Ladakh's Artificial Glaciers, Ice Stupas, and Human-made Ice Reserves

By Sierra Gladfelter
Fulbright-Nehru Student Research Scholar
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Photo by Eben Yonnetti.

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sierragladfelter@gmail.com

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I. Introduction

This is an illustrated review of Ladakh's artificial glaciers (AGs), Ice Stupas (ISs), Artificial Icefall Glaciers (AIGs), and other ice harvesting technologies based on four months of research conducted in villages of Leh and Kargil Districts during a one-year Fulbright-Nehru Student Research Fellowship in India. During this fellowship, I conducted extensive interviews with 30 diverse NGO staff, government officials, engineers, and scientists in order to understand the complex dimensions of climate-exacerbated water scarcity in Ladakh and the role of various ice harvesting interventions.

I also engaged in extensive participant observation with NGOs, helped to construct the IS alongside the project team, and assisted two NGOs in conducting feasibility studies in four villages where they were planning to build AGs in the future. I also conducted independent research in villages benefiting from existing AGs through four research trips to two regions of Ladakh along the Indus River. On these trips, I trekked to AGs above 10 villages, visited three recently constructed AIGs, and photo documented the IS at various stages of formation and melting. I also conducted over 90 in-depth interviews and eight focus groups with villagers directly benefiting from AGs.

Figure 1. Author, Sierra Gladfelter, takes field notes while visiting Likir's artificial glacier. Photo by Eben Yonnetti.

This illustrated report provides a basic overview of the various types of AGs being built in Ladakh today. AGs are essentially human-made ice reservoirs that take various shapes and rely on different techniques to accumulate ice. All are structures designed with the same goal of mitigating the effects of water scarcity by capturing water during the winter in the form of ice. This ice melts in the early spring to provide irrigation water for farmers prior to the arrival of glacial meltwater in mid-summer. I begin this report with an overview of Ladakhi traditions of snow and ice harvesting that pre-existed and inspired contemporary AGs. I then discuss the four main types of AGs being built today, including their advantages, disadvantages, and future potential. The end of each section has a table summarizing the main takeaways. Finally, I conclude with some general reflections on current efforts to build AGs in Ladakh and offer my own suggestions for how these interventions may be improved.

II. The Roots of Ladakh's 'Modern' Artificial Glacier: Local Ice Harvesting Traditions

While engineer Mr. Chewang Norphel is credited with having invented AGs in Ladakh, in reality these structures are similar to pre-existing Ladakhi traditions of snow and ice harvesting that have been practiced for generations in some water scarce villages. Interestingly, these same villages where AGs were traditionally constructed are also the places where contemporary AGs have been the most successful. As part of my research, I documented many of these traditions in the villages of Phuksey, Igu, Nang, and Sakti, where such practices are either alive or have been practiced in recent memory.

Many of the villages and valleys where the first modern AGs were built had previously built similar structures that villagers referred to alternately as *gangs gag* གངས་འགག་ ('ice block'), *kha gag* ཁ་འགག་ ('snow block), *gyang tsik* གྱང་རྩིག་ ('single wall') or *raks* རགས་ ('dyke' or 'embankment'). Regardless of the name, the structures are essentially the same in design: a stone wall, one rock wide, and up to a meter high built across an alpine stream channel or valley usually at or above 14,000-feet in elevation. In interviews with elderly village residents over 70-years-old, I was told that these stone walls were built above villages for generations and were maintained as part of the collective labor system, similar to the work performed annually to clean out community *yuras* ཡུར་བ་ ('canals') and *dzings* རྫིང་ ('reservoirs').

Figure 2. A few original *gangs gag* or *gyang tsik* remain in the valleys above Phuksey, Shara and Sharnos villages. All photos by the author, Sierra Gladfelter, unless otherwise noted.


Figure 3. This is the remainder of a traditional single-stone wall at the site of the modern AG above Igu.

Residents of Nang and Sakti also described constructing long stone walls (also called *kha gag*) on mountain passes to collect snow blowing in the wind. The walls break the wind, thereby causing the snow to drop and form large snow banks that remain long into the spring. Evidence of such ancient walls can still be seen on Changla above Sakti, as well more recently reinforced walls rebuilt on Warila with funds from the state's Watershed Development Programme.


Figure 4. Original *kha gags* or 'snow block' walls built by villagers on the top of Changla.

Figure 5. These snow walls, though in their traditional location, have been reinforced and enlarged with government funds.

Besides stone walls, Takmachik residents described digging a long canal they call Galjur Yura འགལ་འབྱོར་ཡུར་བ་ (Galjur Canal) on a pass above their village to divert snowmelt from north-facing slopes that accumulate more snow in the winter and would otherwise drain to the less populated village of Urbis. Villagers repair the canal annually so that when the snow begins to melt, it flows toward Takmachik. This snow-harvesting technique is similar to recent government-funded projects on Changla and Warila, to divert snowmelt from the Nubra/Changtang side to drier villages like Sakti above the Indus.

Figure 6. *Galjur Yura*, maintained for generations as a method for diverting snowmelt from the snow-covered mountain slopes above Urbis to more water-scarce Takmachik village.


Figure 7. A ‘downstream’ view of *Galjur Yura*, with Takmachik village in the adjacent watershed (over ridge on the right).

Most of these traditional snow and ice harvesting technologies have either died out on their own or were displaced by government and later NGO interventions when the Rural Development Department (RDD) began funding the construction of AGs as part of its Watershed Development Programme in the early 1990s. When Norphel came in 1987 to Nang and nearby Shara to build his first AGs with RDD, villagers stopped building and maintaining their traditional walls almost immediately. From then onward, villagers have come to increasingly depended on outside funds to support the remaking of their traditional *gangs gag, gyang tsik,* and *raks* and to now incorporate crate wire and concrete.

III. Chewang Norphel’s Diversion-Style Artificial Glaciers

When Norphel began experimenting with the construction of AGs in water scarce villages across Ladakh under RDD’s Watershed Development Programme and later LNP, he modified Ladakhis’ traditional ice harvesting systems in several ways. The most significant alteration was his design of a diversion-style AG that enabled the structure to be built outside of the stream channel, on a safer, less flood-prone side of the valley. Using either a gated diversion canal or pipe, Norphel’s design diverts a regulated amount of water from the stream to a series of terraced stone walls.

Figure 8. Built in Alchi in 2017 with funds from the Tata Trusts, this is one of a few diversion style AG functional today.

Figure 9. According to local residents, this diversion-style AG, built above Takmachik village, never functioned due to water loss through the loose stone and sand in this now abandoned diversion canal.

This design requires more engineering expertise, materials, and is therefore more expensive. However, it is less prone to in-stream flood damage or sediment clogging its system during peak summer flows because of its use of a gated diversion canal. Furthermore, this design is supposed to enable more even freezing of ice behind the walls as villagers can control the flow of water with a gate or regulated intake valve. The reality, however, is that adding an intake canal to the design of an AG introduces a set of new problems. One serious challenge is that depending on local soil types, a significant amount of water can be lost through the canal bottom. This is the case with a diversion-style AG built in Takmachik, for example. I also visited several other sites where the projects had completely failed since water never actually reached the walls due to blocked or leaky canals, even after villagers and NGO staff had attempted to patch them with pipes and plastic tarps.

Even in cases where canals are water tight, diversion style AGs require a significant amount of labor and almost constant monitoring throughout the winter as ice forms in the walls. Villagers must form a rotation system or hire a dedicated individual to check the intake canal and keep it free of ice on a daily basis so that water will continue to flow through to the stone walls and form ice. If the water freezes in the delivery canal, it must be broken up with sledgehammers to enable continuous flow to the AG. Moreover, once the water reaches the AG, it must further be channeled to flow over the ice that has already accumulated. If the water burrows under the existing ice, it will flow underneath and fail to form significant ice. To deal with this issue, I witnessed NGO staff at one AG location using soil, bushes, and grass to try to block and redirect the flow of water to encourage freezing over the surface of the AG. All of this requires almost daily maintenance, which is especially difficult to organize when the structures are built up to one thousand vertical meters and many kilometers above villages. For this reason, consistent maintenance throughout the winter tends to be rare and, as a result, the success rate of the diversion AGs is minimal, even among newly constructed structures.

Figure 10. Residents of Likir stand on the concrete edge of the frozen diversion canal to their AG, built in the autumn of 2017 with Tata Trusts' funds, discussing how to manage the blocked flow. Photo by Eben Yonnetti.


Figure 11. A blocked diversion canal at Likir's AG led to little ice forming behind the lowest wall.


Figure 12. One of the greatest challenges that diversion-style AGs face is the almost daily maintenance required to keep water flowing through the canal to the structure and on top of accumulated ice behind the walls.


Figure 13. An NGO worker attempts to get water to spread over the surface of the ice reservoir to promote freezing.

One interesting modification to Norphel's diversion style AG, is a system in Nang that uses a one-kilometer canal to channel water from a stream to a shaded hillside. While residents originally let water flow through and freeze behind rock walls, they found that most of the water disappeared into the loose, sandy soil. Later, they experimented with directing water over the side of a canal so that it would freeze like a waterfall in thick sheets of ice and the stone walls below would capture overflow.


Figure 14. Modified diversion-style AG at Nang where water flows over the edge of a canal and into walled reservoirs.

This design proved so successful that for years Nang residents were mostly happy to maintain the canal and facilitate freezing on a rotation system during the winter. However, warmer temperatures and less snowfall in recent years has led to diminished ice accumulation and villagers describe problems motivating others to properly maintain the canal. Recently, in the spring of 2018, a portion of the canal was wiped out in a mudslide likely caused by overly saturated soil on a loose and alluvial hillside.

Figure 15. Villagers in Nang must manage flows in their irrigation canals throughout the year on a rotation basis.

Figure 16. Damage to the canal due as the ground and frozen ice melted on the hillside, saturating the loose soil.

In Alchi, a more affluent village with an economy greatly supported by tourism, residents decided that rather than relying on collective labor systems or a turn-wise system for maintenance, they would pool resources to hire a Nepali laborer to monitor and maintain the AG and its ice formation throughout the winter months. While this may be a viable and attractive option for more cash-rich communities in the future, it may not be possible in more remote or less affluent villages that still primarily depend on subsistence agriculture and are less cash-rich.

Summary of Diversion-Style Artificial Glaciers

Advantages	• Built outside of the main stream channel, diversion-style AGs are less prone to damage from floods and high summer flows • Can be strategically constructed in shadier places, increasing ice volume • An intake canal and gate enable villagers to control and regulate the flow of water to the AG for more even ice accumulation
Disadvantages	• More expensive and require significant technical knowledge • Harder for villagers to build and maintain themselves • Structures require significant monitoring and maintenance during months when ice is forming • Easy to fail if villagers are not able to visit the site daily to break up ice in the diversion canal • If diversion-style AGs are built in places where the soil is loose and sandy, water may soak into the soil and fail to reach the walls at all
Future Potential	• As climate change threatens to produce more flash floods and cloud bursts in Ladakh alongside water scarcity, diversion-style AGs may become a more adaptive solution and worthwhile investment since they are less prone to damage built outside of the stream channel. • Modifying the design to require less manual labor or to automatically regulate the flow of water to the structure would make diversion-style AGs more viable in villages with insufficient labor. • Alternative structures for maintenance, like pooling village resources to a hire staff to monitor and maintain the structure for critical months during the winter, may reduce failures.

IV. In-Stream Artificial Glaciers in their 'Modern' Form

Although Mr. Norphel's signature project was the more highly-engineered diversion style AG, the reality is that some of his first and most successful structures were relatively low-tech and essentially just reinforced versions of the traditional *kha gags, gangs gag,* or *gyang tsik* that villagers had built traditionally. This type of AG is built as a series of stone walls in a stream channel and sometimes extend along the valley floor. Over time, with new walls added each year during the Watershed Development Programme, AGs at Phuksey, Igu, and Nang, for example, are now between one and three kilometers long and include a dozen to up to 50 separate walls.

Figure 17. The longest and oldest AG, built above Phuksey, Shara and Sharnos villages. While some walls are the remnants of villagers' earlier snow harvesting traditions, most have been rebuilt or reinforced with several iterations of government and NGO funds since 1987.

Figure 18. Igu village's AG built by the Leh Nutrition Project with support from the Tata Trusts. This structure has 24 walls and was built on top of traditional stone walls constructed by villagers over generations.

With funding from the government and the technical advice of engineers, AGs built throughout the 1990s were much stronger than traditional ice harvesting structures with wider, higher and more robust double-layer stone walls. This increased the amount of ice that would accumulate in the structure. In terms of materials, however, most AGs even now are built using local stone and dry masonry construction techniques. It is only in the last few years, that new funders, like the Tata Trusts, have supported the integration of crate wire and even concrete to reinforce stone walls.

Figure 19. Recently constructed (fall 2017) concrete and crate wire-reinforced walls above Phuksey village.

Figure 20. Double-layered stone, concrete and crate wire walls constructed at Likir in 2017 with Tata Trusts funds.

Most villagers believe that concrete makes the walls less vulnerable to damage and also better able to withstand strong currents when snow and glacier discharge greatly increase the flow of streams. Yet, some villagers question whether in the long-term the concrete will be able to withstand Ladakh's winter cold and summer heat and whether, when it cracks, the concrete will actually make it more difficult to repair the walls. For example, if villagers find that a wall fails to accumulate ice, it can easily be disassembled and built elsewhere if it is made of simple stones. Concrete and crate wire, on the other hand, make walls far less mobile. Furthermore, while crate wire generally provides more strength, there also have been instances, like in Takmachik, when a flood carried the entire wire-encased stone wall downstream, rather than causing only minor damage to the upper layer of stones.

Figure 21. A broken wall at the AG above Takmachik, where summer flows in the stream channel rolled the entire wall downstream, shredding the crate wire and spilling out the rock contents.

The reality, however, is that any AG built directly in the stream channel is inherently at-risk to flooding and high-water levels during summer snow and ice melt. While a major flash flood like the 2010 cloud burst that struck Leh and surrounding villages may leave structures damaged beyond repair, one must consider ways to make AGs as resilient as possible to annual high summer flows and designed in such a way that villagers can more easily repair them.

Thus, despite their inherent vulnerability to flood damage, in-stream AGs are now the preferred design of the Leh Nutrition Project, an NGO that has been building AGs under Mr. Norphel's guidance for over 30 years. The current executive director, Mr. Eshey Paljor, expressed that in-stream AGs have the greatest capacity for success because even if certain portions of the stone walls become damaged they will still accumulate some ice and can contribute to the broader formation of frozen valleys. Phuksey, for example, has over 40 walls above it. While some of these are not functional or are operating at only a portion of their potential capacity, combined together they still enable significant ice formation and can easily be extended or modified with additional walls. This is in contrast to a diversion-style AGs that accumulates little or no ice if there is a failure along the intake canal and that is often more limited in scale due to topography and local geography.

Figure 22. When AGs are made with local stone, like this wall above Phuksey, it is somewhat easier to reuse the same materials to repair the wall rather than having to pay for and import expensive cement.

Figure 23. The AG at Stakmo was severely damaged during the 2010 cloudburst that struck Leh and nearby villages.

Most importantly, however, Mr. Paljor asserts, is the difference in terms of maintenance between in-stream and diversion style AGs. The reality is that as agriculture becomes less economically viable and rates of rural-to-urban migration increase, it is increasingly difficult to mobilize people and inspire labor to maintain and monitor AGs of any type. People do not want to or cannot spend hours each day (or even once a week) climbing up to 1,000 vertical meters to check on intake gates and break up ice in canals. It is difficult enough to inspire people to rebuild damaged walls after summer floods and high flows. Most villagers now expect payment from an NGO or the government for such work. In fact, I only found one village where people still claimed to voluntarily go to make annual repairs to their AG even without compensation. Thus, designing structures based on the reality of changing labor systems in Ladakh is increasingly necessary if AGs are to remain a viable solution to water scarcity.

Figure 24. A downstream view of the damage to Stakmo's AG and scouring of the stream channel.

Figure 25. Although partially damaged, this wall continues to accumulate ice even at a fraction of its full capacity.

Summary of In-Stream Artificial Glaciers

Advantages	• Relatively low-tech and easier for villagers to build and repair • Easy to extend these AGs for several kilometers by adding more walls upstream or downstream • Possible to reassemble walls in new places should they fail to accumulate ice • Even if damaged, walls continue to capture ice, even if at a lesser capacity
Disadvantages	• Structures are highly at risk to floods and damage due to peak summer flows as ice and glaciers melt in the mountains • Require frequent repairs, which is not always possible as many villagers will not take this initiative on their own without funding from external institutions • When crate wire is used to reinforce walls, it can also exacerbate damage by pulling the whole structure over in a flood
Future Potential	• In-stream AGs can easily be extended, modified and rebuilt as local hydrology changes. Having several kilometer long human-built ice reserves like the current in-stream AGs in Phuksey, Igu, and Nang may become increasingly necessary for famers as climate change alters precipitation and levels of winter snowfall.

V. Vertical Innovation: Sonam Wangchuk's Ice Stupa Project

Although not as old or widespread as Norphel's AGs, the most well-known AG currently in Ladakh is Mr. Sonam Wangchuk's Ice Stupa (IS).

Figure 26. Here a local elementary school has come for a tour and presentation by the IS team.

The name of this ice reservoir comes from its conical shape, which resembles a traditional Buddhist *stupa* or reliquary mound, and can be built at lower elevations since it allegedly melts slower than terraced AGs due to its shape and smaller surface area. After constructing a prototype in the winter of 2013-2014, Wangchuk's work was recognized by the Tibetan Buddhist leader, HH Chetsang Rinpoche, who offered his support and land near Phyang Monastery for a scaled-up version. The next year, Mr. Wangchuk and his team constructed a larger IS near Phyang village.

Figure 27. Double ISs sit above a plantation of 5,000 trees owned by the monastery that the structures irrigate.

The IS is made by diverting stream water through a 2.3 kilometer-long, 11-inch pipe to the project site at a lower elevation expanse of desert. Here a dome-shaped structure fashioned of willow boughs, plastic PVC pipe, local shrubs, string, netting and wire is used to create the foundation.

Figure 28. Site of the IS during initial stages of construction as the structure is being built.

Figure 29. The first stage in construction is to build a frame which can support the initial structure until ice accumulation enables it to support its own weight. The hollow core also allows new sections of pipe to be added.

Figure 30. Local materials like thorny seabuckthorn accelerate ice formation as water coats it. Other materials that the IS team has experimented with to increase surface area of the base structure include netting, barbed wire and razor wire.

The elevation gradient between the source and stupa site creates enough pressure to eject the water through a pipe to a vertical sprinkler system. The pipes have valves that are turned on at night and off during the day to promote maximum ice accumulation on the underlying structure. Ice formation occurs approximately from late November until the end of February, while melting begins in March as temperatures rise. IS Project staff estimate that each stupa contains up to two million liters of water.

Figure 31. Inside the dome of an IS, new sections of vertical pipe are added to increase its height. Issues with frozen and bent pipes, however, are also some of the greatest challenges to the project and require a full-time team working all winter.

Figure 32. By early May, the IS has already melted considerably, revealing thick layers of ice.

Compared to AGs, which are often far removed from villages and less visible, the IS has received a huge amount of international media attention as well as coverage both within India and Ladakh, as well as internationally. For this reason, it has been quite successful at raising global awareness and has also worked extensively to share with Ladakhis and Ladakhi school children the impacts of climate change. Further, the IS has invested a lot of time and money into research, data collection, and experimentation to develop a prototype over the past four years that is the most efficient and sustainable. This kind of iterative experimentation, systematic monitoring, and troubleshooting to improve design is unfortunately lacking in most other NGO interventions to build AGs in Ladakh both due to funding constraints and human resources at the organizations themselves.

On the other hand, the greatest limitation of the IS is the fact that until this year, it has not directly benefited local farmers as it has been built at the same site in the village of Phyang where it irrigates the monastery's tree plantations. This, along with the IS's diversion of discharge out of the stream to the project site, has created conflict particularly among villagers of Phey located directly downstream who depend on the same water to irrigate their fields. This tension is exacerbated by the fact that, as it currently stands, the IS is too expensive and labor intensive for villagers to realistically afford and maintain themselves. After all, the IS currently employs a full-time team of eleven people who live on site to maintain, monitor, and troubleshoot issues like frozen pipes over the five-month winter. While the IS Project envisions its work and the various prototypes it is developing in Phyang to eventually enable a stream-lined (and even automated) version of the structure to be built in villages across Ladakh, this future is still a long way off.

Summary of Ice Stupas

Advantages	• The IS can be built at lower elevations, making it more accessible and closer to farmland when it begins to melt in the spring • The IS team has dedicated significant time and resources into research, monitoring, and experimenting with local and lower cost materials to make construction more feasible for villagers • The IS has been extremely effective at raising awareness about the impacts of climate change in Ladakh and inspiring people to take action
Disadvantages	• Extremely expensive to build in terms of materials and requires a significant amount of technical skill to set up • Highly labor intensive, currently relying on a full-time team of more than 10 staff to regulate pipes and ice accumulation • Until now, the IS has not directly benefited many villagers or farmers and has even exacerbated tensions over water sharing in communities
Future Potential	• If the IS can be modified and innovated to cost less and require less maintenance, it may become a scalable solution for water scare villages across Ladakh. In the meantime, it is raising a significant amount of awareness and generating new creative ideas in Ladakh like the 'Artificial Icefall Glaciers' discussed below.

VI. Frozen Ice Walls and HH Chetsang Rinpoche's 'Artificial Icefall Glaciers'

The most recent innovation to Ladakh's AGs and ice reservoirs is the 'Artificial Icefall Glacier' (AIG) which is currently supported by HH Chetsang Rinpoche and executed in three villages of Ladakh's Sham region by two of his monks from Lamayuru Monastery. Compared to Mr. Norphel's diversion-style AGs and Mr. Wangchuk's Ice Stupa, these structures are much less expensive and technical, involving little more than a pipe laid out for several hundred meters to just over a kilometer between a spring and a shaded cliff. The water directed through the pipe and sprayed down a cliff wall to form a sheet of ice, resembling a frozen waterfall. First built in Kuksho village in the winter of 2016-2017, the project was expanded in 2017-2018 into Atitse and Henisku at the request of local villagers.

Figure 33. The site of the first AIG above Kuksho was chosen in 2016 by HH Chetsang Rinpoche in consultation with monks from Lamayuru Monastery and villagers. The shaded slopes of this ravine receive little sunlight in the winter, making it an ideal location for ice formation. Nearly 100 meters tall, this structure depends on spring water piped one kilometer from late October to March when temperatures remain below freezing.

One of the most appealing things about this technology is that it is both low-tech and low cost, making it more feasible to be managed by villages and even reproduced in other communities without the financial support and intervention of outside institutions like the government or NGOs. For example, while in-stream or diversion style AGs cost several lakh Indian rupees on average for materials and labor, AIGs can be built for as little as 15,000 rupees using pipes available in local markets and villagers' knowledge of local topography and hydrology. Unlike diversion-style or instream AGs, they are also not at-risk to flood damage. While there have been instances where a small avalanche or rock slide dislodged the pipe for a few months, the flexible nature of the pipe makes AIGs inherently resilient. Not only can the end of the pipe be moved along the cliff to enable a large expanse of ice, if there is disturbance to the pipe, it can usually be recovered and buried again the same or the following year. Thus, besides an initial investment in a pipe, the only real cost is labor, either paid or in-kind.

Figure 34. The AIG at Atitse was first built in the winter of 2017-2018. The flexible nature of the plastic pipe enables the position of the water outlet (visible upper left), to be changed every 10 to 15 days to promote greater coverage of the cliff.

Figure 35. At all sites where AIGs have been built, pipes were buried to provide insulation and mitigate blockage. Here in Henisku where the pipe crosses a small stream, it has been wrapped in cloth and foam.

The reality, however, is that the monitoring and maintenance of these structures can be demanding particularly during winter months as the ice wall is forming. In all three villages where AIGs have been built, designated representatives must go almost daily to check that water is continuing to flow and that the pipe has not frozen or been damaged. One of the drawbacks of using a less-expensive, smaller gauge pipe (AIGs use pipes that are a few inches in diameter compared to the IS's 11-inch pipe), is the greater risk of freezing particularly during particularly cold spells or if the flow of water is disrupted by a pinched pipe or some other disturbance. Furthermore, if the whole system gets backed up and freezes solid, villagers may have to abandon the entire project until the pipe thaws on its own. In Kuksho village, for example, where an AIG has been built for two years, villagers have had to deal with both frozen pipes and small avalanches wiping out the pipeline between the spring and project site. If villagers are able, they dig up buried pipes to try to identify the blockage or lay new pipes, but depending on the weather and snowfall the project may have to be abandoned until spring.

Another issue is that for effective surface ice accumulation, AIGs require the right combination of rock and soil type. Villagers in Henisku, for example, found that without a solid rock wall to pipe their spring too, most of the water simply soaked into the ground and did not form ice on the surface. Furthermore, the ice that did accumulate mostly soaked into the loose alluvial soil rather than flow into the stream channel below. While there is the possibility that this may have some benefit by recharging local aquifers, the reality is the villagers and monks do not have a clear understanding of local hydrology or geology.

Figure 36. While AIGs have flexibility in their structure, when pipes freeze due to insufficient pressure and low temperatures it can cause a lot of labor for residents. Here a man from Henisku, trekked over 1.5 hours to the site, only to discover the pipe frozen. He must return to dig up several hundred meters of pipe, clear the blockage, and bury it again.

Finally, as with other AGs, there is no simple way to calculate the amount of ice or volume of water preserved in these AIGs for spring irrigation. However, by taking advantage of local topography and shaded cliff sides, AIGs are able to encourage ice formation on both vertical and horizontal surfaces of a valley. Although the vertical ice waterfall is usually most visible and draws the most attention, much of the volume of the AIGs in Kuksho and Atitse is actually in the bed of ice that accumulates in the stream channel below the structures as the water slows and hardens into ice. This indicates great potential for AIGs to be combined with other structures like in-stream AGs to increase ice formation.

Figure 37. Unlike Kuksho and Atitse that have rocky cliffs, Henisku has only loose alluvial slopes. Unfortunately, most of the piped water did not freeze on the surface, but soaked into the ground leading to limited ice formation.

Figure 38. AIGs have great potential to be combined with other AGs like in-stream ones. Here, Atitse's AIG was built above a series of dilapidated rock walls. Even in their current state of disrepair, these walls greatly increased ice accumulation in the valley below and residents are hoping to build more walls in the future.

Summary of Artificial Icefall Glaciers

Advantages	• Relatively low-tech and by far the lowest cost AG, making them feasible for villages to initiate without external support • The flexible nature of the pipe makes it possible to move the outlet along a cliff to accumulate a larger expanse of ice • Resilient to flood or avalanche damage as they are typically located above the stream channel, involve no permanent walls or structures, and the pipe can easily be recovered and reused if an avalanche or rockslide strikes
Disadvantages	• Not all villages can build AIGs, because these structures require a certain topography: shady cliffs with a spring located within a few hundred meters • AIGs can require a significant amount of time and labor to monitor during the months ice is forming. If pipes freeze, which is not uncommon, residents may have to dig up and replace the entire length of pipe to identify and open a blockage.
Future Potential	• Because they are so cheap and easy to construct, AIGs currently have the most potential for replication in many villages without the support of outside institutions. As climate change and water scarcity become more immediate issues, having solutions that villagers can do and manage themselves may be essential. • Furthermore, AIGs have the potential to be combined with other forms of AGs like, in-stream ones, that can increase ice formation and take advantage of both vertical and horizontal surfaces for ice storage.

VII. Lessons Learned and Broader Takeaways for a New Generation of Artificial Glaciers

In this final section, I lay out a few broader suggestions for organizations and institutions currently implementing, innovating, and investing in snow and ice harvesting 'solutions' for water scarcity in Ladakh. I hope that these reflections may inspire new ideas and interventions designed in new ways to better serve Ladakhis and the current climate challenges they face.

1) Build structures that are as low maintenance as possible

Interventions should be realistic about communities' capacity to, and interest in, monitoring and maintaining AGs and should consider this both when selecting a project site and the type of AG. The reality is that across Ladakh, farming is becoming a less desirable source of income for many villagers. Particularly in communities closer to Leh and with more access to its markets, rural to urban migration is high and many men have taken up jobs in the tourism sector as well as supporting service industries. This decreases the amount of labor available in villages for agriculture and supporting maintenance of structures like AGs. Thus, expecting villages to be able to mobilize themselves in a daily rotation system to monitor and maintain gated diversion canals or deal with frozen pipes, particularly if the project site is at a considerable distance from the village, may be unrealistic. As some maintenance will inevitably be required, and most interventions expect this responsibility to be the villagers' as NGOs have limited funds for follow-up visits, keeping designs as simple and easy to manage as possible will greatly increase an intervention's long-term success rate. Furthermore, in communities where people are simply not willing or interested in maintaining structures, developing alternative systems like Alchi has to hire a dedicated individual to maintain the structure throughout the winter may be a more realistic alternative and still enable local investment and ownership through the cash they contribute to this individual's wage.

2) Design interventions to encourage, not displace collective labor systems wherever possible

In communities where collective labor systems for maintaining traditional irrigation infrastructure and any existing snow and ice harvesting infrastructure are still alive, try to design interventions that tap into, rather than displace these practices. Many of the early AGs built by the government and NGO partners in the 1990s and 2000s as part of the Watershed Development Programme directly displaced or eroded communal systems of labor for building and repairing ice harvesting structures like *raks* and *gyang tsik.* In places where villagers continue to maintain structures even during years they do not receive external funding (i.e. Igu, Shara occasionally) or where residents maintain their traditional ice harvesting infrastructure (i.e. Takmachik, Sakti), it is important to understand how these systems work and support and incentivize them rather than unintentionally displace them by promises of intermittent, paid labor. While residents certainly appreciate this opportunity to earn cash, there may be ways to promote more ownership and investment in projects, by for example, asking people as part of a project to dedicate a certain number of days annually to make repairs to existing walls in exchange for receiving continued NGO support and compensation to build a number of new walls each year. This is a challenge that cannot be easily solved, particularly given labor shortages in villages as a growing number of residents shift from strictly agriculture-based livelihoods to other forms of wage labor.

3) Invest in research, monitoring, and knowledge sharing before and after intervention

Most AGs in Ladakh are being constructed without any baseline data on local hydrology upstream or downstream from project sites. This lack of understanding of both local hydrology and geology means that the placement of structures is not very scientific and is difficult to assess the real impacts of the structures. Most implementing NGOs do not have the funds or human resources to revisit project sites beyond the terms of a grant, so even basic evaluation and monitoring of structures is sometimes lacking. This means that both NGOs and villages are missing out, in some ways, on an opportunity to study and learn from the successes and failures of existing AGs in order to design and build more effective structures in the future. While the Ice Stupa Project has employed its team to collect data on temperature, stream discharge, ice formation, etc., as far as I could find, this kind of research is not currently being conducted for any of the other AG interventions. Also, while the Ice Supa Project and the Leh Nutrition Project (the first NGO to build AGs in Ladakh), have experimented with different methods for estimating the volume of their AGs, the reality is that these calculations are extremely rough, indicating that more investment in needed to understand and improve the concrete impacts of all AGs.

At the same time, even more informal lessons learned during design and implementation are rarely shared among NGOs. While the Tata Trusts' recent funding of three NGOs to work collaboratively and divide labor on a new series of interventions has facilitated more engagement, there is limited interaction between the builders of contemporary diversion-style and instream AGs with members of the IS Project and individuals building AIGs in Sham. As there is great potential for various types of AGs to be combined in the same village (for example, Atitse's desire to build an in-stream AG below their current AIG and Takmachik's plan to build an AIG above their in-stream walls), bringing institutions and individuals together that have experience building different style AGs through workshops or exposure visits may facilitate more collaboration. This could ultimately lead to villages having a broader set of options to more effectively cope with water scarcity.

4) Encourage local ownership and innovation of solutions

As highlighted above, many early AGs built by the government and NGOs through the Watershed Development Programme had the effect of making villages more dependent on outside funders to maintain new and existing irrigation as well as snow and ice harvesting infrastructure. While most villages today still practice collective labor systems to clean and maintain their *yuras* (canals) and *dzings* (reservoirs), they do not make repairs to AGs without being paid a wage for their labor. This is a reality that NGOs face and must navigate today when designing interventions. However, there are ways that organizations can design their interventions to intentionally resist creating a greater sense of dependency and reliance on outside funders by promoting local creativity and problem solving. This might mean not only building the most expensive and highly technical AGs, but also investing in smaller scale efforts and demonstration projects (like AIGs) that villagers may be able to do on their own. The IS Project has been most effective at this—inspiring efforts like AIGs in Sham as well as other villagers that are now brainstorming ways they can harvest ice through low-tech means. After all, NGOs and funders have the capacity to take some risks in supporting creative ideas that emerge from within villages, and then study, improve and simplify new designs so they can be replicated elsewhere.

5) Modify current claims and project representation to more honestly reflect reality

One of the greatest issues I found in examining AGs in Ladakh, and particularly the way in which they are being represented and publicized in the media, is the lack of honesty in terms of what these structures are, and are capable of, achieving for Ladakhis. Contemporary AGs, in all their forms, are an example of a locally-rooted adaptation certainly worth celebrating and perhaps even replicating across the Himalayas and in other mountainous regions. However, the reality is that AGs, in any form, melt completely by June or July, for they are designed only to store ice from late November until the spring. In this way, AGs *do* assist Ladakhis in coping with seasonal water scarcity, especially in recent years when there has been significantly less winter snowfall. However, these structures are certainly not *solutions* to climate change nor can they solve scarcity in the long-term as they only preserve, for a few months, water already present in the mountains.

This humility, should be more present in interventions. The Ice Stupa Project, for example, invites visitors on its website to “join Ladakh as it gears up to fight climate change and melting glaciers.” The reality, however, is that AGs are *not* a weapon to combat climate change. Rather they are a way for Ladakhis to partially cope with its most immediate effects and to try to hold on, at least for now, to life in this landscape. Yet, no matter how high-tech or automated AGs become, the reality is that if Ladakh’s natural glaciers continue to melt and the skies refuse to snow, AGs will do very little to secure communities from, let alone undo, an impending climate crisis.

Being clear about this, Ladakhis on the frontlines of climate change should continue to build and innovate AGs to meet their water needs just as funders and NGOs should continue to invest in them. However, it seems to me that some of these interventions might also think more broadly about what climate adaptation is, and could *be,* for communities in Ladakh. While supporting agriculture in villages may certainly be one way to help them adapt to climate change, it is also important to recognize the realities that villages face and are navigating. People, even in remote places, increasingly depend on other forms of labor and income for their financial security. As the labor force in villages decreases and climate change poses new challenges, agriculture may just no longer be viable, at least in the same way that it once was. After all, AGs currently benefit farmers, particularly those investing in cash crops, but the reality is that in many villages most of the population sees their future not in cultivating the land, but rather in Leh. For this reason, it may be necessary to think more broadly about what it *means* to adapt to climate change, and what other means and livelihood options Ladakhis may have to experiment with and cultivate in order to continue to carve out an existence in their home.

Figure 39. Posing with Mr. Chewang Norphel, the inventor of Ladakh's modern artificial glacier, near his home in Leh. Photo by Eben Yonnetti.

Figure 40. My research partner, Chosdup Mehru, pauses during an interview with a resident of Phuksey. Ladakhi elders like her, and those who came generations before them, are the true inventors, innovators, and keepers of Ladakh's AGs.