



Testing Natural Siphon Technology for GLOF Hazard Reduction: Lessons from Thorthormi Glacial Lake



**NATIONAL CENTRE FOR HYDROLOGY AND
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EXECUTIVE SUMMARY

Natural siphon technology is a widely applied method for controlled reservoir drainage and has been recognized globally for its simplicity, cost effectiveness and ease of construction compared to other conventional glacial lake lowering techniques. In this context, the National Centre for Hydrology and Meteorology (NCHM) conducted a pilot test for a natural siphon system at Thorthormi Glacial Lake to evaluate its feasibility as a Glacial Lake Outburst Flood (GLOF) mitigation measure in Bhutan.

The siphon system was successfully constructed; however, sustained flow could not be initiated during the test phase. Post test assessment identified several contributing factors, including an excessive head difference between the lake water level and the siphon apex, complex and unfavorable topographic conditions along the downstream (falling) limb of the siphon and the unavailability of appropriate siphon valves. These constraints collectively hindered the initiation and maintenance of siphon flow.

Given the potential of siphon technology to offer a cost effective and scalable solution for GLOF risk reduction in Bhutan, a second trial is recommended. The proposed trial site is along the existing natural outlet channel of Thorthormi glacial lake where key limitations encountered during the first test- particularly those related to head difference and topographic complexity can be substantially minimized.

The second trial will be implemented in consultation with a Swiss multihazard expert scheduled to visit the site in March 2026 under the collaborative project between NCHM and the Swiss Polar Institute (SPI).

In the event that the siphon technology cannot be successfully demonstrated, NCHM is concurrently strengthening the existing GLOF early warning system in the Puna Tsang Chu basin through the NCHM-SPI project. This parallel effort aims to enhance downstream preparedness and reduce potential loss of life and property in vulnerable communities

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We extend our gratitude to the health assistant of Lunana BHU for his valuable coordination and support during the Glacial Lake Outburst Flood (GLOF) awareness program, particularly focused on women in vulnerable communities in Lunana.

We are equally grateful to the management of the National Centre for Hydrology and Meteorology (NCHM) and the project focal of the RIR Project for their unwavering support during the implementation of field activities in Lunana.

Our heartfelt thanks also go to Mr. Jim Long from Alaska, USA, for his expert guidance in the construction of the siphon system. Mr. Long graciously volunteered his time and expertise, which greatly contributed to the team's effort in testing the siphon system.

The team remains deeply thankful to the people of Thanza and Toenchoe for their support in providing workforce at the project site, as well as to the cooks and helpers who assisted the team throughout the journey and at the site. We also acknowledge the horsemen who managed logistics under harsh weather conditions with utmost dedication.

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Introduction

Thorthormi glacial lake in Lunana is considered to be one of the most critical glacial lakes in the country in terms of Glacial Lake Outburst Flood (GLOF) Risk. The lake is rapidly transforming into a large glacier lake impounded by unstable moraine dams and this process has heightened the threat of GLOF posing significant risk to lives and livelihoods downstream.

Given the severe and escalating threat posed by GLOFs, proactive risk mitigation is imperative; however, conventional approaches present significant limitations. Traditional engineering solutions, such as the construction of permanent drainage tunnels or spillways, are often prohibitively expensive and logistically daunting in remote and high-altitude places like in Lunana, while methods involving controlled breaching with explosives carry substantial environmental disturbance risks and require highly specialized expertise.

It is within this context that testing a natural siphon system offers a compelling alternative rationale. This pilot project is motivated by the need to evaluate a method that leverages simple gravitational principles to create a passive, controlled outflow. The proposed siphon system promises substantial advantages: it is inherently low-cost, utilizes readily available materials, minimizes environmental impact through its non-explosive and low-footprint operation, and offers a scalable, potentially rapidly deployable intervention to incrementally lower lake levels and reduce the hydrostatic pressure on unstable moraine dams, thereby enhancing community resilience through a practical and adaptable tool.

The siphon system presents a suite of distinct advantages for GLOF risk mitigation due to its simplicity. Fundamentally, it operates as a passive technology, requiring no external power source once primed, as it harnesses natural gravitational principles to create a continuous, controlled flow of water from the lake surface over the moraine dam. This reliance on basic physics translates directly to a **low-cost and logistically feasible** intervention, utilizing relatively simple, portable materials like large-diameter pipes, making it accessible for deployment in remote areas where complex engineering is impractical. Furthermore, its operation is characterized by a **minimal environmental footprint**; unlike excavation or explosives, it causes no physical alteration to the fragile moraine structure, avoids introducing pollutants, and creates negligible noise disturbance, thereby preserving the integrity of the fragile ecosystem while directly addressing the hazard.

Despite its compelling advantages, the natural siphon system is subject to significant limitations that constrain its application and effectiveness. Its operational efficiency is highly vulnerable to environmental conditions; freezing temperatures can cause ice blockage in the hose, air ingress from vortex formation at the intake or micro-leaks can break the siphon prime, and floating ice or debris can clog the system, requiring frequent and hazardous manual intervention in a remote, hostile environment. Furthermore, its capacity is inherently limited by physics, as the flow rate is

dictated by the elevation difference from Apex to Water Level, pipe diameter and the vertical drop. These technical and scale limitations necessitate that siphon systems be viewed not as a standalone fix, but as a potential component within a broader, layered risk management strategy for specific, lower-risk scenarios.

Objective

The primary objective of this pilot test is to demonstrate the practical feasibility of installing and operating a large diameter natural siphon system within the demanding constraints of a remote, high-altitude glacial environment. This focus extends beyond merely proving the hydraulic principle of siphoning, to rigorously field-testing the entire operational chain—from the transport and assembly of materials in a logistically challenging setting, to the secure deployment of an intake in a dynamic ice-marginal lake, and the maintenance of a continuous siphon prime across a rugged moraine dam amidst extreme and variable weather conditions. Success is therefore defined not solely by water discharge metrics, but by the comprehensive evaluation of the methodology's robustness, the identification of unforeseen technical and practical hurdles, and the validation of safety protocols, thereby generating critical, real-world data to assess the system's viability as a deployable tool for proactive GLOF risk reduction.

The secondary objective of this pilot test is to move from qualitative demonstration to quantitative assessment by meticulously measuring the system's hydraulic performance under real-world conditions. This involves establishing a reliable monitoring regimen to capture key operational data, specifically the **achieved flow rate** (in liters or cubic meters per second) and the **cumulative total volume of water removed** over the test period. By comparing these empirical results against the theoretical maximums derived from the siphon's design specifications—considering factors such as hose pipe diameter, vertical head, and friction losses—the test aims to quantify the system's actual efficiency and effectiveness. This data is crucial for calibrating predictive models, evaluating the potential impact of a single siphon unit on lake level reduction, and providing a foundational metric for scaling the intervention, such as determining the number of units required to achieve a meaningful risk-reduction target for a given lake.

Besides, this pilot test is to conduct a critical operational examination to identify and document the key technical, logistical, and safety challenges inherent in deploying siphon systems at this scale. This involves systematically cataloguing obstacles encountered throughout the project lifecycle, from the difficulties of transporting bulky materials via helicopter or porter to the site, to the technical intricacies of maintaining a siphon prime amidst freezing temperatures and shifting ice. It specifically aims to pinpoint failure modes—such as Pipe behavior at such environmental conditions, intake clogging mechanisms, or vulnerabilities in the priming process and other logistic challenges at this high-altitude environment. The resulting lessons-learned shall be an essential feasibility filter and planning for larger scale.

Environmental and Social (E&S) Compliance

Throughout the execution of the pilot siphon test, the project team strictly adhered to the E&S risk management instruments a) Labor Management Plan, b) Environmental and Social Management Plan (including a Biodiversity Management Plan), and c) Emergency Response Plan prepared based on the E&S screening. All site operations were conducted in accordance with the approved ESMP. This included the enforcement of safety zoning, mandatory use of personal protective equipment (with the specific, risk-based exemption of helmets, as they did not provide adequate protection from sun and cold), and the implementation of the "Leave No Trace" protocol. All non-biodegradable waste, including HDPE pipe grindings and packaging materials, was systematically collected at the worksite, transported to our site office complex at Thanza. This collected waste is slated to be disposed at the dzongkhag disposal center in Gasa. Biodegradable waste was safely disposed of in covered pits on-site. The Labor Management Procedures were followed diligently, with no underage laborers engaged, daily work schedules adapted to weather safety, and a safety record maintained with zero injuries to the project team or laborers. The Biodiversity Management Plan guided routing and anchoring to avoid disturbance to the fragile alpine vegetation. The pipes were laid along the profile by anchoring on the outcropped boulders. This diligent on-ground compliance ensured that the project's environmental footprint was minimized and occupational risks were managed, fully aligning the field implementation with the pre-approved environmental and social safeguard commitments

Activities

As part of this test siphon activity and leveraging the available resources and time, the team was also tasked to conducting an awareness program on glacial lake outburst flood (GLOF) focusing on women and also to conduct bathymetry survey on Thorthormi glacial lake. The various activities implemented during this phase of the test siphon are elaborated in the following sections.

GLOF Awareness Program

The field team conducted three GLOF awareness program in three major communities in upper Lunana (Tsojong, Toenchoe-Dota and Thanza communities). The program was conducted along



Photo 1: GLOF Awareness Program in Tsojong and Tenchoe-Dota communities

aside with the monthly health checkup program in coordination with the Health Assistant from Lunana Basic Health Unit at their designated Outreach Clinic Centre (ORC). Such an arrangement was made to have a maximum number of participants from the communities. As the season coincided with the barley harvesting season in Lunana, persuading people to participate in such forums was found to be very challenging. Leveraging the available resources during this time the awareness program was organized for all people who came and attended the health program irrespective of their gender. In total **161** people attended the program from three communities, of which **85** were women and rest male.

Bathymetry survey

Bathymetry survey on Thorthormi lake was attempted in the last field activity in the month of May 2025, however due to presence of numerous icebergs floating it was too risky to conduct the survey since the team was using inflatable rubber boats. Taking the advantage of this season during which minimum ice pieces were found floating an attempt was made to survey the entire lake. Since Thorthormi lake has a very large surface area which is about 4.35 km^2 , the survey profile was designed in patches and tried to cover the lake over several days. However, after successfully covering the lower part of the lake, the **measured depth** started to increase above **300 m** which was beyond the depth range of the instrument that the team was using (FISH ELITE SONAR). Therefore, the bathymetry survey was confined to the lower half of the lake and the upper part of lake still remains to be covered.

Lake bathymetry survey refers to the systematic measurement and mapping of underwater lakebed topography to determine water depth, lake volume, and basin morphology. Echo sounding is the most widely used technique for bathymetric surveys. It is based on the **transmission and reception of acoustic (sound) waves** through water. An echo sounder mounted on a boat or remotely operated platform emits a short sound pulse vertically downward into the water column. This pulse travels through the water at a known speed (depending on temperature, density, and

salinity). When the sound wave strikes the lakebed, it is reflected back to the transducer as an echo and the lake depth is recorded. The schematic diagram (Fig..) shows the basic concept of how the bathymetry survey is being conducted.

In mountain regions, particularly in glacial and moraine-dammed lakes, bathymetric surveys are essential for understanding lake dynamics, assessing flood hazards such as Glacial Lake Outburst Floods (GLOFs), and supporting climate change and cryosphere studies. Lake bathymetry survey was conducted on Thorthormi glacial lake to determine and map lakebed morphology and estimate lake volume for providing baseline data for long-term monitoring and risk assessment.

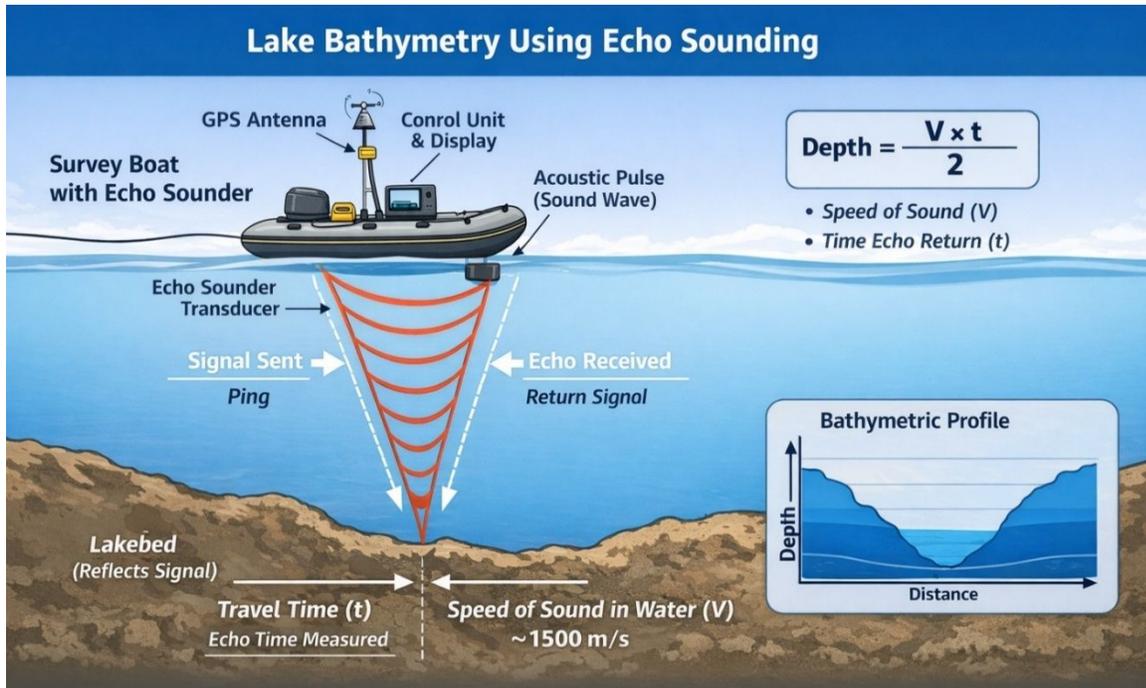


Figure 1: Schematic diagram of lake bathymetry survey

The echo sounder (sonar FishElite) integrated with a Geographical Positioning System (GPS) was mounted on an inflatable rubber boat and survey was conducted by navigating the boat on the glacial lake surface. The continuous lake depth data measurements were georeferenced and recorded on control unit. Several consecutive days of survey attempts were made to conduct a complete bathymetry survey. However, high concentrations of suspended sediments (silt) in the lake water, combined with the lake's large depth range, hindered the instrument's performance and prevented full-depth profiling. As a result, only partial bathymetric mapping was achieved, with a **maximum recorded depth of 326 m** as shown in Figure 2.

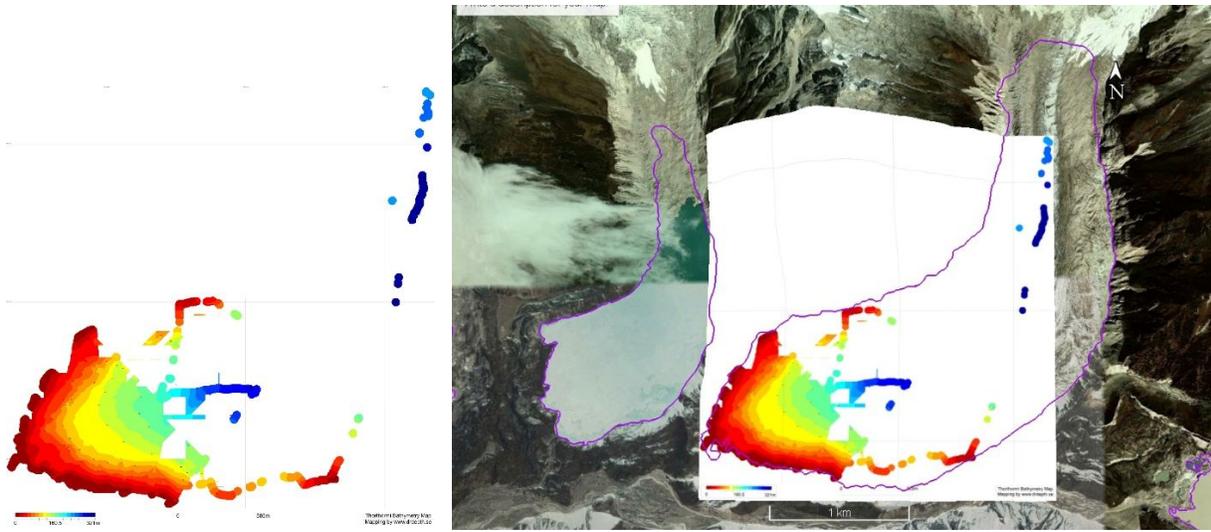


Figure 2: Portion of Lake Bathymetry map of Thorthormi (left) and the same map overlaid on Google Earth image showing the shoreline (purple line) of the lake

Changes at the outlet of Thorthormi main lake and Subsidiary lake I

Thorthormi main lake is separated from the Subsidiary Lake I by moraine which are underlain by ice. This area was observed to be very active since the underlain ice are melting rapidly exposing fresh ice cliffs regularly. As a result, the main lake is expanding downstream towards subsidiary lake I and the Subsidiary Lake is expanding upstream towards the main lake. It is highly probable that the main lake will join with the subsidiary lake I very soon. Infact it was observed that the lakes have initiated merging on the surface (Photo 2)

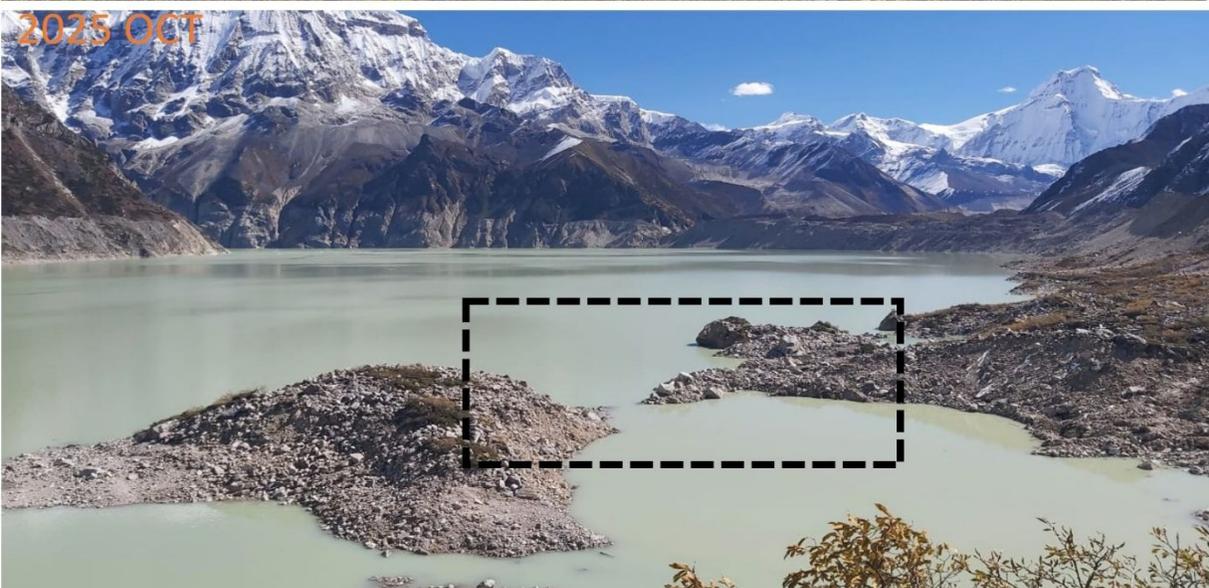
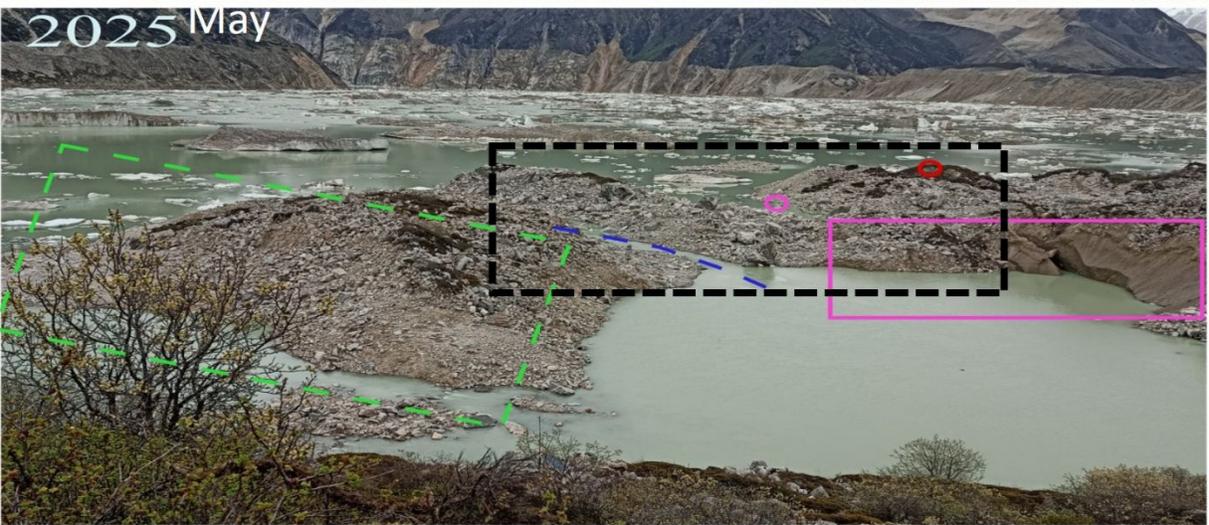
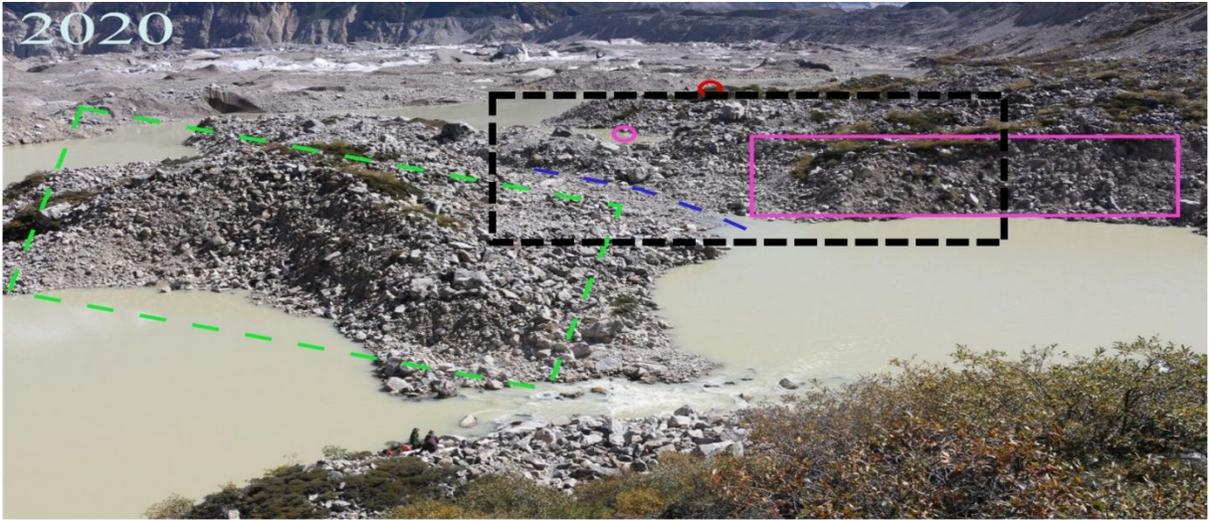


Photo 2: Photos showing are between main lake and subsidiary lake I

Pilot Test of the Natural Siphon

Siphon System Design and Installation:

The system operates on the fundamental hydraulic principle of a natural siphon, where a fluid flows from a higher-elevation reservoir to a lower-elevation outlet through a continuous, primed conduit, driven solely by the gravitational potential energy difference. For successful operation, the entire conduit must first be filled with water ("**primed**") to initiate flow, after which the weight of the water column in the descending leg creates a partial vacuum that draws water over the crest of the moraine dam ("**Apex**") from the lake, establishing a continuous, gravity-driven discharge as long as the outlet remains below the lake's surface level. The key **design criteria** were calculated based on site surveys and hydraulic formulas. A HDPE Pipe **diameter** of 5 inches (125 mm) was selected for the test siphon based on the portability by air lifting (helicopter) to work site and workability. The total **conduit length** was around 750 meters (125 M * 6 m) to safely route from a stable intake point, over the moraine crest, to a secure outflow point below the dam toe at the out-flow channel. The **required priming head initially** (the vertical distance the lake surface must be above the siphon's crest during priming) was 9.711 meters as per the field survey (Fig.3 & Fig.4)

With 9.711 meters of height difference, 125 mm of HDPE pipe a theoretical maximum flow rate (Q_{max}) was estimated at around 14.14 ltrs/sec) using standard pipe flow equations accounting for the measured static head and assumed friction coefficients. However, it clearly indicates that additional frictional losses, intake variables, pipe bends, air leakages and height difference could easily reduce the energy to overcome the pipe friction. As the objective was focused on proving feasibility and operational procedures and maximize water removal for risk mitigation, we went ahead with the pilot testing.

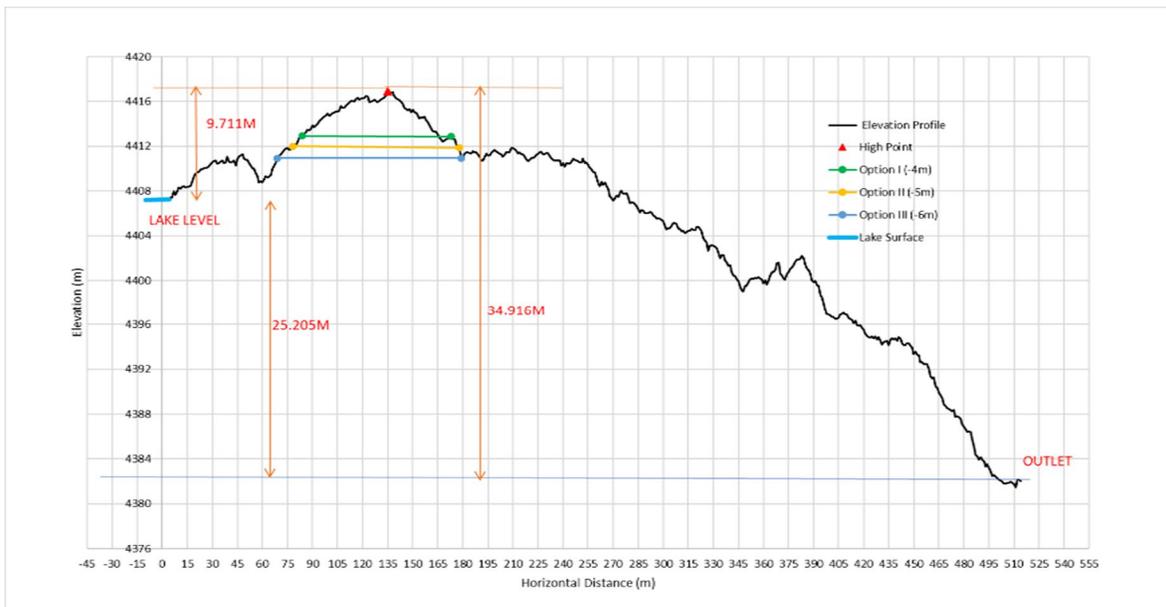


Figure 3: The profile of the site

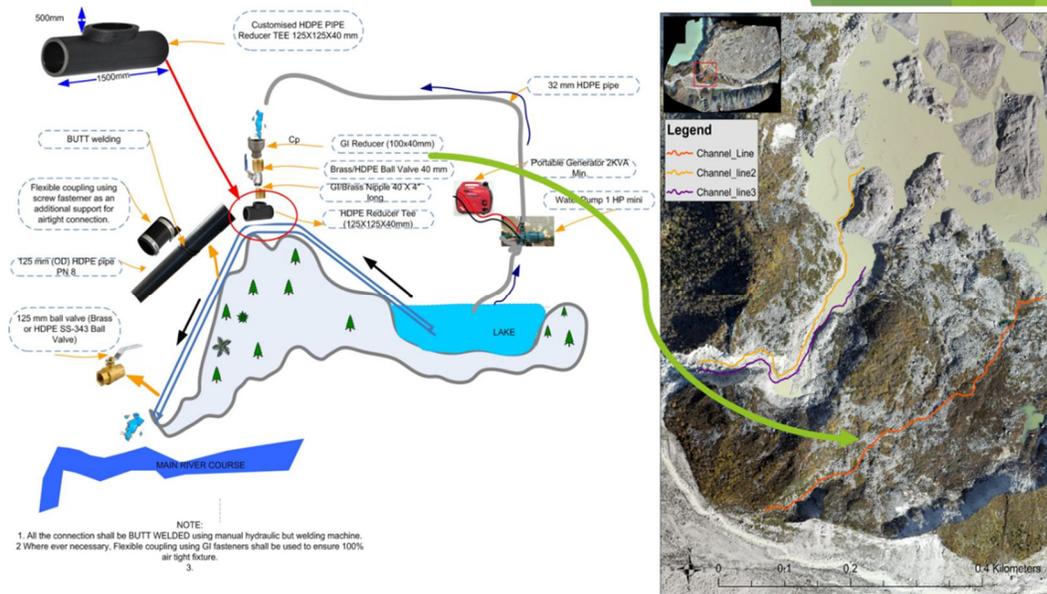


Figure 4. The concept design for project.

Transportation of Materials:

The major components of the test siphon such as HDPE Pipe, Butt welding, Flexi Joints, coupling, were transported using helicopter **slings-loads (Photo 3)** in May 2025. These transported materials were further transported manually from the drop area to the specific Project site. The remaining materials such as cement, tools and plant, protective gears, rations for the project team, valves fuel and others were transported in **August 2025** using ponies.



Photo 3: The Airlifting of the materials for the project.

Installation and Deployment:

The Project Team led by Mr. Karma, Specialist arrived at Thorthomi Base camp by **17th September 2025**. Upon arrival a secure **Base Camp** and a **smaller Worksite Camp (Photo 4)** were established based on stable ground, safety from environmental hazards, proximity of work site and base camp, accessibility to clean drinking water and above all minimal environmental disturbances.

Mr. Sangay Tenzin, Project Engineer along with Mr. Jim Long, a volunteer expert arrived at the site on 19th Sept 2025 via helicopter service.



Photo 4: Base camp and worksite camp

Installation: Pipe laying and jointing:

The laying and jointing of the HDPE pipes constituted a major logistical and technical effort, conducted entirely on the rugged moraine profile. First, all pipe sections were manually unrolled and laid out along the predetermined route from the lake intake to the downstream outlet. The joining process utilized the **butt-welding** technique, where pipe ends are heated with a hot plate and fused under pressure. This work was executed in sections, welding multiple pipe lengths together on stable ground before maneuvering the now-longer, more cumbersome assemblies into their final position along the pre-determined profile. The primary challenge during this phase was **insufficient and unreliable power generation**. The project's 3 KW portable generator **failed**

to work at site upon deployment, necessitating a hiring of a 65-kilogram generator from the Lunana community school, located 3 hours from the site. Transporting this heavy unit to the project site required a team of over ten people, significantly delaying operations. Even with a functional generator, the extreme ambient low temperature at the high-altitude site presented a critical welding hurdle: the heating plate lost its required temperature (approx. 210°C for HDPE) rapidly between cycles, preventing a proper melt zone from forming. This required repeatedly overheating the plate, carefully insulating the work area with tarps, shades and executing welds in quick succession, greatly increasing the time, complexity, and risk of producing sub-optimal, weak joints.



Laying of pipes



Butt welding in process



Manually transporting generator set from community school to work site



Laying sectional pipes along the profile

Photo 5: Laying and joining of pipes at the site using butt welding machine

Installation: Intake assemblies and parts:

The deployment of the intake system was a critical and high-risk operation, requiring secure placement at a sufficient depth to ensure a stable water column and minimize vortex-induced air entrainment¹. The assembly was prepared on shore. It consisted of the primary **125 mm HDPE intake pipe, fitted with a permanently welded ball valve** at its terminus for controlled priming, emergency flow cessation managing the water column during startup. The prepared intake was manually launched from a shoreline and floated into position using an inflatable rubber boat (Photo 6a). Using a combination of sonar and weighted line measurements, the assembly was positioned **at a distance from the shore sufficient to achieve a final submerged depth of approximately 4.5 meters below the lake surface**, placing it well below the active wave zone and potential surface ice layer.

The intake pipe was secured against a large, stable **boulder on the moraine dam face (Photo 6b)**. Using a portable rock drill, **anchor bolts** were installed directly into the boulder and then fastened around the pipe and bolted to this anchor point, preventing lateral or vertical movement. To further resist the significant hydrodynamic thrust force from the siphon flow, a Random Rubble Masonry **(RRM) thrust block** was constructed *in-situ* around the pipe's base where it contacted the boulder and moraine substrate. This RRM block effectively transferred the operational loads from the pipe into the stable ground, completing a secure, multi-point anchoring system designed to withstand dynamic lake conditions.



Photo 6: laying and securing of siphon section at the inlet part (lake)

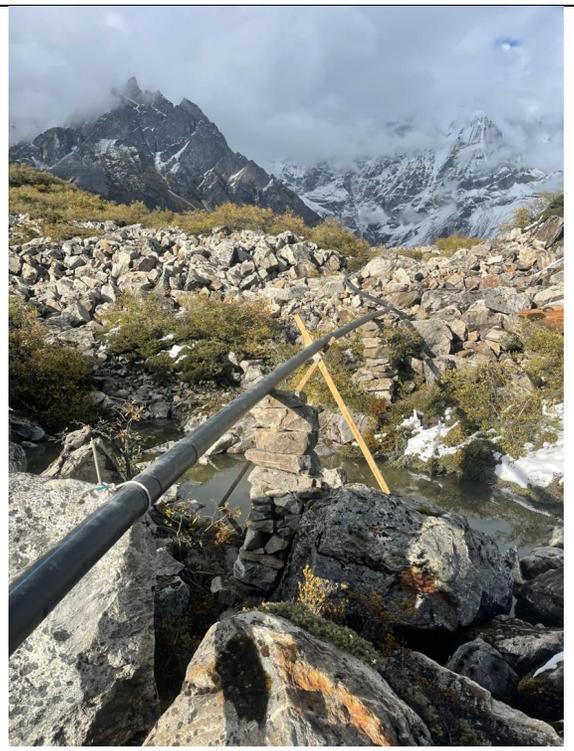
¹ **Vortex-induced air entrainment** is a hydraulic phenomenon where a rotating, funnel-shaped column of water (a vortex) forms on the surface of a body of water as it is drawn into a submerged or partially submerged intake pipe.

Installation: Laying and securing the HDPE Pipes Over the Moraine Dam:

The routing and securing of the HDPE conduit over the irregular moraine dam carried out on the terrain-dependent operation. The total conduit was segmented from the apex as **148.35-meter** section on the **rising limb** (from the lake intake to the Apex) and a **457-meter** section on the **falling limb** (from the Apex to the downstream outlet). A T-section was joint at the apex for priming the system (Photo 7a). The sections wherever possible were anchored to prevent slippage and reduce vibration during the operation using rock bolt anchoring system. Primary anchoring for both segments was achieved using rock anchor bolts drilled into stable boulders, with stainless steel straps securing the pipe. To maintain a hydraulically smooth profile essential for priming and air management, significant site work was undertaken. At unavoidable positive kinks, particularly on the falling limb, Random Rubble Masonry (RRM) thrust blocks (Photo 7b) were constructed to fix gentle curves. In more severe constrictions, selective excavation of boulders and soil was performed to create a shallow trench, straightening the pipe's path. This process ensured the conduit maintained a continuous, optimized gradient from intake to outlet, minimizing friction losses and points of potential air accumulation.



(a) T section at the apex



(b) pipe laying over depression using thrust blocks

Photo 7: T section joint at the apex and pipe profile along depression

Installation: Out Let Assemblies and Parts:

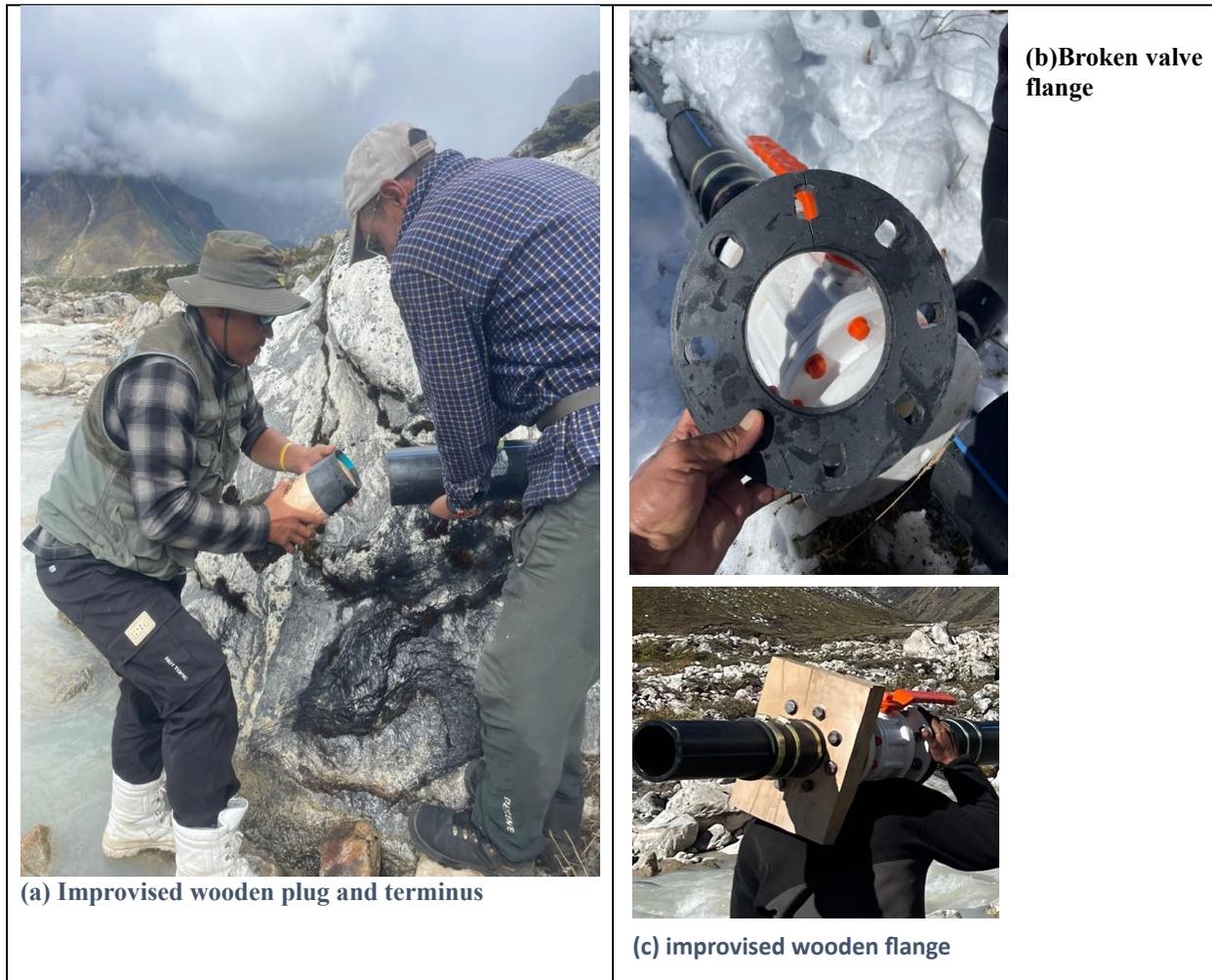


Photo 8: Terminal block of the siphon

The outlet pipe terminus was securely anchored to a large, stable boulder using rock anchor bolts and stainless-steel straps to withstand the thrust of the discharging water column at the toe of the moraine joining the natural flow channel. Initially, a standard 100 mm ball valve was installed to allow for controlled opening and closing of the siphon. However, during the first priming attempt, the excessive hydrostatic pressure caused a shearing the valve's PVC flange (Photo 8b). As an immediate improvisation, the team attempted to seal the outlet using a hand-tightened wooden plug wrapped with rubber bands (Photo 8a), but this proved incapable of achieving a watertight seal against the high pressure, resulting in significant leaks that prevented the system from holding prime. Following this, a local repair was undertaken: the broken flange was mended using an improvised wooden collar, fabricated on-site to reinforce the connection. Once the valve housing was restored, the 100 mm ball valve was reinstalled (photo 8c). This repaired configuration

successfully allowed for the controlled manual operation of the outlet, enabling priming of the conduit and initiating the siphon flow.

Installation: Priming Component at the Apex:

To facilitate the process of filling the siphon conduit with water, a priming component was installed at the system's hydraulic apex—the highest point of the conduit located on the moraine dam crest. This component consisted of a **125mm x 125mm x 40mm HDPE reducer** (a fabricated section reducing from the main pipe diameter to a 40mm port), which was integrated into the pipeline via butt welding (Photo 9b). This port provided a secure connection point for the hose from the portable water pump, allowing water to be injected directly into the top of the system and to displace air both from the rising and falling limbs. To ensure absolute stability at this vital and high-stress location, the entire apex assembly, including the reducer and adjacent pipe sections, was fully secured by encasing it within a (RRM) thrust block (Photo 9a). This block was constructed *in-situ* around the pipe, bonding it to the underlying stable moraine material, thereby preventing any movement, vibration, or stress on the welded joints during the priming process and subsequent operation.



(a) apex secured on RRM thrust Block



(b) assembly of priming component -reducer

Photo 9: Priming components on RRM thrust block

Priming Operation:

Upon completion of installation, the first priming attempt was initiated by sealing both the lake intake (via its ball valve) and the downstream outlet (via the repaired 100mm ball valve), and connecting the water pump to the apex port. Using the portable gasoline pump connected to the 40mm port at the apex, water was injected to displace air from the conduit. Theoretically, with a sealed system, injected water should displace air, forcing it air out through priming intake as no dedicated air-release valve were installed. However, the process immediately revealed significant problem as excessive **return flow** was observed (Photo10a) at the Apex thereby increasing the time for priming by **2 to 3 hours**. This might have occurred because air became trapped at high points in the conduit—particularly along the 457-meter falling limb. The **air pockets trapped at high points** along the conduit, which acted as blockages resulting in prolonged pumping, high fuel consumption, and an inability to establish a continuous, air-free water column necessary to initiate the siphon effect. This necessitated a troubleshooting and adaptation particularly realigning the pipes on the falling limb to avoid high ground kinks and bends (Photo 10b).



Photo 10: Back flow during priming and realignment of pipes.

Operational Testing of the System Performance:

Following troubleshooting and realignment of the conduit to eliminate major air pockets, the priming procedure was initiated by filling the system with water. Operational testing commenced with a carefully sequenced startup protocol. With both the **outlet and inlet ball valves sealed** and the conduit fully primed, the **apex priming port was sealed using a wooden plug tightly bound with rubber bands**. The **outlet valve was then opened first** and simultaneously monitoring at the intake to the **transfer of suction pressure** through the water column. A slight pressure drop (suction) was indeed felt at the intake valve shortly after the outlet was opened, confirming hydraulic connectivity. **The inlet valve was then immediately released to initiate flow.**

The system's performance, however, was critically sub-optimal. While suction was initiated and a brief flow commenced, the siphon **failed to surpass the apex** and establish continuous flow over the moraine crest. The water column from the lake only partially ascended the rising limb before stalling, indicating that the **driving force generated by the falling water column in the 457-meter outlet leg was insufficient to overcome the combined static head and friction losses to lift water over the crest.** This resulted in a partial siphon that quickly equalized, failing to achieve the intended, self-sustaining gravitational flow.

Iterative Testing with Varied Valve Timing

Following the initial failure, a controlled test series was executed to determine if the precise sequencing of valve operations could trigger a successful siphon start. The procedure was repeated with systematically varied time delays—**from 3 to 23 seconds**—between opening the outlet valve and subsequently opening the inlet valve (Table 1). This was designed to test whether allowing momentum to build in the falling limb could overcome the system's inertia.

The results from this series were **erratic and showed no specific improvement correlated with any particular timing interval.** Whether the inlet valve was opened after 3 seconds or 23 seconds, the outcome was almost consistently the same with occasionally observed better observations. But most of the test result was a momentary pulse of suction and flow would initiate, but the water column would **fail to surmount the apex** and promptly stall. The lack of an apparent successful timing pattern, and the absence of any run that achieved continuous flow, provided strong reasons for the failure was not due to operational technique. Instead, it conclusively indicated a **fundamental design limitation**, where the available gravitational head was insufficient to overcome the cumulative friction losses and static lift required to establish and sustain a full siphon over the moraine crest.

Furthermore, repetitive tests using the same delay time often yielded completely different outcomes—one trial might show a slightly longer pulse of flow while the next would stall immediately. An additional test configuration was also conducted by initiating the sequence with the inlet valve already open before opening the outlet valve and result showed no improvement. A log of iterative testing with different timing is given below Table 1.

Table 1: A log of iterative testing with different timing

Test Run	Outlet-to-Inlet Valve Delay (seconds)	Observed Result
1	3	Suction felt. Flow initiated but stalled before reaching apex. No continuous siphon. A substantial amount of water flows back to the lake from intake before suction starts. Water column ascended approximately 1/4 of rising limb before falling back
2	5	Suction felt. Flow initiated but stalled before reaching apex. No continuous siphon. A substantial amount of water flows back to lake from intake before suction starts. Water column ascended approximately 1/4 of rising limb before falling back
3	7	Suction felt. Flow initiated but stalled before reaching apex. No continuous siphon. flow back to the lake from intake before suction slightly reduced. Water column ascended approximately 1/3 of rising limb before falling back
4	10	Suction felt. Water column ascended approximately 1/2 of the rising limb before falling back. No continuous siphon.
5	11	Suction felt. Water column ascended approximately 1/4 of the rising limb before falling back. No continuous siphon.
6	13	Suction felt. Water column ascended approximately 1/2 of the rising limb before falling back. No continuous siphon.
7	15	Suction felt. Water column ascended approximately 2/3 of the rising limb before falling back. No continuous siphon.
8	18	Suction felt. Water column ascended approximately 2/3 of the rising limb before falling back. No continuous siphon.
9	17	Suction felt. Water column ascended approximately 1/4 of the rising limb before falling back. No continuous siphon.
10	19	Suction felt. Water column ascended approximately 1/5 of the rising limb before falling back. No continuous siphon.
11	20	No suction felt, did not know how far the water column rose.
12	22	No suction
13	23	Slight suction and water rose to 1/5 of the section.
14	Open out let	The water flows back to the lake from the rising limb suction starts and the water column rises approximately up to 1/3 of rising limb.

System Redesign and Subsequent Performance:

Following the conclusive failure of the iterative valve-timing tests, the team undertook a significant redesign of the system's core geometry and components to address the suspected fundamental hydraulic limitations. The modifications were aimed at increasing the net driving force and reducing losses as follow:

1. The outlet pipe was extended by 30 meters to increase the effective static head;
2. The apex (crest) was physically lowered by 1.55 meters by re-routing the pipe over a lower point and surface boulder removal on the moraine to decrease the lift required (Fig. 5)
3. The intake pipe on the rising limb was shortened by 12 meters to reduce friction.
4. The intake point was raised from a depth of 4.5 meters to just 1 meter below the lake surface to minimize the initial suction lift needed.
5. The outlet valve was replaced with a larger 150 mm diameter unit to eliminate a major downstream flow restriction (Photo 11).

Despite these substantial alterations, which collectively represented a major recalibration of the system's theoretical hydraulic profile, operational testing showed no measurable improvement. The siphon still failed to establish continuous flow, stalling at the apex as before.

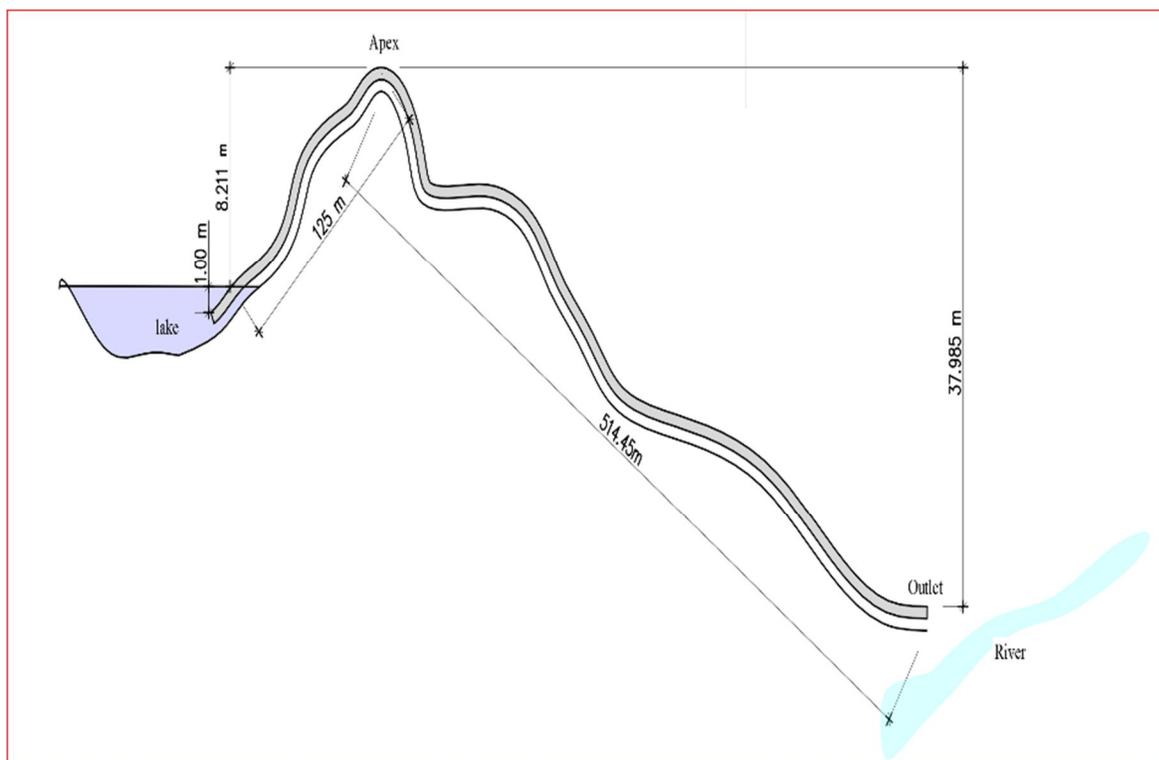


Figure 5: The Re-designed profile as constructed with lowered Apex by 1.55 m



Photo 11: Swapping of Ball valve at the outlet

Final Test: Alternative Intake at Elevated Pondage

As a diagnostic final resort, the intake was relocated from the main lake to a small, isolated **pondage** (a shallow, contained water body) located approximately **1.767 meters above the original lake surface level**, as verified with dumpy level surveying (Fig.6 & Photo 12). This test was conducted to determine if the system's consistent failure was due to the key theoretical constraint: the maximum possible siphon height (h_{max}) at altitude around 4300 m was 9.771 m. By raising the intake by 1.767 m and lowering the apex by 1.55 m, the effective static head driving the siphon was reduced to approximately **6.444 meters** (calculated as: $9.771 \text{ m} - 1.767 \text{ m} + 1.55 \text{ m}$), thereby testing the system's sensitivity to a significantly lower (h_{max}).

Results from this configuration showed a slight but notable behavioral improvement. During priming and startup, the water column successfully rose to approximately **three-quarters (¾)** of the length of the rising limb, a marked increase compared to previous tests. This indicated that with a reduced total lift, the system could more effectively begin the process of drawing water over the crest.

However, the siphon still failed to establish continuous, self-sustaining flow. The water column consistently stalled at the apex, unable to complete the transfer over the crest. Following each stall, the water in the rising limb gradually drained back into the elevated pondage, emptying the conduit as in all prior tests.

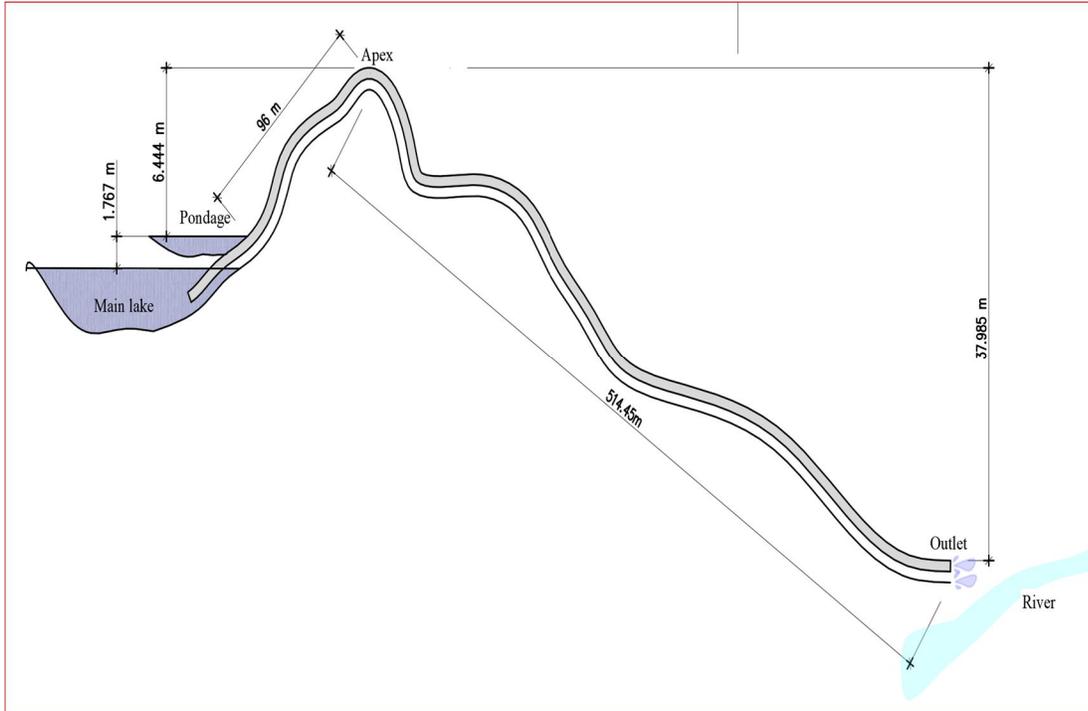


Figure 6: Test on pondage located 1.7 m above lake surface



Photo 12: Hydraulic Profile on the pondage

Results and Discussion:

The pilot test generated a series of sub-optimal results that collectively point to multiple constraints. The discussion interprets these results in the context of **Hydraulic Theory of Siphons and the Altitude Constraint**, environmental conditions and siphon construction methods. From the overall lessons it can be summarized that the following are the main contributors for sub-optimal result of the siphon test as follows:

- I. The vertical separation between glacier lake and the siphon crest (Apex) refer table 2.
- II. Trapped air pocket between submerged pipe inlet and the sealed ball valve and Water Level (Fig.7)
- III. Frictional Loss due to internal bead, or **fusion ring**, at each butt-weld joint (Photo 13).
- IV. A section measuring approximately 80 m on the **falling limb with a near-zero slope** (Fig.8)

Table 2: Maximum allowable siphon height difference at different altitude (from Som Gurung (2021))

Altitude (M)	Air Pressure (Pa)	Maximum Height of Siphon (<i>hm</i>) (M)
2,000	79,495	8.10
3,000	70,109	7.15 ⁱ
4,000	61,640	6.29
5,000	54,020	5.51
7,000	41,061	4.20

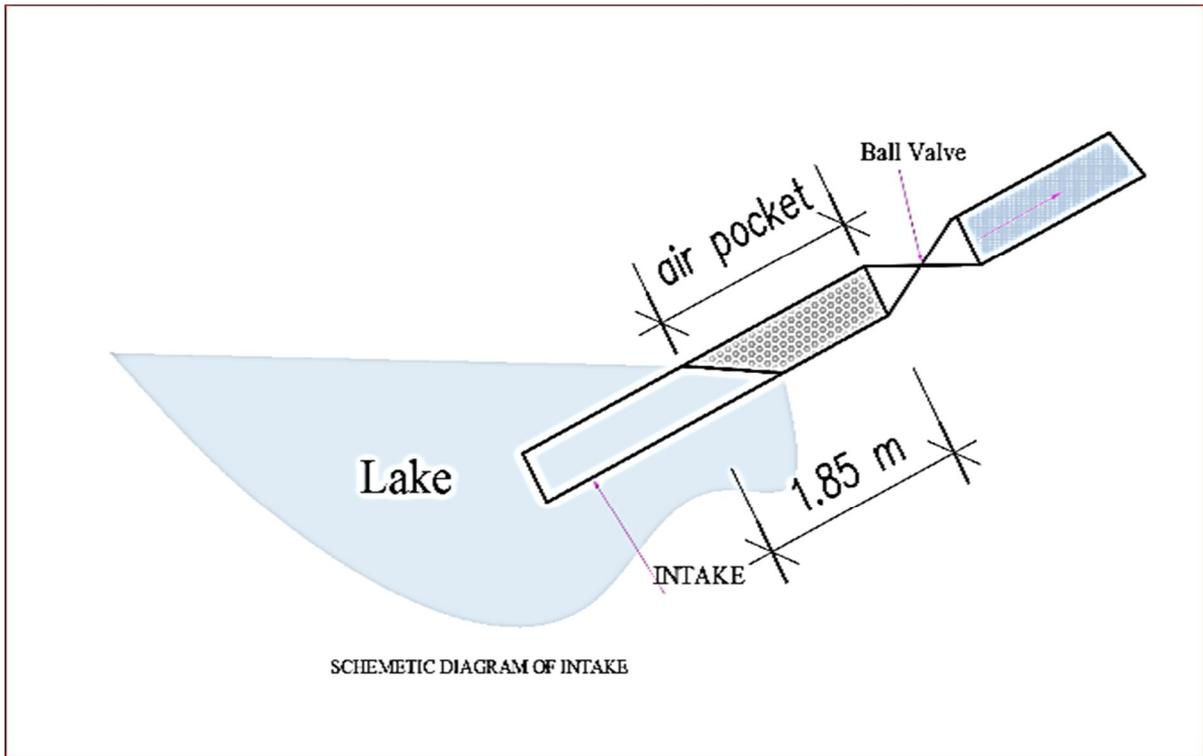


Figure 7: illustration of trapped air pocket between lake water level and sealed ball valve at the inlet section of the siphon

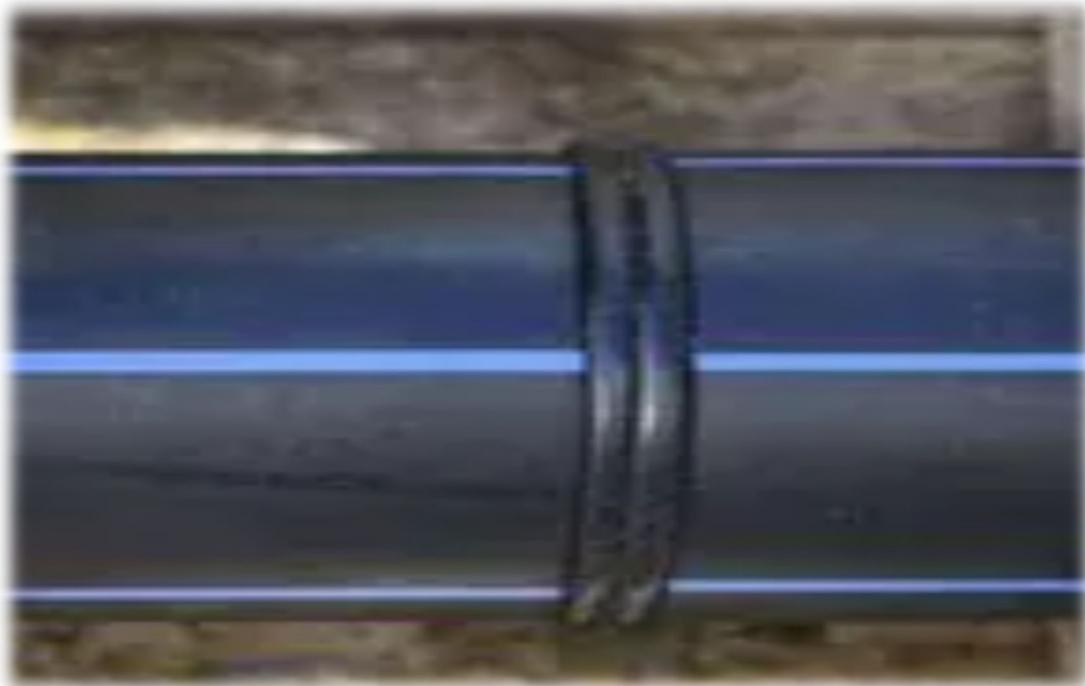


Photo 13: Fusion ring at each butt weld joint of the siphon pipes

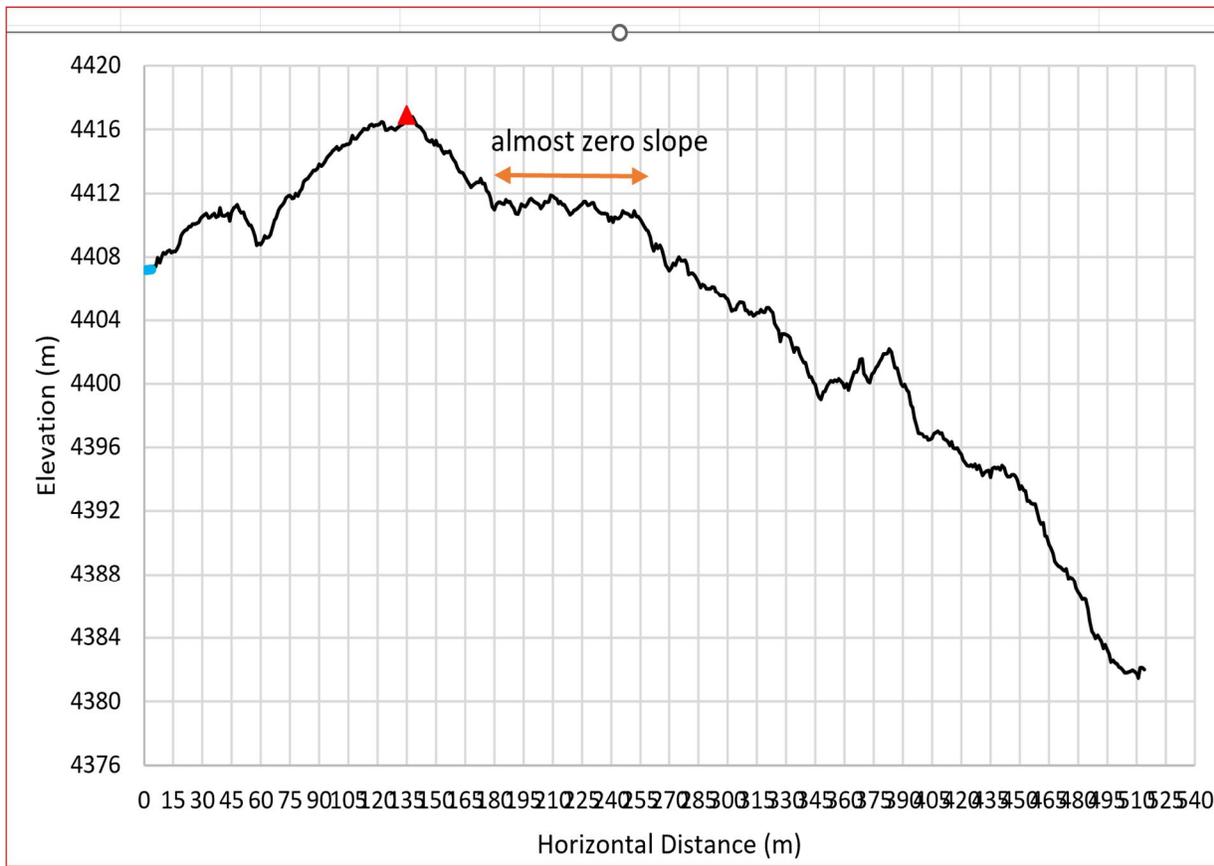


Figure 8: Siphon profile on falling limb showing section with near zero slope

A detailed results and discussions are presented below:

1. The siphon system failed to achieve its primary operational goal of establishing a continuous, self-sustaining flow. Across all configurations, including the original setup, multiple valve-timing sequences, geometric redesign, and the final elevated-pondage test—the outcome was consistent. A primed system would initiate a pulse of flow upon valve opening, but the water column would stall before or at the hydraulic apex and subsequently drain back toward the intake. The most promising result was observed during the final test with an effective head of 6.444 m, where the water column ascended approximately three-quarters of the rising limb, indicating a marginal sensitivity to reduced lift.
2. Atmospheric pressure at approximately 4,300 meters (~58,000–61,000 Pa) establishes a maximum theoretical siphon height (h_{max}) (**height difference from intake water level to apex**) of only 6.0–6.4 meters only as per in **Som Gurung's 2021 study, "Feasibility of using siphons to drain glacier lakes to provide electricity to remote communities in Bhutan"**). The original design's operational head of 9.771 meters exceeded this limit,

rendering a functional siphon physically impossible from the start. Subsequent modifications, which aimed to reduce the head, concluded in a test with an effective head of ~6.444 meters, bringing the system to the very brink of theoretical feasibility. However, practical operation requires the operational head to be **less than (h_{max})** to provide a necessary pressure margin to overcome friction losses in the long conduit and system imperfections. A head of 6.444 meters at this altitude provided zero margin, guaranteeing failure and confirming that the system had encountered an absolute, altitude-imposed hydraulic ceiling that could not be overcome by design adjustments alone.

3. The backflow during priming highlighted the need for proper laying of pipes avoiding kinks and bends and integration of air **vent valves** at the apex.
4. The lack of correlation with valve timing and inconsistency between repeated tests suggest that use of submersible non return valve be used instead of ball valve at the intake.
5. One of the contributors to the system's hydraulic inefficiency was the increased frictional loss introduced by the internal bead, or **fusion ring**, at each butt-weld joint. During the field welding process, the heated ends of the HDPE pipe are pressed together, forming a raised internal ridge where the material fuses. While this creates a strong mechanical joint, it also introduces a localized reduction in the effective internal diameter of the pipe. For a siphon system operating with a marginal driving head, the cumulative effect of these periodic restrictions along a 550-meter conduit with numerous welds is substantial.
6. The topographic survey and as-built profile, section measuring approximately 80 m on the **falling limb showed a near-zero slope**. During operation, water velocity in this flat section might be reduced due to friction, losing water momentum. We assumed that this is probably acting as bottle-neck causing the net siphon effect to diminish. **There was no option to re-rout this profile section.**
7. For operational convenience, the ball valve at intake was positioned above the lake water level. This created a presence of a trapped air pocket between submerged pipe inlet and the sealed ball valve located further up the rising limb. During priming, this pocket could not be evacuated as it was sealed off by the closed ball valve. We assumed that upon opening the valves to initiate flow, this compressed air pocket would expand into the rising limb as pressure dropped, interrupting the continuity of the water column.

Conclusion:

The pilot natural siphon test at Thorthomi Lake demonstrated the difficult logistical and technical challenges of implementing in a remote, high-altitude environment, while ultimately proving that the system, as initially configured, was hydraulically unviable. The primary constraint was identified as the fundamental physical limit imposed by low atmospheric pressure at altitude.

Despite sub-optimal results, the project yielded invaluable practical insights into installation methodologies, material performance, and the absolute necessity of incorporating altitude-adjusted hydraulic calculations. Therefore, the pilot stands as a vital proof-of-concept that defines the boundary conditions for future work, providing the essential empirical foundation needed for future similar mitigation work. The system built shall not be abandoned, instead relocated to a suitable location and conduct a re-test with modification and redesigning.

Recommendations and Way Forward:

The pilot test, while not achieving operational success, provided invaluable lessons and data to validate the fundamental knowledge on natural siphon designing and construction methodology at remote high-altitude location to mitigate the GLOF risk. The recommendation is **not to abandon the developed system** but to strategically **relocate and reconfigure it** at a suitable site. where the due consideration on fundamental physical constraints, construction methodology is re-examined and incorporated. Re-initiating the syphon system can be done with minimal cost as the substantial upfront investments in equipment, materials, and, most critically, lesson learnt and knowledge have already been made and are preserved on-site. The following recommendation outlines the steps for repurposing the existing assets including hundreds of meters of HDPE piping into an yet another attempt. Inview of the above, the team is proposing the following recommendation as a way forward action:

1. The current pilot test site is evident that the **location** is hydraulically unsuitable for a natural siphon system because the operational head from the intake water surface to the siphon apex (9.771 m) significantly exceeds the maximum possible siphon height (~6.4 m) at this altitude, imposed by low atmospheric pressure. This is a fundamental physical constraint that cannot be overcome by design modifications or improved procedures at this site. Therefore, it is recommended to **relocate the setup to an alternative site**.
2. An alternative location for deploying the system has been already identified close by the existing lake outlet. Though it has its inherent limitation and challenges such as unstable moraine at the falling limb and underneath barrier between the main lake and the new proposed intake pond (subsidiary lake I), the profiling survey data indicates that the vertical height from lake water level to the highest point (apex) is less than **6.00 m** that would be within the operational head **from intake water surface to siphon apex**.
3. Conduct a detailed bathymetry survey at the outlet subsidiary lake to ascertain the depth of the barrier between the main lake and the subsidiary lake from where the inlet of the siphon shall be positioned.
4. To replace the ball valve with a **submersible non-return (check) valve** directly at intake assembly to eliminate: a) The trapped air pocket that formed between the lake surface and

the sealed ball valve: b) Timing sequence between valve openings. With this set up the **single action of opening the outlet valve** only would be required to initiate the siphon.

5. NCHM is currently engaged with Swiss Polar Institute (SPI) under the project “Reducing Imminent Risk due to GLOF in Punatshang Chhu Basin”. It is recommended to leverage the project's existing partnership with the Swiss Polar Institute (SPI) and engage an expert in the field of multi hazard management to conduct a field visit to the project site. The expert would conduct evaluation, review and assess the installed system to provide further recommendation. This recommendation to be incorporated into the final redesign.
6. The current proposed SPI project has included the activities to enhance the existing GLOF Early Warning System in Puna Tsang Chu basin by installing high-resolution CCTV camera and sensors for real time monitoring on lakes with star- link Satellite communication.

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