o Undertake comprehensive geomorphological studies of glaciers to understand landform genesis, spatial distribution, and temporal evolution of glacial landscapes.
  - o Set up a dedicated Glaciological Research Centre in the Eastern Himalaya to strengthen glacier and wetland-linked cryosphere studies.
  - o Promote multi-disciplinary, ecosystem-level studiesthrough institutional collaboration linking biological, hydrological, and geomorphological processes for a holistic understanding of HAWs.

- **Biodiversity Documentation & Conservation**
  - o Develop a comprehensive inventory of species of ecological significance, aligned with IUCN Red List assessments, to guide conservation priorities
  - o Integrative and Ecosystem-Level Research and integrative research approaches linking multiple biological resources (plants, animals, microbes) to understand ecosystem interactions, dependencies, and resilience..
  - o Conduct ecosystem service valuation studies to quantify the benefits of HAWs (water regulation, carbon storage, cultural services, biodiversity habitat) for downstream regions and communities.
  - o Establish a Conservation Reserve Management Committee, including local stakeholders, religious institutions, Joint Forest Management Committees, and NGOs.
  - o Engage and incentivize highland communities in sustainable resource management,

- **Restoration Framework**
  - o Develop a holistic restoration strategy that includes delineation of wetland boundaries, creation of a complete inventory of HAWs, characterization of wetlands and catchments, and implementation of effective field-based measures.
  - o Ensure post-restoration monitoring with active participation from all stakeholders.

- **Address High-Altitude Stressors**
  - o Monitor GLOF risks (glacial lake expansion, unstable moraines, sediment pulses).
  - o Track tourism and grazing pressures (waste, trampling, nutrient enrichment).
  - o Include sediment quality and trace metals in sites downstream of mining or urban influence

- **Regulation of Human Activities**
  - o Impose strict restrictions on unsustainable anthropogenic activities in high-altitude areas to minimize degradation.
  - o Formulate and implement robust waste management policies, particularly for tourist-frequented wetlands.

- **Community and Stakeholders Engagement and Capacity Building**
  - o Engage local communities, herders, eco-clubs, and park staff in co-monitoring and data collection.
  - o Provide training, simple observation tools (photo-points, water level boards), and ensure benefit-sharing (feedback bulletins, dashboards).
  - o Build awareness of wetland values to strengthen stewardship.

- **Policy & Institutional Support**
  - o Define ecological thresholds and link monitoring results to management actions (control grazing, regulate tourism, manage waste).
  - o Integrate high-altitude wetlands into climate adaptation, biodiversity, and disaster risk reduction policies.
  - o Secure long-term institutional and financial support, with regional collaboration for knowledge exchange

- **International Recognition**
  - o Identify select HAWs with global importance and nominate them for Ramsar site designation to strengthen protection under internationally recognized frameworks.

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Saussurea obvallata (Brahmakamal)
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