Resilience in the Cold: How Artificial Glaciers Influence Social Resilience in Ladakh

A comparative case study of Ursi and Igoo

Archana Chikatmarla

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Supervisor: Sara Brogaard, LUCSUS, Lund University

Abstract:

Glacier retreat driven by climate change has created intense water scarcity in Ladakh, India, threatening both the local agriculture and livelihoods. In response, Artificial Glaciers (AGs) have emerged as an adaptive strategy. This study examines the role of AGs in enhancing social resilience in the villages of Ursi and Igoo using the Six Attributes of Social Resilience framework. A mixed-methods approach, combining household surveys and semi-structured interviews, was employed to assess knowledge systems, people-place connections, governance, infrastructure, and community networks. Key findings indicate that AGs have significantly improved water availability and agricultural productivity in Ursi, while the impact in Igoo is more mixed. Furthermore, their impact on social cohesion and people-place connections differs between the two villages. Disparities in knowledge, infrastructure, and economic diversification persist. The study concludes that while AGs are a promising strategy, more targeted training, improved governance, and broader economic integration are needed to improve social resilience. These insights are important for future climate adaptation strategies in vulnerable, water-scarce mountain regions.

Keywords: social resilience; glacial retreat; water scarcity; Ladakh; artificial glaciers; six attributes of social resilience

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Abbreviations

HKH- Hindu-Kush Himalaya

AG - Artificial Glaciers

SS- Sustainability Science

LNP - Leh Nutrition Project (NGO)

SECMOL- Students' Educational and Cultural Movement of Ladakh (NGO)

Acres of Ice – Social Enterprise

UT - Union Territory

1. INTRODUCTION

All forms of life are intricately linked to the functioning of the cryosphere and world oceans**.** The cryosphere encompasses glaciers, ice sheets, ice shelves, snow cover, ice caps, permafrost, sea ice, lake and river ice, and serves as a crucial component of the Earth's climate system (Copernicus, 2024; Lemke et al., 2007). It helps regulate global temperature by surface reflectivity (albedo) (Copernicus, 2024), serves as a primary reservoir for approximately 75% of the world's freshwater (Li et al., 2022), and influences global sea level dynamics (Abram et al., 2022). As a sensitive component of the climate system (Wang, 2024), it has been majorly affected by anthropogenic climate change over the recent decades (Abram et al., 2022; Qin & Ding, 2010), with glacier retreat emerging as one of the most immediate and observable indicators of global warming (Lindsey, 2025; UN, 2025).

Over the past century, glaciers have been melting at an alarming rate, losing an average of 267 billion tonnes of ice annually between 2000 and 2019 (Zemp et al., 2025). This rapid decline in glacier mass is largely attributed to human-induced climate change (Swain et al., 2024). It has contributed significantly to the rising sea level. In total, glaciers across 19 regions have collectively lost approximately 6,542 billion tonnes of ice, resulting in an estimated 18 millimetres of global sea level rise over the last two decades (Marchand, 2025). Beyond sea level rise, glacier loss affects freshwater availability by altering river runoff (IPCC, 2022), consequently influencing irrigation and hydropower generation (Davies, 2024).

Among the most critically affected regions is the Hindu-Kush Himalaya (HKH) (ETH, 2021), often known as the "Third Pole," the HKH contains over 54,000 glaciers and holds the largest amount of permanent ice outside the Arctic and Antarctic (Shrestha et al., 2019). It supplies water to ten major river basins across a vast area of approximately 4.2 million square kilometres (Shrestha et al., 2019) and is recognised as one of the most climate-vulnerable areas in the world, experiencing warming nearly three times the global average (GRID-Arendal, 2015). Current projections indicate that the HKH could lose up to two-thirds of its glacier ice by 2100 under continued GHG emissions, or around 36% under the 1.5°C global warming limit (Shrestha et al., 2019). These changes pose severe implications, including increased risks of flash floods, landslides, and glacial lake outburst floods, particularly projected to peak between 2050 and 2060 (Chugh, 2019).

Regional Focus: Ladakh within the HKH

Within this broader context of HKH, Ladakh stands out as a distinct and vulnerable region located in northern India (Bhat et al., 2023). As a trans-Himalayan cold desert, it is characterised by a high-altitude, arid climate and a large glacial presence (Juyal, 2014). Ladakh is home to over 2200 glaciers in the region (Soheb et al., 2022), including the Siachen Glacier, the second largest outside the polar regions (Bhutiyani, 2014), as well as other major glaciers like the Drang-Drung glacier (Azam et al., 2025). The region experiences extremely harsh conditions, with winter temperatures reaching 40°C and annual precipitation of approximately 90 mm (Ahmad et al., 2019). Additionally, warming in this area is occurring at rates surpassing the global average (Mankotia et al., 2025), which has resulted in a 20% reduction in glaciated areas across various parts of the region (Mandal et al., 2024).

Water security continues to be a critical concern in Ladakh, where only 6% of the region's 215 villages depend on river systems, while the remaining 94% rely on glacial meltwater for drinking and agriculture (Balasubramanian et al., 2025; LNP, 2022). Historically, a self-sustaining agrarian society with nearly 70% of the population engaged in agriculture-based livelihoods, Ladakh now faces increasing pressure on its limited and seasonally variable water resources due to rising population demands (Stobdan, 2023) and loss of glaciers (Mandal et al., 2024). In response, local communities have employed indigenous water conservation methods, including traditional water storage tanks (zings) and, more recently, ice reservoirs (Artificial glaciers/AG) (Saxena, Suna, et al., 2021). These AGs have gained attention for their positive impact on water availability for agriculture and their broader influence on the livelihoods of local communities. Despite this, a comprehensive understanding of their long-term effectiveness remains uncertain, and empirical evidence regarding their true impact on agriculture and social resilience is still limited.

1.1. Thesis Aim and Research Questions

To address the current research gap, this thesis aims to investigate the impact of artificial glaciers on the local livelihoods and understand social resilience by employing a six-attribute of social resilience framework. The study adopts a comparative case study approach, focusing on the villages of Igoo and Ursi in Ladakh, to provide a localised understanding of both the challenges and opportunities associated with AG interventions.

The research addresses three key questions:

RQ1: How do community characteristics influence engagement with artificial glaciers?

RQ2: In what ways do artificial glaciers affect the livelihoods and socio-economic well-being of local communities?

RQ3: What role do governance structures play in the implementation of AGs?

This study employs mixed-methods research combining semi-structured interviews with NGO representatives and private organisations, alongside surveys with the community members. The Six

Attributes of Social Resilience framework guides the analysis, examining how knowledge systems, social networks, and governance structures influence AG implementation and outcomes.

1.2. Contribution to Sustainability Science

This research contributes to Sustainability Science (SS) by providing a transdisciplinary analysis of climate adaptation strategies through the lens of artificial glaciers in Ladakh. In this study, insights from traditional practices, resilience theory, and community adaptation are combined to analyse how high-altitude communities respond to climate change, which is in line with the principles of SS (Lang et al., 2012). By understanding the role of local knowledge, social networks, and governance arrangements in AG implementation, the research underscores the value of community-centred approaches for building adaptive capacity. While time constraints limited direct knowledge coproduction, the inclusion of perspectives from NGOs, communities, and academic analysis reflects a transdisciplinary approach.

The findings further contribute to global sustainability by linking grassroots adaptation practices to the SDGs. Specifically, the study advances SDG 13 (Climate Action) by examining community-led responses to climate-induced water stress, and SDG 6 (Clean Water and Sanitation) by identifying strategies that improve water security in vulnerable mountain regions. More broadly, this research advances SS by providing insights on how local adaptation practices intersect with sociocultural contexts, and by offering practical recommendations for strengthening resilience and adaptive capacity in high-altitude environments.

1.3. Thesis Outline

This thesis is structured into seven chapters. Following this introduction, Chapter 2 reviews relevant literature on traditional water management in Ladakh, artificial glacier technology, and governance models. Chapter 3 outlines the theoretical framework, while Chapter 4 details the research methodology, including case study selection, data collection methods, and data analytics. Chapter 5 presents findings from the comparative analysis of Igoo and Ursi villages. Chapter 6 discusses the implications of these findings and the limitations of the research. Finally, Chapter 7 concludes the study.

2. Background

Ladakh, a union territory[1] in northern India, lies between the Karakoram and Himalayan ranges (Ganjoo & Koul, 2025; Sandup, 2020) and is administratively divided into the Leh and Kargil districts, with a population of 274,289 (Sandup, 2020). Culturally, Ladakh has been shaped by Tibetan influence, particularly during the Tibetan regime from the 8th to the 13th centuries (Ganjoo & Koul, 2025). The Ladakhi language, derived from Tibetan script, remains widely spoken across the territory (Namgyal, 2013). Economically, agriculture forms the primary livelihood for most residents, supplemented by animal husbandry as a secondary occupation (Sandup, 2020). However, in the last two decades, there has been a shift towards the tourism sector, which now contributes nearly half of Ladakh's economy (Kandari et al., 2022; Ladon, 2025).

2.1. Water Resources and Their Management

2.1.1. Water resources and sustainable practices

Water resources in Ladakh are historically rooted in glacial systems, with human settlements established along the streams that provide the primary source of water for irrigation and agriculture in the otherwise arid landscape, as shown in Fig. 1 (Kandari et al., 2022). These streams have been diverted through carefully designed canal networks to enable cultivation. However, their seasonal variability poses many challenges. For instance, limited meltwater available in April and May coincides with the critical sowing season, resulting in acute water shortages. Contrarily, rapid glacial melt in June often leads to excessive flows and occasional flash floods (LNP, 2022). Alongside these hydrological aspects, Ladakh has developed adaptive practices that reflect sustainable resource use, such as the dry toilet system locally called Dechot, as shown in Fig. 2, which eliminates water consumption for sanitation while producing compost that supports agriculture (Kandari et al., 2022).

[1] Union territory - The president controls them through an appointed Administrator (India Book, 2020)

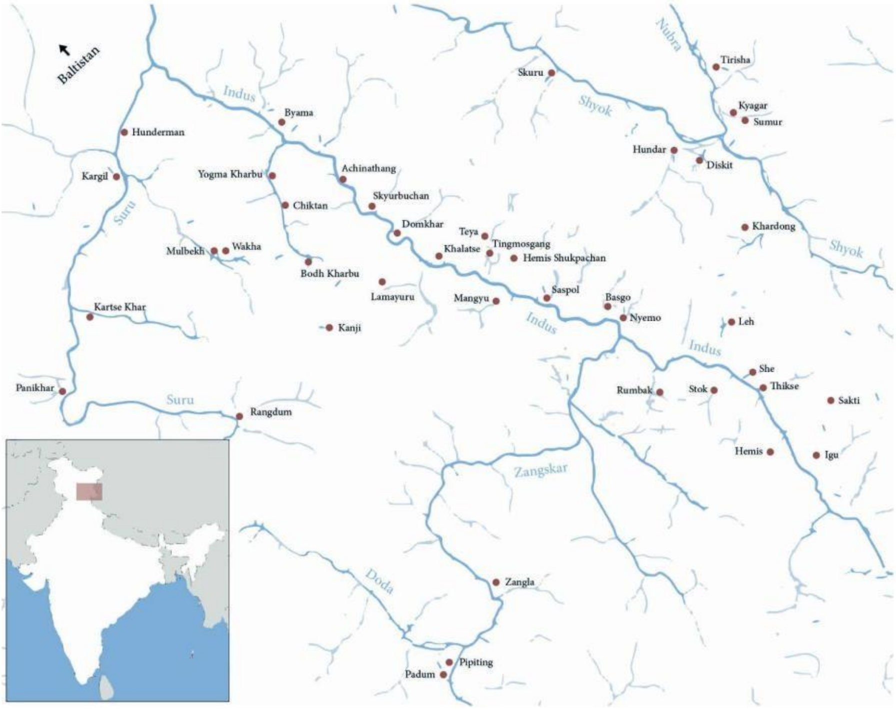

Fig. 1: Settlements established across the river streams in Ladakh (Kandari et al., 2022)

Fig. 2: Dry toilet system (Dechot) (Source: Own Picture)

2.1.2. Traditional water management

The Ladakhi water management is organised through a system of water channels locally known as kuhls, which distribute glacial meltwater across multiple levels (Saxena, Suna, et al., 2021). The network begins with the *togpo* (main stream), which feeds into *ma-yur* (mother channels) that serve as main canals built along mountainsides to divert water from glacial streams. From these, smaller *yu-ra* (subsidiary channels) branch out to distribute water to individual fields or field clusters, ultimately reaching *nang-yur* field-level channels that carry water directly to agricultural plots, as shown in Fig. 3 (Angchok & Singh, 2006). Distribution is further regulated by efficient junction points such as *yurgo*[2], *ska*[3], and *snang*[4], ensuring equitable flow to different areas. In some villages, water from the *ma-yur* is temporarily stored in *dzings/zings* (stone-lined reservoirs) before being released into the *yu-ra*, adding a layer of additional storage capacity within the system (Angchok & Singh, 2006).

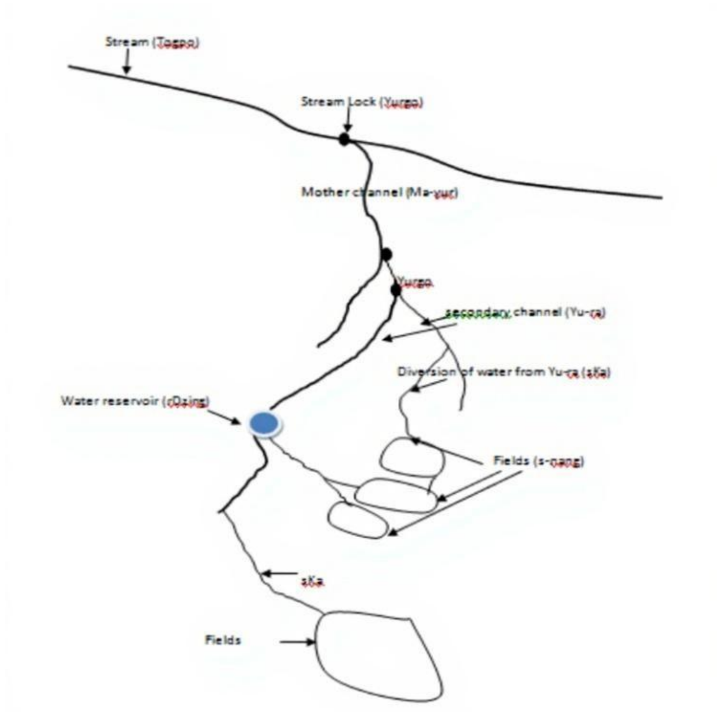

Fig.3: Schematic of water management system (Saxena, Raghuvanshi, et al., 2021)

2.1.3. Water Governance

The governance works through interconnected institutional layers, with the goba (village head) serving as the overall community leader who coordinates with chhur-pon regarding water management and cultivation timing (Bajpai et al., 2022). The yulpa (village assembly) serves as a forum where water allocation decisions are made collectively (Bajpai et al., 2022). The *chhur-pon* known as the lord of the water, acts as the primary authority in the village, overseeing water distribution for irrigation in Ladakh. Traditionally selected by consensus and now often appointed on a rotational basis, the *chhur-pon* ensures equitable water distribution through the rota system, particularly during periods of scarcity

[2] Yurgo - point where togpo water is diverted into ma-yur (Angchok & Singh, 2006)
[3] Ska - point where ma-yur water is diverted into yu-ra (Angchok & Singh, 2006)
[4] Snang – water channel where water from ska is guided to fields (Angchok & Singh, 2006)

(Angchok et al., n.d.). They are expected to know the fixed order of water diversion, crop-specific requirements, and strategies for conserving water, while also treating all village fields as their own. The role also carries cultural significance, with rituals such as keeping the *gon-cha* (long overcoat) untucked when diverting water as a mark of respect for the resource (Angchok et al., n.d.; Angchok & Singh, 2006).

2.2. Artificial glaciers and global trends

Artificial glaciers lack a universally accepted definition but can be broadly understood as a simple technique for capturing and freezing unused winter water in the form of ice. By freezing water during the colder months, the process delays its release until spring, when meltwater becomes most critical for agricultural and domestic needs (A frozen desert, 2017). AGs are also referred to as Raack (cascade structure), ice stupas, and Ice Reservoirs[5] (Balasubramanian et al., 2022; Nüsser et al., 2019).

2.2.1. Evolution of AGs and types of AGs

The practice of diverting the natural glaciers in Ladakh for irrigation purposes dates back to the nineteenth century (Clouse, 2014). But the modern concept of an artificial glacier was engineered in 1987 by Chewang Norphel (Glacier Man of India) through the implementation of cascade structures (Nüsser et al., 2019). This innovation has paved the way for many distinct types of AGs, each representing technological advancement from traditional water harvesting methods to modern automated systems. These range from simple basin structures that rely on natural topography to Sonam Wangchuk's ice stupas, as well as the incorporation of sensors for creating automated ice reservoirs (Balasubramanian et al., 2025; Nüsser et al., 2019), as shown in Table 1 and fig. 4.

Table 1: It describes different types of AGs, their construction methods, location, and how they work (Dolker, 2023; Nüsser et al., 2019; Pandey, 2024)

Type	Construction method	Location requirements	How it works
Cascade	Build loose rock walls in the riverbed 3-6 feet high, but leave a small gap for water to pass.	Across natural stream channels.	Water flows through step-like formations, gets trapped and freezes layer by layer

[5] ice reservoirs / ice stupas are sometimes interchanged with AGs in the paper

Diversion	Diverts water from streams through a narrow diversion canal to shaded valleys.	North-facing or shaded valleys.	Water is diverted into the valley and allowed to freeze in terraced ice fields (a series of built walls)
Basin	The basin is created between the village and the glacier.	Mostly located above the cultivated fields	Water flow is directed into the basin and then collects there and freezes naturally
Ice stupa	High-density plastic pipes are buried to prevent freezing and use gravity to divert water from higher altitudes to desired locations.	It can be suitable at lower altitudes.	Water pressure creates fountains that freeze into conical ice towers (the conical shape minimises the surface exposed to direct solar radiation, thus slowing the melting process)
Automated Ice reservoirs (AIR)	Like Ice stupas, but use of Sensors, valves, switches, WiFi controls, with automated spray systems and weather stations	Various altitudes	Automated monitoring of weather conditions allows the pipes to flow

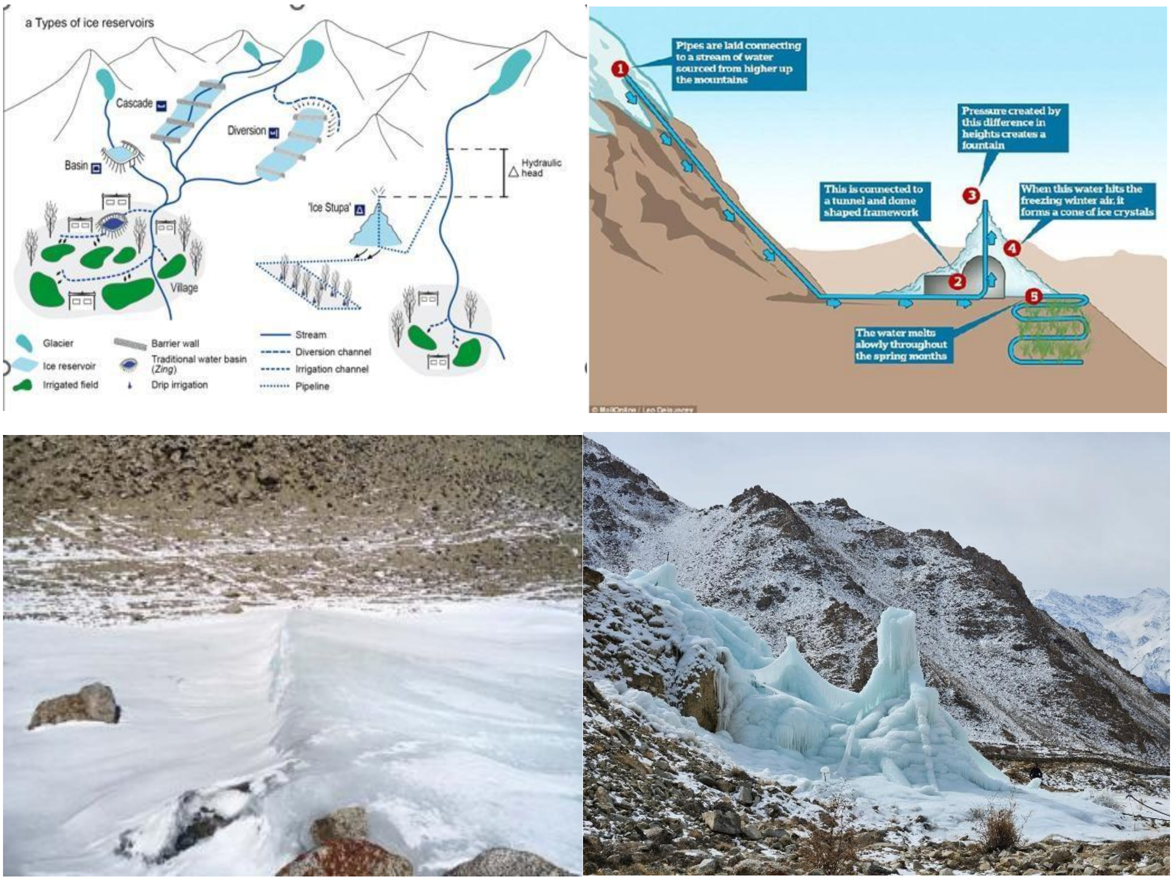

Fig. 4: a) This shows all the different types of AGs. b) The figure explains how the Ice stupa works. c) a figure depicting a cascade structure d) a figure showing an automated Ice reservoir at Likir (Clouse, 2014; Dolker, 2023)(d: own picture)

The selection of the appropriate type of AG depends on the implementing agency, but is influenced by several factors, including the geographical characteristics of the site, the feasibility and, importantly, the insights and knowledge of the residents (LNP, 2022).

2.2.2. Global Relevance

The AG technology, which started in Ladakh, has now spread across other high-altitude regions worldwide, showing its adaptability to diverse climatic and geographical conditions. For instance, Pakistan has started AG projects with its first project in Paari in 2019, with the help of UNDP and has extended it to over 20 villages in Gilgit-Baltistan (Ebrahim, 2025). Kyrgyzstan has launched the systematic implementation of AGs through an FAO-led initiative, following a comprehensive 'GlacierReservoir-Farmer' system that integrates artificial glaciers with small reservoirs and modern irrigation methods, capable of irrigating 300-500 hectares per glacier (Pechurin, 2025). Chile started the advanced adaptation through the Nilus Project, which combines Himalayan practices with artificial intelligence and renewable energy systems to address the water crisis (Lyons, 2023). Mongolia used

AG for a different application, implementing urban cooling projects in Ulaanbaatar, creating massive naleds or ice shields that slowly melt during summer to reduce city temperatures and to regulate urban drinking water (Peralta, 2011). The technology is also being explored in other regions, including the European Alps, through the 'Glaciers Alive' project.

Global trends show AG has been expanding across various regions. According to a report from Acres of Ice, there is a potential for implementing these solutions in the Andes, as well as in other areas of the Hindu-Kush Himalayan region, alpine regions, and more, as shown in Fig. 5 (Balasubramanian et al., 2025).

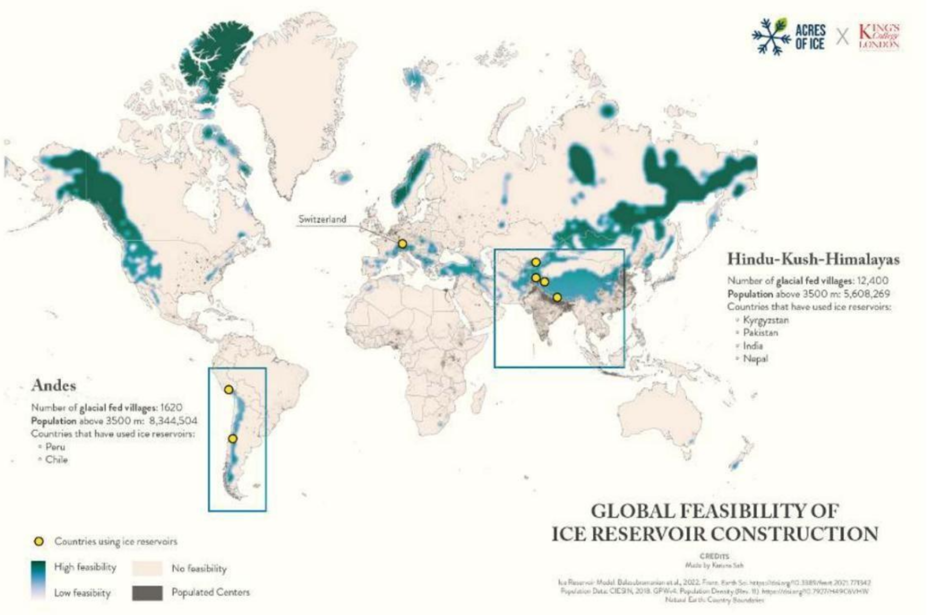

Fig.5: A map illustrating the countries that are feasible for the implementation of AG projects (Balasubramanian et al., 2025)

2.3 Existing Literature on AG and Social Resilience

Currently, no literature examines AG from a social resilience perspective. However, a study conducted by GERES (2012) documented certain impacts of AG on livelihoods through surveys in three different villages. Their findings noted examples of crop diversification in Nang and an increase in cultivated land area in Shara village following the AG installation. The analysis also highlighted income diversification through improved agriculture (GERES, 2012). A similar study concluded that Ice stupa improved irrigation and noted an instance where an ice café within ice stupa attracted youth to participate in ice stupa competition (Dolker, 2023). Another study conducted by Nüsser et al. (2019) provides a critical analysis of the socio-hydrology of artificial glaciers in Ladakh. Their research distinguished between different types of artificial glaciers and evaluated their effectiveness (Nüsser et al., 2019). Social innovation has been documented by Kumar et al. (2023), who analysed the Ice Stupa project and highlighted the need for institutional recognition of community innovation (Kumar & Saizen, 2023).

The existing literature reveals a gap in our understanding of how knowledge systems, cultural acceptance, and social cohesion interact with AG technologies. Another crucial aspect is the governance structures and policies that shape the implementation and impact of these technological projects. This study aims to explore and address this gap by examining the ways in which these factors influence each other.

3. Theoretical Framework

3.1. Social Resilience

Resilience theory has become central in understanding how socio-ecological systems (SES) respond to increasing global challenges. Originally, Holling's (1973) theory of resilience was framed within the ecological terms, referring to the systems to absorb shocks, reorganise, and continue functioning (Folke, 2006; Holling, 1973) . While the ecological focus remains important, many argue that the resilience of human systems, particularly the social dimension, has been overlooked (W. Adger, 2000; Berkes & Folke, 2002; L. Olsson et al., 2015). This gap arises from the fundamental difference in how each field conceptualises system and system boundaries. In contrast to the natural sciences, the discipline of social science struggles to universalise the system properties, making it difficult to integrate (L. Olsson et al., 2015).

Social resilience is defined as the capacity of individuals or communities to cope, adapt, transform, and thrive in the face of environmental, economic, and political change (W. Adger, 2000; Cuthill et al., 2008; keck & Sakdapolrak, 2013). It underscores the importance of social networks, governance, collective action, and cultural contexts (W. Adger, 2000; Folke, 2006). While social resilience provides a valuable lens for understanding how communities adapt to environmental and socio-economic challenges, measuring the social aspects of resilience is a difficult process as communities evolve over the period. Many scholars have tried to measure resilience through comparing resilience across regions, tracking resilience over time, assessing resilience across disaster phases and evaluating hazard-specific resilience (Copeland et al., 2020; Saja et al., 2019). Several frameworks have been developed to guide measurement. For instance, Adger (2008) introduced the Social Limitations to Adaptation (SLA) framework, which measures ethical considerations, knowledge systems, risk perception, and cultural values (W. N. Adger et al., 2008). Similarly, Maclean et al. (2014) proposed assessing social resilience through six attributes of resilience by considering knowledge systems, community networks, people–place connections, community infrastructure, economic diversity, and engaged governance (Maclean et al., 2014).

The six-attribute framework provides a more comprehensive approach to assessing resilience, as it incorporates governance and economic dimensions that are neglected in the SLA framework but are essential to any societal system, since they play a critical role in shaping adaptive capacity and understanding resilience (Maclean et al., 2014).

3.2. Six Attributes of Social Resilience

The Six Attributes of Social Resilience framework, developed by Maclean et al. (2014), was built on the foundation of social resilience principles, through key elements like social networks, knowledge systems that facilitate information sharing, and cultural contexts that influence adaptation (W. N. Adger et al., 2008; Folke, 2003). This framework provides insights into how communities can adapt to challenges and strengthen their resilience, as shown in Table 2.

Table 2: Six attributes of the social resilience framework with key features (Maclean et al., 2014)

Attribute	Key information
Knowledge, Skills and Learning	Refers to the ability of individuals and groups to address local needs and issues through knowledge partnerships. Improved knowledge, skills, and learning have enhanced local people's capacity to cope with and adapt to changes.
Community Networks	During times of change, community networks provide essential support and hope. Strong community networks help individuals adapt to challenges.
People-Place Connections	A sense of connection to the natural environment, rooted in cultural values, motivates communities to protect and sustainably manage their natural and cultural landscapes. This connection drives individuals to strengthen their ability to adapt to change.
Community Infrastructure	Accessible and good infrastructure improves economic opportunities, social well-being, and adaptive capacity in times of change.
Diverse and Innovative Economy	Creating a varied regional economy with a strong local focus and openness to new ideas reduces vulnerability to external shocks and improves social resilience
Engaged Governance	Collaborative decision-making processes that include diverse stakeholders, supported by cross-sector partnerships, a shared

	vision, and effective communication, help co-create solutions to regional challenges and improve resilience.

To understand how these six attributes play a key role in social resilience, let us apply them to a practical example by considering the case study of Ladakh.

3.3. Relevance of six attributes of social resilience to Ladakh

Ladakh has struggled with a water crisis due to its reliance on glaciers, a situation that has been exacerbated by climate change. In response, local communities have adapted AGs to enhance their livelihoods and economic stability. In this study, social resilience refers to the capacity of individuals, communities, and societies to adapt and transform in the face of environmental, social, economic, or political pressures (Cuthill et al., 2008). The research aims to understand how AGs contribute to building social resilience among mountain communities experiencing climate-related water shortages. AGs serve not only as physical water-harvesting structures but also as socio-cultural institutions deeply rooted in local networks, traditions, and governance practices. Their effectiveness depends on collective knowledge, strong connections between people and place, and community-based decision-making dimensions that are accurately captured by the Six Attributes framework.

For example, the design and implementation of AGs rely on traditional knowledge, transferred across generations and adapted through learning (Berkes, 2009). Community networks organise labour, coordinate construction, and ensure equitable water distribution. People-place connections improve the fragile high-altitude ecosystems, while engaged governance, often through community leaders, facilitates participatory decision-making. Social resilience of AGs is further shaped by supporting infrastructure and the extent to which local economies can absorb innovation and change (Maclean et al., 2014). This framework thus provides a comprehensive theoretical foundation for examining how societies facing environmental challenges can effectively achieve resilience.

4. Methodology

This chapter outlines the philosophical viewpoint, research design, and fieldwork procedures employed to understand social resilience in Ladakh. The methodology combines quantitative survey insights and qualitative interview findings to capture both measurable patterns and contextual understandings of social resilience.

4.1. Philosophy of knowledge

This research employs a mixed-methods approach, integrating survey data with interviews to create a comprehensive understanding of social resilience in the context of water scarcity in Ladakh. This approach is chosen because resilience is best understood through both quantitative data and personal narratives. It requires a combination of indicators and detailed insights into governance, practices, and lived experiences. The study is grounded in a pragmatist epistemological stance that values using different methods of understanding knowledge and recognising the strengths of various types of knowledge. It does not stick to one way of thinking, but instead focuses on what works best for addressing the research questions (Maarouf, 2019).

A pragmatic approach is particularly suited to social resilience research, which deals with complex and dynamic socio-ecological systems. Communities' responses to challenges like water scarcity are shaped by their social networks, cultural ties, and governance arrangements. No single method can capture this complexity in isolation. By combining quantitative and qualitative methods, the research can give a holistic picture of how resilience is built, maintained, and experienced (Maarouf, 2019).

4.2. Research design

The research design combines questionnaires and semi-structured interviews to capture attributes of social resilience and deeper insights into governance processes. This combination ensures a balanced view of community-level practices as well as institutional dynamics shaping resilience.

Questionnaire design

The household questionnaire was developed by drawing on existing literature on key attributes of social resilience, including knowledge systems, community networks, people-place connections, community infrastructure, diverse economy, and governance. Additional insights were gained through informal discussions with organisations involved in constructing artificial glaciers, as well as an exploratory visit to a village (Likir) to understand the cultural context better. Based on this groundwork, the questionnaire was structured primarily with closed-ended questions to generate quantifiable data, supplemented by a small number of open-ended questions to understand some indicators more deeply. A pilot study was conducted to test the survey, which proved useful in refining question clarity, removing unwanted questions, and enhancing cultural relevance (De Vaus, 2013). The final survey can be found in the appendix section of the paper.

Semi-Structured Interviews

Semi-structured interviews were employed to complement the quantitative data by exploring governance-related aspects of resilience in greater depth. Governance and institutional arrangements are recognised as central to shaping adaptive capacity and resilience (W. Adger, 2000; Folke et al., 2005). The interviews explored themes such as Governance structures in water management, community participation in AGs, policy frameworks and institutional support regarding AGs, transparency, and accountability. Semi-structured interviews were chosen for their flexibility, allowing respondents to elaborate on issues most relevant to their experience while still maintaining focus on governance and institutional dynamics (Knott et al., 2022).

4.3. Study Area

The study was conducted in the Ladakh region, where artificial glaciers (AGs) have been used as an adaptation strategy to water scarcity. While precise data on AG and their distribution is limited, one source reports that by 2021, more than 80 villages have implemented these structures (Sara, 2021). A case study approach was used to examine social resilience attributes. Two villages were ultimately selected for in-depth study.

Both practical and research considerations shaped the process of site selection. Fieldwork was carried out during peak winter, which created logistical challenges and harsh weather conditions. Collaboration with a partner organisation helped address these issues, and villages were narrowed down to those where the organisation was already active. This resulted in an initial shortlist of seven villages: Igoo, Sakti, Likir, Tuna, Stakmo, Ayee, and Ursi.

Several factors guided the final selection of case study sites. First, it was essential to choose villages where artificial glaciers had been in place long enough to observe their impact on water availability and livelihoods. Second, both selected villages needed to have a strong agricultural base, ensuring relevance for assessing how ice reservoirs affect farming practices and productivity. Finally, the research aimed to capture variation in geographical settings, one village without access to natural glacier-fed streams and reliant on springs, and another with access to glacier meltwater. This filtered down the list to Ursi and Igoo, as shown in Fig. 6

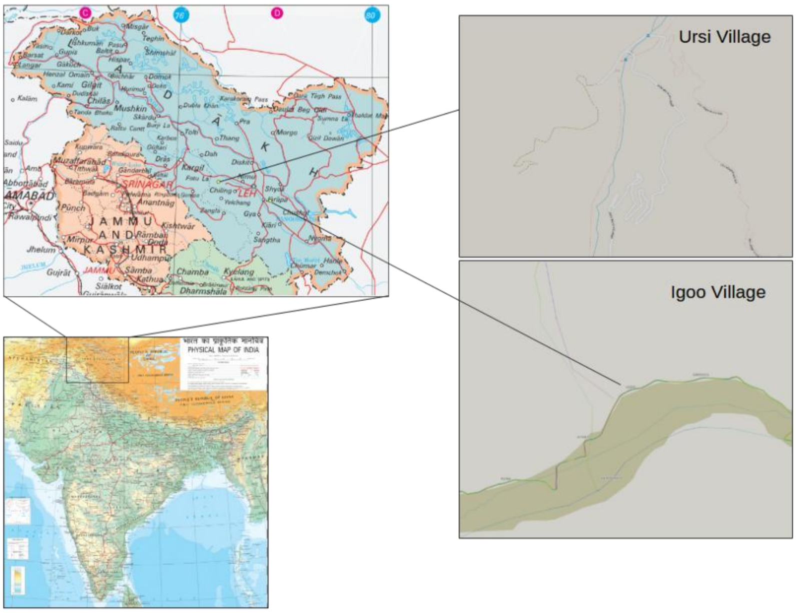

Fig. 6: Location of Ladakh and the two research areas Igoo and Ursi (Source: Own illustration)

Ursi: a remote mountain village at 3,700 m between the Zanskar and Indus rivers, is home to just 16 households. Lacking a natural glacier and relying solely on springs, the community has struggled with severe water shortages for a long time, even considering abandoning the village once (Balasubramanian et al., 2025). Watershed suggests its catchment is entirely snow-fed, with streams active only after heavy snowfall, as shown in Fig. 7a. Earlier cascade structures failed, but inspired by the ice stupa model, local youth began building ice reservoirs in 2018 (Balasubramanian et al., 2025).

Igoo: a south-facing village of about 260 households in the Indus belt, lies 50 km east of Leh at 3,300–4,100 m. The village faces severe spring water shortages affecting agriculture despite having a natural glacier and the Tso Lake, as shown in Fig. 7b. Igoo has a long history of water conservation, and artificial glaciers have been built since 2009, and it also won the ice stupa competition in 2021 (Balasubramanian et al., 2025).

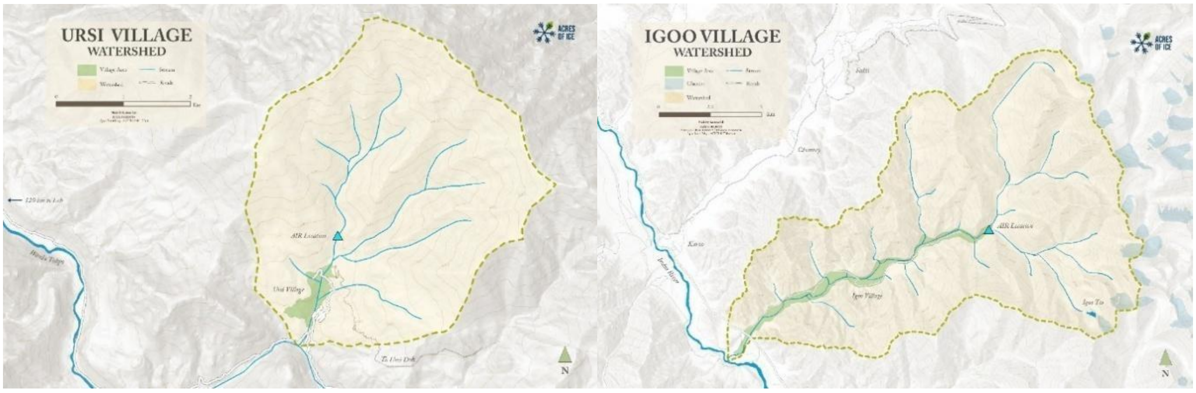

Fig. 7 a) The map shows the watershed of Ursi, where the village lacks the presence of Glacier 7 b) the watershed of Igoo highlights the presence of Glacier and Tso Lake (Balasubramanian et al., 2025)

4.4. Data Collection

The surveys were conducted using convenience sampling, selecting participants based on their availability and willingness to take part (Golzar et al., 2022). The process involved walking around the village and engaging with individuals casually to determine their interest. Once a participant agreed, informed consent was obtained, and the purpose of the research was explained. The survey was designed in English but was administered orally in Hindi. If any participant did not understand Hindi, it was translated into Ladakhi with the assistance of a translator for those who spoke Ladakhi, and all responses were recorded manually. Each survey took approximately 35 minutes to 1 hour, depending on the participant's level of engagement. Some respondents were unable to complete the survey due to personal reasons.

In total, 68 surveys were collected, of which 52 were from Igoo, eight from Ursi, and eight from Sakti[6], as shown in Table 3. The difference in the sample size is proportional to the village size. For this study, only the data from Ursi and Igoo were analysed. The survey contributed to an understanding of the first five attributes of social resilience, along with preliminary insights into governance structures.

For semi-structured interviews, I employed purposive sampling, selecting participants based on their direct expertise and involvement in artificial glacier projects in Ladakh, ensuring deep insights into the topic (Knott et al., 2022). Acres of Ice and Leh Nutrition Project (LNP) were chosen due to their extensive experience with artificial glaciers, governance processes, and community-based climate

[6] Even though the initial pilot study was conducted in Sakti, it is excluded from the final analysis and exclusion is based on a lack of knowledge of AGs within the community.

adaptation, allowing the research to capture informed and contrasting organisational perspectives, one representing a social enterprise model and the other a non-governmental organisation. After obtaining informed consent, two semi-structured interviews were conducted, one in person and the other online. The interviews were semi-formal in nature, focusing on governance-related aspects of artificial glacier projects, and each lasted approximately 50 to 60 minutes. All interviews were audio-recorded and documented for subsequent analysis.

Table 3: A breakdown of the entire fieldwork from both the interviews and surveys

Reference	Data collection method	Number of Surveys	Location	Date
NGO -LNP	Informal Interview	-	Leh	13/02/2025
Field Visit 1	Informal with interactions villagers	5	Likir	18/02/2025
Field Visit 2	Survey	8	Sakti	07/03/2025
Field Visit 3	Survey	13	Igoo	13/03/2025
Field Visit 4	Survey	14	Igoo	14/03/2025
Field Visit 5	Survey	9	Igoo	15/03/2025
Field Visit 6	Survey	7	Igoo	16/03/2025
Field Visit 7	Survey	9	Igoo	24/03/2025
Acres of Ice	Semi-structured Interview	-	Online	26/03/2025
LNP	Semi-structured interview	-	Leh	27/03/2025
Field Visit 8	Survey	8	Ursi	28/03/2025

4.5. Data analysis

All survey data were initially digitised using Google Forms and later exported to Excel spreadsheets. The data were systematically organised into thematic categories which reflect the six attributes of social resilience. Given the extensive dataset, which included multiple indicators for each attribute, relevant indicators were identified and analysed using Excel charts, and the process was repeated for the second village. Comparative analysis of the charts from both villages was then conducted to draw conclusions.

The semi-structured interviews were transcribed and converted into an intelligent verbatim format by removing repetitive expressions and unnecessary filler words (e.g., “hmm,” “uh,” “umm”) manually by using Microsoft Word (Knott et al., 2022). The transcripts were analysed through a thematic analysis following a deductive approach, which involved familiarising with the data to ensure a deep understanding (Braun & Clarke, 2006; Knott et al., 2022). The research objectives, such as governance, funding, collaboration, and participation, guided the deductive themes. Each of them is then coded and organised into themes using Microsoft Excel, leading to a detailed analysis (Braun & Clarke, 2006).

4.6. Ethical considerations

All participants provided informed consent before participating in the study, ensuring that they fully understood the research objectives, procedures, and their right to withdraw at any point. Participant privacy was taken care of by maintaining anonymity throughout the study. As a researcher from a different region, I adhered to local cultural protocols throughout the research process. This research was well aligned with all the core ethical principles, like voluntary participation, maintaining confidentiality and respecting communities (Israel & Hay, 2006).

5. Results & analysis

This chapter presents the findings of a household-level survey conducted across the two villages and analyses of semi-structured interviews in the region to assess the influence of artificial glaciers (AGs) on the social resilience of local communities. The results are structured based on the research questions posed earlier, addressing community characteristics, impact on livelihoods, and governance structures

5.1. Community characteristics and engagement with AG

The community's engagement plays an important role in understanding how they adapt and cope with adverse situations (Maclean et al., 2014). To explore this, we can analyse it through different attributes such as knowledge systems, social cohesion and people-place connections, addressing RQ1.

5.1.1. Climate Change perceptions/ knowledge

Surprisingly, communities in both villages have shown a clear awareness of environmental changes associated with climate change, despite not being familiar with the term itself. All respondents (Ursi, Igoo: n=8, n=52) have observed perceivable shifts in their local environment over the past decades. Given the average age of respondents, 56 in Igoo and 65 in Ursi, most of them have experienced these changes firsthand. Some commonly cited observations include a consistent decline in snowfall, reduced water flow in glacial streams, and an increase in temperatures. Some lesser known responses include erratic and irregular rainfall and glacial recession. These personal experiences reflect a lived understanding of climate variability rooted in long-term observation.

One respondent reflected on their memories, stating, *"There used to be a lot of fish in the water,*" which implies a time when the streams supported aquatic life, this reveals a landscape where not only water volume but also its life-giving potential has reduced. Another participant, aged 83, recalled that "flooding *was common in the olden days, but not now*". This highlights the environmental changes that have taken place, which means a shift in both climate patterns and local ecosystems.

5.1.2. Knowledge Systems

The two case studies presented contrasting knowledge characteristics that shaped their engagement with AGs. In Ursi, community knowledge of AG construction and maintenance is largely rooted in learning through community members(n=6) and elders(n=1), which is intergenerational and informal knowledge sharing. Although AGs are a new technology, all respondents(n=8) expressed confidence in building and maintaining AGs, indicating effective learning within the community. The community has also been familiar with water-efficient practices, such as drip irrigation (n=6) and water-efficient crops(n=4), through the knowledge gained by NGOs and mutual learning, meaning that the community is proactive and open to technical innovations and water-efficient strategies.

On the other hand, Igoo's initial exposure to the concept of AG primarily came from external actors, with about 65% of participants learning about AGs through NGOs (SECMOL). All the villagers connected the new ice stupa technology to their traditional RAACK system, perceiving it as a combination of indigenous knowledge and modern engineering. Despite this initial exposure to AGs, the community lacked formal training, with 50 participants having reported no training at all. This lack of training was reflected in their confidence levels to manage AGs, with only 17% expressing confidence, while 20% reported no confidence at all. The rest of the participants showed a conditional confidence in managing AGs, which means they could do so if provided with adequate training, equipment or funding. Furthermore, many respondents (n=48) are unaware of methods like drip irrigation or improved crop varieties.

5.1.3. Social Cohesion and Participation

This attribute tries to capture the community-based relationships, participation in collective activities, and the ability to manage water-related conflicts.

In Ursi, the data revealed a strong sense of social cohesion among the villagers. They voluntarily organised themselves to construct and maintain the ice reservoirs each winter, without any external support for the past few years. Importantly, respondents noted that the AG initiative did not change existing patterns of cooperation within the village. Most households reported that community dynamics remained stable, suggesting that the AG project was integrated into existing social structures rather than changing them; for instance, water allocation continued to be governed by the Churpon. This resulted in no conflicts(n=8) related to water distribution. As quoted by one participant, "*We get to use the water once a week, taking turns. Therefore, no conflict occurs, as it is decided by the churpon"*

In Igoo, direct community participation in the construction of artificial glaciers (AGs) was much lower, with only 19% of households involved either actively or occasionally. The limited engagement may be attributed to Igoo's larger population and more dispersed which complicates accessibility. Many participants expressed dissatisfaction with the external agents in the construction process. Around 71% felt that the construction of AGs should be a local effort, as the majority emphasised water as a shared resource, and the responsibility for managing and sustaining it should also lie with them, underscoring a lack of ownership in externally led efforts. Nonetheless, the AG initiative in Igoo did spark some discussions about water sharing, though it has not improved cooperation among community members. However, approximately 30 respondents reported water-related conflicts, indicating tensions around access and distribution. As quoted by a midstream participant, *"Earlier, the police used to come to resolve the issues; now in recent times, it has improved"*.

Resolution of these disputes primarily occurs through informal mechanisms, rooted in local social settings and dialogue. Some participants also identified the involvement of a three-member water committee in conflict resolution, meaning some presence of semi-formal governance structures.

5.1.4. Cultural acceptance and Place attachment

It refers to communities' emotional, spiritual, and cultural relationship with their landscape and environmental interventions (like AGs).

In Ursi, respondents showed a strong sense of belonging, with the majority (n= 5) attributing this to place identity, while some(n=3) cited this due to strong community bonding. All eight participants reported that artificial glaciers (AGs) have become an integral part of the village identity, and that these structures are now viewed as more than mere technological interventions. Most participants expressed a spiritual connection to the AGs. For some, this connection was rooted in the belief that water is sacred and auspicious. Surprisingly, none of the respondents perceived AGs as violating the sacredness of the place.

Conversely, in Igoo, attitudes were more mixed and utilitarian. A strong sense of belonging was expressed by 87% of participants, tied to nature bonding, community bonding, place dependence and identity, but a sizeable portion(n=31) saw no spiritual association to the AG. Several Igoo respondents acknowledged that the AG had put their village "on the map" externally; in fact, Igoo gained regional recognition a few years ago by winning an Ice Stupa competition (a competition in Ladakh for constructing the biggest AG). This brought pride and a sense of identity to the community through its association with the ice project. Concerns regarding the cultural integrity of the landscape were more visible in Igoo, as about 29% expressed worries about the potential desecration and sacredness of the place.

5.2. Livelihood Impacts and Economic Outcomes

The primary purpose of AG in Ladakh is to improve the spring water in the region, for both agriculture and livelihood. This section of results explores RQ 2 by discussing how AG impacted water availability and its economic impacts.

5.2.1. Livelihood Impacts

In Ursi, most respondents (n=7) reported a significant improvement in water availability following the implementation of artificial glaciers (AGs), with one participant mentioning a slight improvement. In addition to these qualitative responses, quantitative data from the *Acres of Ice* organisation further substantiates this observation, indicating that AGs had accumulated about 4.6 million litres of water as solid ice, which will lead to an increase in water to the stream in the current year (Balasubramanian et al., 2025). The improved water availability resulted in an immediate positive effect on local agriculture. This is clearly visible in terms of increased crop yields, as well as the opportunity to adopt new crop varieties. Every household experiences some form of crop diversification (Dolker, 2023), moving beyond the traditional crops. They were even able to cultivate plantation crops such as Apricot, apple, and walnut crops that were previously not viable in the region. Some participants attributed this not only to improved water access but also to a rise in temperatures, which together created a favourable condition for such crops. One participant mentions, "*He is happy with the apricot yield, describing the variety grown in Ursi as uniquely special within the region*"

Although water availability has improved, respondents emphasised the need to expand water storage systems in the region. Currently, only one zing exists, which is insufficient to store the additional water. Participants stressed constructing Zings or tanks to use AG water. One respondent mentioned: *"Upstream zing construction should happen soon, and downstream should be connected to upstream so that the system can recycle itself. Also, not more than one ice stupa should be constructed, as there will be no water left for the community due to their dependence on spring water."*

In Igoo, the impact of artificial glaciers (AGs) on water availability was less noticeable than in Ursi. A little over 27% of participants reported a significant improvement, while 41% saw a slight change, and about 32% observed no change in water availability at all. This community perception stands in contrast to quantitative data from the Acres of Ice organisation, which indicates that AGs are expected to contribute about 4 million litres of water to the village stream this year (Balasubramanian et al., 2025). Additionally, the location was not optimal, or its meltwater did not reach downstream effectively, making it not useful enough for people living downstream. Lastly, limitations in supporting infrastructure have worsened the issue, as 54% of respondents indicated that there is a lack of community infrastructure (mainly Zings).

The mixed outcomes in water availability have been reflected in Agricultural impacts. Around half of the participants reported no noticeable improvement in agricultural practices, while the other half indicated an increase in crop yields. One respondent noted no change in agricultural productivity due to the unavailability of fertilisers, remarking that, "*earlier, sheep manure was used as an organic fertiliser; now sheep rearing is not a major part of the livelihood in the region*". Although some respondents acknowledged some kind of crop diversification, this was often assigned more to enhanced knowledge about new crops, possibly through NGO outreach or community exchange, rather than improved water availability. For example, Igoo farmers have started growing vegetables such as cabbage, cauliflower, carrot, tomato, and non-Ladakhi peas, as well as fruits like muskmelon and watermelon, due to the availability of seeds.

Lastly, aside from agriculture, participants in both villages reported no significant improvements in other aspects of their livelihoods following the implementation of artificial glaciers.

Sectors such as livestock productivity, tourism, and the construction of new hotels were largely unaffected.

5.2.2. Diverse and Innovative Economy

One way to measure the livelihood impact is by understanding whether it improved household income and the local economy or not. Let us explore that in this part.

In Ursi, the substantial boost in crop yield directly resulted in increased household income for most of the families. Farmers could produce more surplus and sell extra produce at nearby markets, thereby enhancing their economic well-being. The benefits remained confined to farming; there is no indication of any other income sources, such as tourism or any homestay /construction aspects, except for two respondents who got some money from the organisation to maintain AG. All in all, AG has not helped in creating alternate livelihoods.

In Igoo, the impact of artificial glaciers (AGs) on household income was even more limited. Approximately 50% of respondents reported slight improvements in income, while only 8% noted significant gains, and the remaining 42% participants indicated no noticeable change in their income levels. This implies that while AGs may have had a positive influence on agricultural productivity for some, the overall economic benefits have been limited and not uniformly experienced across the community, which can be understood from the uneven distribution of water. Only two out of 52 surveyed households reported receiving financial compensation from NGOs for activities related to the construction or maintenance of AGs. This points to a low level of direct economic engagement or incentivisation associated with the AG initiative in Igoo, which may have contributed to the relatively low levels of household participation and perceived benefit. Moreover, no respondents reported generating additional income through tourism or other activities linked to AGs.

5.3. Governance Dynamics: Structure, Transparency, and Policy Frameworks

The governance of AG initiatives is complex and still evolving. To address research question 3, this section examines governance structures, policy frameworks, and transparency mechanisms and their influence on AGs.

Governance Structure: the findings from the interview reveal a dual governance model in which informal institutional arrangements and private organisations play a central role, while government involvement remains limited. Two distinct governance models were observed:

1. NGO (LNP) led community-centric model: This bottom-up approach allocates more than 80% of decision-making authority to local communities. Villagers collectively determine project locations, methods to build AGs, and other operational criteria required to implement AGs.
2. Private organisation (Acres of Ice) led model: This approach establishes formal *"water management committees"* as intermediary institutions between the organisation and communities.

In both models, the government plays only a minimal role, primarily providing funding through tendering processes. At the operational level, once AGs are functional, water distribution remains a community-managed process overseen by the churpon, who ensures fair allocation of water.

Policy Framework: Despite the growing trend of AG projects, they lack formal recognition within national or state-level policy frameworks. However, various schemes exist to support AGs. The Ministry of Tribal Affairs, in collaboration with the SECMOL, launched a two-year action research project aimed at constructing ice stupas across 50 villages (Samvaad, n.d.). Similarly, under the Jal Jeevan Mission[7], the administration of Ladakh incorporates artificial glaciers to ensure rural water security, with plans for twenty to be created and maintained (JJM, 2024).

Transparency: Both governance models reveal several shortcomings in their monitoring and evaluation mechanisms. Interviewees acknowledged the lack of standardised methods for quantifying water yield across varying altitudes and sites. Current practices heavily depend on self-reporting by implementing organisations, with little or no independent verification. Moreover, there is no database documenting AG structures or outcomes. As a respondent from LNP noted, *"We don't have the accurate data that from this chunk of solid ice we have got this much of liquid water."* These gaps undermine transparency and accountability, raising questions about the long-term scalability of AG projects.

6. Discussion

The findings from the two villages reveal that the same AG technology can lead to very different social outcomes. Ursi's experience points to how strong local knowledge, close social ties, and cultural acceptance can transform a new water source into shared benefits. In contrast, Igoo's experience indicates that external implementation, inadequate training, scattered settlements, and infrastructure deficiencies can reduce those benefits and, in some cases, create tensions about access. These differences are significant; they highlight the mechanisms that connect technology, people, and institutions. In simple terms, AGs yield positive results when the systems of knowledge, social

[7] Jal Jeevan Mission – it aims to provide safe drinking water through household tap connections to all rural households in India, a central govt scheme (jaljeevanmission, n.d.).

relationships, culture, and governance are aligned to support them. In this discussion section, I will explore these findings in relation to existing literature and reflect on the limitations of the research and provide suggestions for future studies.

6.1 Discussion on Community Characteristics and Engagement (RQ1)

The findings reveal differences in community characteristics that influence engagement with artificial glaciers between Ursi and Igoo, highlighting the critical role of knowledge systems, social cohesion, and cultural acceptance in the success of AG projects

Knowledge Systems

The findings indicate that community engagement with AG initiatives is shaped less by general awareness of the technology and more by the community's capacity to adapt it to their own needs. While both villages show a clear understanding of climate change, their adaptive approaches differ significantly. In Ursi, residents acquired skills in AG construction and maintenance through informal peer-to-peer learning, integrating these practices with the water-efficient methods they were practising (Folke, 2003). As a result, confidence in managing AGs was high, and participation was both voluntary and widespread. On the other hand, in Igoo, most individuals initially encountered AGs through external sources, with little to no formal training, leading to limited confidence and reduced participation.

Why does this exist? The knowledge systems play a crucial role in shaping community adaptation and resilience (Folke, 2003). In Ursi, learning was shared through trusted social networks and intergenerational exchanges, fostering a process of continuous, community-based learning. People engaged in AG activities, often interacting with neighbours and elders, which made the learning process effortless and engaging (Thi Hong Phuong et al., 2017). In contrast, in Igoo, awareness was primarily generated through NGOs and external organisations. While this sparked interest, insufficient training and resource support left many residents feeling ill-equipped to construct or maintain AGs independently. For artificial glaciers (AGs) to be effective, continuous skill building and social learning are essential (Folke et al., 2005; Maclean et al., 2014). This aligns with broader research showing that adaptive capacity is strengthened when communities have the ability to learn (Maclean et al., 2014; Thi Hong Phuong et al., 2017). Recommended measures include offering hands-on training sessions, workshops on water-efficient practices, engagement with new technologies (automated AGs), and developing local capacity-building initiatives.

Social Cohesion and Participation

The patterns of social cohesion observed offer valuable insights into the influence of existing community structures on adaptation outcomes. In Ursi, strong social bonds enabled residents to selforganise AG construction and maintenance each winter without external help (W. Adger, 2000). The project complemented existing systems, such as the *churpon* water allocation method, and no conflicts occurred. This integration ensures that AGs can be successfully incorporated into existing social structures when communities have well-established collective action and strong cohesion (Maclean et al., 2014). In contrast, Igoo's experience shows how weak social cohesion can undermine participation, with only 19% of households participating directly in AG construction and 30 respondents reporting water-related conflicts. Although 71% of participants expressed that AG construction should be a locally driven effort, actual engagement remained limited, revealing a gap between the sense of community ownership and the capacity to build it (Berkes, 2009). Furthermore, many Igoo residents voiced dissatisfaction with the external organisation's role, citing inadequate community involvement in the AG development process.

Why does this exist? Firstly, Ursi's bottom-up, community-driven approach meant people felt ownership from the start and could build AGs according to their own priorities and schedules, even when an external organisation facilitated the AG. This created a sense of ownership towards the AG, which helped in enhancing community adaptation (Itsumi et al., 2025). Igoo's more external-led approach made the project feel more like it belonged to outsiders rather, as reflected by midstream residents. This reduced motivation to participate and weakened the social bonds. Secondly, factors such as scale and geography also influence outcomes. Igoo's larger and more dispersed population makes coordinating activities and mobilising people for construction and maintenance challenging, as residents from downstream, for instance, must travel over 10 km to reach the AG site. Ursi's smaller, tightly knit community makes collective action easier to organise. Lastly, the perception of fairness is varied across the village. In Igoo, differences in access based on location (upstream, midstream, downstream) led to unequal benefits. When downstream people felt that meltwater was not reaching them, their motivation to participate declined, leading to dissatisfaction, as no tangible outcomes were achieved (Itsumi et al., 2025). In Ursi, the situation is quite different; with only 16 households and no natural glacier, everyone has depended on AGs for the past decade, resulting in high interest and participation in AG skills.

Some strategies to improve participation include clearly defining roles and responsibilities and ensuring community ownership towards shared resources by involving them (AG). In locations like

Igoo, where distance and population size pose coordination challenges, engagement strategies should be made to specific sub-regions (for example, by creating separate work groups for upstream, midstream, and downstream activities). This approach makes participation feel more meaningful and ensures that benefits are accessible to all participants.

Cultural acceptance and place attachment

The cultural acceptance and place attachment findings reveal that the spiritual and cultural dimensions of climate adaptation are often overlooked in technocratic approaches. In Ursi, participants exhibit a strong emotional and spiritual bond to both their ancestral landscape and the ice stupas. This attachment is rooted in multi-generational ties to the land and the perception of water as sacred, leading community members to view the ice structures not merely as technical installations but as an integral part of village identity. In contrast, Igoo's engagement with AGs is more instrumental. While 87 percent of respondents maintain a strong place attachment, only a small portion associate the ice stupas with spiritual importance. Instead, pride comes from external recognition, winning the regional Ice Stupa competition, rather than from a sacred connection to the intervention itself. Besides, around 29 per cent of villagers expressed concerns that AGs might violate culturally significant landmarks or disrupt the sacred landscape. These mixed attitudes reveal that when technological interventions are perceived as externally introduced rather than local innovations, they may strengthen identity through prestige but risk undermining deeper cultural bonds.

The experiences in Ursi and Igoo show that attachment to a resource, such as an artificial glacier (AG), does not automatically arise simply from its presence in the local landscape; rather, this connection must be developed through inclusive processes that respect local culture (W. N. Adger et al., 2008). Historically, villagers would consult Lamas[8] and hold festivals during the irrigation and sowing seasons in the early 16th century, but these traditions have gradually disappeared over time (Kandari et al., 2022). Measures such as integrating local rituals, symbols, and cultural expressions into the design and implementation of AGs can transform these water-harvesting structures into symbols of shared identity. Organising community events like blessings for new ice stupas or creating festivals can strengthen emotional connections. By designing AGs that respect both cultural significance and local traditions helps communities cultivate a strong sense of connection, thereby enhancing their overall adaptive capacity (Folke, 2004; Kandari et al., 2022; Maclean et al., 2014)

[8] Lama- is a spiritual leader (monk) who acts as a philosopher, a guide to the Ladakhi villages (Mann, 1985)

Summary of discussion for RQ1

To summarise that community engagement with artificial glaciers (AGs) is shaped by knowledge systems, social cohesion, and cultural attachment. In Ursi, strong informal learning, social networks, and willingness to participate enabled successful adoption and maintenance of AGs, supported by no water conflicts. The community's emotional and spiritual connection to the landscape further reinforced engagement, making AGs integral to local identity. In contrast, Igoo's limited training, lower participation, and mixed cultural perceptions resulted in weaker ownership and reduced adaptive capacity (Kandari et al., 2022). These findings underscore that effective adaptation requires not only technology transfer but also inclusive knowledge-building, cohesive social structures, and culturally sensitive interventions (Maclean et al., 2014).

***6.2. Discussion on Livelihood Impacts and Economic Outcomes* (RQ2)**

AG techniques have the potential to improve agricultural productivity, but their effectiveness depends on several conditions, like the additional water must be supplemental during essential sowing periods, it must be stored and delivered to fields as required, and farmers must be able to translate this water into higher-value production. In Ursi, all three conditions were fulfilled or partially fulfilled. Residents reported significant improvements in water availability, linked these improvements to increased yields and crop diversification (including the introduction of orchards), and successfully sold surplus produce, leading to higher household incomes. These outcomes align with existing research on the link between water access and agricultural diversification (Dolker, 2023). In contrast, Igoo struggled in several areas: improvements in water availability were perceived as inconsistent, infrastructure for meltwater storage was often inadequate, and downstream fields did not receive a reliable supply. As a result, agricultural benefits were uneven, resulting in modest income increases for most households.

Why does this exist? In Igoo, the presence of a glacier-fed stream meant that AGs offered relatively limited additional benefits, with some users reporting little to no change. Ursi experienced more seasonal water constraints and had fewer alternative sources, making the supplementary water from AGs highly significant. Infrastructure was also critical; without sufficient zings or storage ponds, even substantial meltwater flows can go unused or arrive at non-optimal times. This was seen in both Ursi and Igoo, but was particularly evident in Igoo, where more than half of the users indicated a lack of storage capacity. The location and flow paths of AGs further influenced their value. If the AG is positioned in a way that prevents meltwater from consistently reaching vulnerable fields, its perceived value declines. This issue appeared in certain areas of Igoo, particularly midstream and downstream, where participants in Igoo are in favour of building an ice stupa midstream. Finally, market accessibility shaped outcomes. Farmers in Ursi successfully utilised the extra water to cultivate high-value crops and sell surplus in the accessible markets, while in Igoo, attempts at diversification were less successful or constrained by factors such as inputs, knowledge, and connections to markets. As highlighted in the existing literature, integration into markets is essential for building resilience within farming communities, allowing them to adapt to changing conditions (W. Adger, 2000).

Neither village experienced an increase in non-farm income directly associated with AGs. Tourism did not develop around AG sites, and compensation for construction and maintenance reached only a small number of households, those who work for NGOs or private organisations. This is important because resilience improves when income sources are diversified (Maclean et al., 2014). Unless AGs are integrated into wider development initiatives such as eco-tourism, homestays, ice cafés, ice climbing, or market support for agriculture, their benefits will remain largely concentrated in farming and thus more vulnerable to climate-related risks (Kandari et al., 2022).

In simple terms, AG alone does not ensure improved livelihoods. To transform AGs into potential benefits, it is essential to have the right infrastructure (such as zings) and additional support in the form of knowledge about crop selection, as noted by the respondent from LNP (Copeland et al., 2020). Farmers also require access to seeds and markets. When these elements are lacking, initiatives may result in more water, but the same outcomes. It is clear AGs should be integrated into a broader system that combines water storage infrastructure, distribution, agronomy support, and market mechanisms to have broader economic outcomes (Maclean et al., 2014).

Summary of discussion for RQ2

Artificial glaciers (AGs) improved agriculture where water was timely, well-stored, and could be converted into higher-value crops. In Ursi, these conditions led to increased yields, crop diversification, and higher incomes, while in Igoo, benefits were limited due to inconsistent water supply, poor storage, and weaker market access. Pre-existing water sources and infrastructure (AGs) placement also influenced outcomes. Neither village saw any non-farm income gains, highlighting that without integration into broader economic diversification, AG benefits remain concentrated in farming.

6.3. Discussion on Governance

The governance landscape for AGs reveals a major disconnect between how water interventions should be managed and the way they are currently administered. The study identified two approaches, like community-led models, where villagers make 80% of the decisions, and organisation-led models that rely on formal committees as intermediaries. Meanwhile, government involvement remains minimal, primarily focused on funding through standard tender processes. Traditional churpon systems continue to oversee day-to-day water distribution, regardless of the external model employed. However, across all approaches, major gaps in monitoring exist, along with a lack of standardised methods for measuring outcomes and no central database to track effective practices. This results in decision-making based on incomplete information, making it nearly impossible to learn and adapt across different sites.

The tendering system reveals a deeper problem as the government treats AGs like typical infrastructure projects, such as roads or pipelines, focusing on physical deliverables rather than outcomes. As one interviewee mentioned, when early AG pioneer Chewang Norphel's structures were built, "the tender was about building rock walls. It did not mention ice anywhere. So, what happened is rock walls were built, but ice did not form" This shows how systems designed just for the sake of infrastructure fail when applied to climate interventions that depend on various complex socioecological components. AGs success depends on site-specific variables that do not fit standard procurement frameworks. Another factor is accountability, which pushes implementers toward measurable deliverables rather than uncertain outcomes. It is easier to report "X rock walls built" than "Y litres of ice formed that melted at the right time to help Z farmers". When funding is limited and donors want visible results, there is a strong motivation to focus on construction completion rather than long-term water security. This also explains why monitoring remains weak; tracking actual water outcomes requires sustained observation over multiple seasons, which does not align with project timelines.

Collaboration among different actors is crucial for the success of AG projects. Government agencies hold regulatory authority but have limited presence in the field and little understanding of village-level realities, while NGOs and private organisations bring technical expertise but lack sufficient resources (or funding). Residents do not have the capacity to manage projects independently and are often excluded from key decisions, which are typically made by external bodies. To improve outcomes, communities should be empowered with greater authority and involved throughout all stages of the project. This emphasises the importance of collaboration and engaged governance in developing better solutions (Maclean et al., 2014).

What should be done?

To strengthen the effectiveness of artificial glaciers (AGs), monitoring and evaluation should be integrated into every project through standardised methods for measuring the volume of ice and meltwater obtained from each glacier. Establishing a centralised database with real-time project details would improve transparency. Accountability can be strengthened by combining community-based monitoring and organisational self-reporting with audits conducted by independent institutions. Alongside, AG governance should operate within a formal UT-level policy framework supported by established institutions and guided by principles of adaptive governance and collaborative governance, as noted by the LNP respondent (Berkes, 2009; Janssen & van der Voort, 2016; Kumar & Saizen, 2023; P. Olsson et al., 2004). As stated by Janssen et al., a core component of adaptive governance is learning; similarly, AG management should transition from a project-delivery focus to a learning-oriented approach through systematic documentation of successes and failures, structured knowledge exchange, and engaged governance with policy measures that prioritise adaptation (Janssen & van der Voort, 2016).

Summary of discussion of RQ3

Overall, the governance of AGs faces challenges due to weak monitoring, unclear responsibilities, and a tendering system that treats them as standard infrastructure rather than adaptive climate interventions. Strengthening their effectiveness requires standardised evaluation methods, a centralised database, and integration into a formal policy framework, alongside adaptive governance and collaborative governance and continuous learning that prioritises outcomes over deliverables.

6.4. Is social resilience achieved?

The thesis aimed to understand whether AGs improved social resilience or not by employing the six-attribute framework. The findings indicate that social resilience has been achieved more in Ursi than in Igoo, as shown in Fig. 8. In Ursi, adaptive capacities have evolved over time through continuous community learning, peer-to-peer knowledge exchange, and integration of AG practices into existing water management systems. The community's ability to self-organise labour and incorporate new techniques reflects an active process of adaptation. Over time, AGs have also become part of their local identity with some spiritual connection, showing that the community has not only adapted but also changed the way it organises and relates to AGs. This merging of technical and cultural adaptation shows a transition from short-term coping to long-term transformation. Although the change has not happened at a governance level, it suggests that Ursi displays not only adaptive capacities but also some signs of early transformation (keck & Sakdapolrak, 2013).

In Igoo, social resilience has been partially achieved. The AG project has provided an additional water source; however, adaptive capacities remain weak due to limited training, low participation, and an over-reliance on external organisations. Knowledge transfer has also been insufficient. As a result, and because the benefits are not distributed equally across different parts of the village (upstream, downstream and midstream), the AGs might not have lasting change. While the community has the capacity to cope, it has to establish the learning systems or strong networks necessary for long-term adaptation and transformation (keck & Sakdapolrak, 2013).

Overall, the comparative analysis indicates that social resilience is an evolving and ongoing learning process that enables communities to adapt and transform in the face of challenges (P. Olsson et al., 2004). Igoo's experience shows that the potential for adaptation and transformation remains limited without proper community ownership and continuous learning. Therefore, AGs can strengthen social resilience effectively only when they recognise and address the underlying social and institutional frameworks that govern water use (Folke, 2003; Maclean et al., 2014).

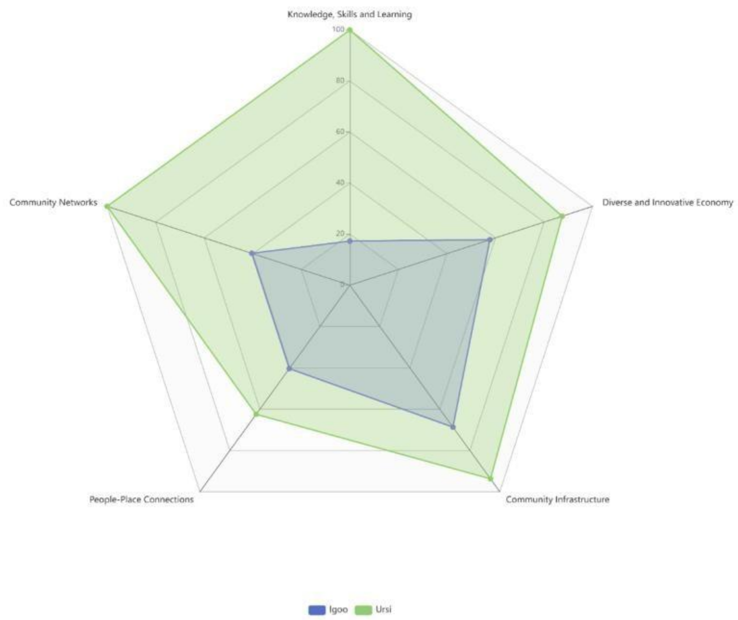

Fig. 8: The figure illustrates the adaptive capacity of the communities in Ursi and Igoo[9] (Source: own figure)

6.5. Limitations and Future Research

The research faces several limitations that must be acknowledged. The use of convenience sampling, though practical under challenging field conditions, may have introduced bias and limited representativeness (Golzar et al., 2022). Temporal constraints further narrow the study's scope, as data were collected over a brief two-month period. This short timeframe restricts the ability to capture

[9] A radar chart was created by normalising the data to 100% for each village (8 surveys for Ursi and 52 for Igoo). One indicator was used from each attribute: Knowledge (Village confidence in construction and maintenance of AGs), Community networks (no conflicts in water sharing), People-place connections (Spiritual significance towards AGs), Community infrastructure (Improved water availability from AG), Diverse economy (Increased income through AG). All attributes try to show adaptive capacity in varying degrees (eg, knowledge high implies high adaptive capacity and so on)

seasonal variations in social dynamics, water availability, and community engagement with artificial glaciers. The absence of longitudinal data limits insights into long-term patterns of social resilience and adaptation.

The study's geographic focus on two villages in Ladakh further limits generalizability. With more than 80 villages in the region employing diverse models of artificial glacier adoption (including NGO-led, privately managed, and hybrid approaches), the results may not fully reflect the range of community experiences across Ladakh, as my experience was only in two villages that adopted AIRs. Additionally, language barriers encountered during data collection, involving translation between English, Hindi, and Ladakhi, may have led to a loss of meaning or led to misinterpretations, particularly regarding people-place connections and spiritual aspects (van Nes et al., 2010). Finally, the study lacks quantitative water measurement data at the community level, relying primarily on organisational estimates and community perceptions of water availability changes.

Future research should focus on long-term, broader studies to gain a better understanding of how AGs influence social resilience over time. A longitudinal study that covers multiple seasons and years would effectively capture changes in water availability, participation, and income that a short-term study cannot. Additionally, expanding the research to include more villages across Ladakh representing different models, such as NGO-led, community-managed, private-led and hybrid models, would provide a clearer picture of how governance systems and social contexts shape adaptive capacities. Such a comprehensive study should incorporate data from quantitative hydrological measurements alongside community perceptions.

It should also explore the social and cultural dimensions of AGs more deeply, including the roles of language, belief, and spiritual connection in shaping community engagement. Using participatory and ethnographic methods would help get deeper insights into local perceptions and values that influence adaptation. Finally, research should examine how policy frameworks and institutional support can strengthen adaptive and transformative capacities at the regional level. By combining social and policy perspectives, future studies can help design AG initiatives that are both effective and culturally grounded, contributing to improving climate resilience in mountain communities.

7. Conclusion

This study aimed to examine how artificial glaciers influence the social resilience and livelihoods of local communities in Ladakh. The research focused on the villages of Ursi and Igoo and utilised a six-attribute resilience framework. By comparing the two villages based on community characteristics, livelihood outcomes, and governance structures, the study sought to understand the conditions under which artificial glaciers can contribute meaningfully to climate adaptation in high-altitude arid regions

Key findings indicate that the impact of AGs depends on existing social and governance structures. In Ursi, strong social cohesion, effective informal knowledge systems, and cultural integration of AGs led to widespread participation, improved water availability, increased agricultural productivity, and higher household incomes, ultimately strengthening social resilience. In Igoo, the experiences are more limited due to more external influence, partial knowledge transfer, dispersed settlements, and insufficient water infrastructure (zings). While some improvements in agriculture were noted, social cohesion and community ownership remained weaker, resulting in only partial resilience.

The results underscore that technological interventions like AGs cannot achieve their full potential in isolation. Their effectiveness depends on the alignment of local knowledge, social networks, cultural acceptance, improved infrastructure and adaptive and collaborative governance frameworks. The study also highlights critical gaps in monitoring, evaluation, and formal policy integration that affect their effectiveness and future learning. By addressing these gaps and making it culturally sensitive, AGs can be more effectively leveraged to enhance both water security and social resilience in high-altitude communities.

In conclusion, this research suggests that artificial glaciers have the potential to serve as a climate adaptation strategy in Ladakh and beyond, but their success depends on combining technical innovation with increased monitoring, the establishment of a centralised database, and integration into a formal policy framework. Additionally, engaging people with capacity-building programs and connecting AGs to local cultural traditions. By integrating local knowledge, strengthening community bonds and governance, AGs can not only support water resources but also act as a medium for building resilient and adaptive communities in the face of climate change.

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Appendix

Appendix-1

Interview Guide

1. Can you introduce yourself? could you please share a bit about your organisation's work in artificial glacier projects?

2. What are the key lessons learned over the years in building AG, starting from Norphel's introduction of the Ice Stupa to now?

3. Are artificial glaciers formally recognised (or have some policy backing) in water management policies (at the UT level), or is their implementation mostly NGO-led?

4. Have you encountered any bureaucratic challenges, such as delays in funding, permits, or policy restrictions? Or resistance from local communities about AG projects? how did you address these challenges?

5. How do you engage or make sure local communities are involved in the decision-making process when implementing artificial glaciers?

6. What kind of collaboration exists between your NGO and government agencies on water security initiatives? (beyond AG)

7. Do you receive financial or technical assistance from the government, or is your work independently funded?

8. If there was a collaboration with the government in the past, what are the challenges your org faced?

9. What do you think should be the role of scientific institutions or universities in research, innovation, or technical knowledge to improve artificial glaciers?

10. Are there any formal mechanisms in place for monitoring and evaluating the success of these projects over time? If not, what can be done to improve transparency and accountability?

11. How can AGs be included in policy-making? What should we keep in mind when creating a policy? (Can the introduction of a subsidy or any incentives can play a role?)

12. In your opinion, should artificial glaciers be community-managed, NGO-driven, or government-led? (What kind of governance model works? collaborative or polycentric governance)

13. If artificial glaciers were to be institutionalised as a water conservation strategy at a UT level, what other governance mechanisms would be necessary? (or should be declared as a national policy - by bringing the central govt into the picture)
14. Should water conservation go beyond AGs, by providing knowledge to communities on waterefficient crops, drip irrigation practices etc?

Appendix 2

Household Survey

Household survey (Ice structures) - Ursi

We are committed to protecting the confidentiality of all information gathered during this study. All data will be used exclusively for academic research purposes, ensuring it remains secure and anonymous. Before you proceed with the survey, we will obtain your informed consent, which means you will be fully aware of the study's aims and methods. Participation is entirely voluntary, and you may withdraw at any time without any consequences.

1. Name

   ____

2. Age & Gender

   ____

3. Occupation

   ____

4. Years of residency in this village

5. Has there been any change in the area due to climate change? (Understanding of snowfall, water , temp, & Glacier receding)

6. Do you know ice structures? If yes ? How did you first learn about Ice structures?

Mark only one oval.

- Through elders
- Local NGOs
- Community members
- Govt
- If other (please specify)

7. Is the concept of ice structures new or part of the traditional knowledge in storing winter water? (Ancient/new)

8. Do you or anyone from your family participate in the construction of ice structures?

Mark only one oval.

- Active Involvement
- Occasionally involved
- Not at all involved

9. Have you received formal training on ice structures construction or maintenance?

Mark only one oval.

- Extensive training received
- Limited training
- No training given

10. Are Ice stupas a topic of discussion in community?

Mark only one oval.

- Yes, informal discussions
- Yes, village meetings
- No

11. How confident is the village in constructing/maintaining an ice structures without external support (NGOs/govt)?

Mark only one oval.

- Confident enough to maintain
- Lack of knowledge- but if given, can construct
- Lack of equipment - but if given, can construct
- Lack of Funding- but if given , can do
- Not confident

12. Have you ever received knowledge on utilizing glacier water effectively? (e.g., drip irrigation, water-efficient crops etc.) The question focuses more on water conservation practice in general for people

____

13. Who in the community is primarily responsible / supports the maintenance of artificial glaciers?

Mark only one oval.

- Community members collectively
- NGOs
- Government agencies
- Voluntary participation by the community
- If other (please specify)

14. Do you believe the community should be primarily responsible for maintaining artificial glaciers?

Mark only one oval.

- Yes, it should be a local effort
- No, external agents should maintain
- It should be a combined effort
- Don't Know

15. Do you think artificial glaciers in any way improved community cooperation in water related Issues?

Mark only one oval.

- Significant improvement
- Little improvement
- Not improved
- Worsened (due to conflict in water sharing)

16. Does your community have a system to resolve conflicts regarding water sharing/distribution issues?

Mark only one oval.

- Conflicts happen, resolve through community meetings(Churpon)
- Conflicts happen, we cooperate informally
- Conflicts are common, but no mechanism
- Don't know
- No conflicts

Section 3: People Place connection & cultural significance

17. Do you have a feeling of sense of belonging to the place where you live?

Mark only one oval.

- Community bonding
- Place identity
- Place dependence
- Nature bonding
- Land ownership
- No

18. Are artificial glaciers important to your village's identity?

Mark only one oval.

- Yes
- No
- Somewhat

19. Does AG hold any cultural or spiritual significance? Why?

20. Do you think constructing AGs violates the sacredness of the place?

Mark only one oval.

- Yes, it violates the belief
- Yes, against the belief and should not be constructed
- No (as it has a practical use)

Section 4: Community Infrastructure

21. Have AG improved water availability in your village?

Mark only one oval.

- Significantly improved
- Slightly improved
- No change
- Worsened

22. Has the accessibility to water changed since the introduction of AG?
How far do you walk to get the water ? - ?? diff btw women and men

Mark only one oval.

- Yes, shorter distance to get the water
- Not improved
- Worsened (even far)

23. What impact did the AG had on local agriculture?

Mark only one oval.

- ⬭ It extended the farming season
- ⬭ Increased agricultural yield
- ⬭ Helped in trying new crop varieties
- ⬭ No noticeable change

24. What other aspects of livelihoods have been improved due to AG

____

____

____

____

____

25. Does water availability helped to diversify the crops?

____

26. Are there any existing local storage systems to store the water from AG?

Mark only one oval.

- ⬭ Yes, Zings are in place
- ⬭ Other water storage systems (like tanks or other)
- ⬭ No

27. What infrastructure improvements would help you better utilise the water from artificial glaciers?

28. If there is extra water, what do you plan to do with it?

Section 5: Diverse and Innovative Economy

29. Has the availability of water from AG improved your income? (Agriculture)

Mark only one oval.

- Significantly
- Slightly
- No change
- Reduced (compared to previous decade)

30. Has AG impacted non-agricultural economic activities, thereby improving income?

Mark only one oval.

- Tourism
- Other local industries
- Construction of New hotels
- Livestock productivity
- If other (please specify)
- No

31. Did you receive any additional income from the government or NGOs to maintain or construct the AG?

Mark only one oval.

- Yes
- No
- Maybe

32. If crop yields have increased due to AG, are there any new markets to sell the produce?