Received: 1 April 2020 | Revised: 17 December 2020 | Accepted: 17 December 2020
DOI: 10.1002/ird.2563

RESEARCH ARTICLE

WILEY

Agricultural water management challenges in the Hunza River Basin: Is a solar water pump an alternative option?*

Madhav Prasad Dhakal[1] | **Amjad Ali**[2] | **Muhammad Zafar Khan**[2] | **Nisha Wagle**[1] | **Ghulam Muhammad Shah**[1] | **Muhammad Mudassar Maqsood**[1] | **Ajaz Ali**[1]

[1]International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal

[2]Karakorum International University (KIU), Gilgit, Gilgit-Baltistan, Pakistan

Correspondence
Madhav Prasad Dhakal, International Centre for Integrated Mountain Development (ICIMOD), GPO BOX 3226 Kathmandu, Kathmandu province 3 3226, Nepal.
Email: madhav.dhakal@icimod.org

Funding information
ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland and the United Kingdom; Australian aid; the AKAH team; the Pakistan Council of Research in Water Resources (PCRWR)—Pakistan team; Indus Basin Initiative team of ICIMOD, the WWF Gilgit team

Abstract

In the glaciated mountains of the Upper Indus Basin of Pakistan, glacier- and snowmelt- based irrigation systems have been established over several centuries to secure water for cultivation. However, these systems are now facing several challenges, being sensitive to climate change and thus exposed to the resulting extreme events such as glacial lake outburst floods (GLOFs) and flash floods, also difficult terrain and access paths, male outmigration, limited technical capacity and a weak policy and governance system. Hence, exploring the potential options for overcoming the challenges and irrigating arable barren land could lead to economic prosperity and environmental gains.

A literature review, stakeholder consultation and semi-structured questionnaire survey in two villages of the Hunza River basin was conducted to synthesize information in different domains. Information on the irrigation system and its sources, water distribution/allocation system, challenges and adaptation strategies were collected, and based on community preferences, an alternative irrigation technological package was established to overcome the challenges and irrigate barren land. A customized solar water lifting pump with an efficient micro-irrigation package was piloted which proved to be climate resilient. The system is simple to adopt, uses clean energy for operation and is economically feasible, with a benefit–cost ratio of 4.96 and a payback period of around 11 years.

KEYWORDS
adaptation, alternative options, hazards, traditional irrigation challenges, water lifting

Résumé

Dans les montagnes glaciaires du bassin supérieur de l'Indus au Pakistan, un système d'irrigation basé sur les glaciers et la fonte des neiges a été établi

* Les défis de la gestion de l'eau agricole dans le bassin de Hunza: la pompe à eau solaire est-elle une option alternative?

pendant plusieurs siècles pour sécuriser l'eau pour la culture. Cependant, ces systèmes sont confrontés à plusieurs défis en raison de leur sensibilité au changement climatique et à son exposition aux événements extrêmes qui en résultent tels que l'inondation du lac glaciaire (GLOF) et les crues éclair, le terrain et le chemin d'accès difficiles, l'émigration des hommes, la capacité technique limitée, la faiblesse des politiques et système de gouvernance. Par conséquent, explorer les options potentielles pour surmonter les défis et irriguer les terres arables stériles pourrait conduire à la prospérité économique et aux gains environnementaux.

Une revue de la littérature, une consultation des parties prenantes et une enquête par questionnaire semi-structuré dans deux villages du bassin de Hunza ont été menées pour synthétiser les informations dans différents domaines. Des informations sur le système d'irrigation et ses sources, le système de distribution/allocation de l'eau, les défis, les stratégies d'adaptation ont été collectées et, sur la base des préférences de la communauté, une technologie d'irrigation alternative a été mise en place pour surmonter les défis et irriguer les terres stériles. Une pompe solaire de levage d'eau personnalisée avec un ensemble de micro-irrigation efficace a été testée, ce qui s'est avéré résilient au climat. Le système est simple à adopter, utilise de l'énergie propre pour son fonctionnement et est économiquement réalisable, avec un rapport bénéfices–coûts de 4.96, et une période d'amortissement d'environ 11 ans.

MOTS CLÉS

dangers, défis de l'irrigation traditionnelle, options alternatives, levage de l'eau, adaptation

1 | INTRODUCTION

The Hindu Kush Himalaya is home to the Upper Indus River basin (UIB) in Pakistan, which is the one of the most glaciated of landscapes (Khan, 2013) with perennial snow and ice covering over 20 000 km^2 (Hewitt, 2011). The snow and glacier melt are important hydrological processes contributing to more than 70% of the streamflows (Ali *et al*., 2015). In the UIB, glaciers are at an altitude where human settlement is possible, therefore glacier melts contribute significantly to several activities such as irrigation, hydropower and drinking water. Irrigation is the most melt dependent sector in this region, since steep slopes and strong water currents makes river water unusable. Therefore, agriculture is possible only through irrigation channels diverting glacier and snowmelt water to the arable land (Sidky, 1993; Parveen *et al*., 2015). Ninety-five per cent of the total cultivated area in northern Pakistan was heavily dependent on irrigation channels (*kuhls*) carrying meltwater (Velde, 1989).

In Gilgit-Baltistan, agriculture accounts for up to 48% of total farm income, followed by livestock (41%) and forestry (11%) (World Bank, 2010). Therefore, irrigation is considered the main component of livelihood security, and agriculture the major economic activity. Irrigation in the high mountains is generally categorized as socio-hydrology, which incorporates the social and natural sciences across various scales, and also provides a flexible and nuanced way of dealing with several water hazards (Nüsser, 2017). Various water-related disasters, water distribution mechanisms, socio-economic developments and other external developments shape the socio-hydrological interactions (Parveen *et al*., 2015; Nüsser, 2017).

The irrigation system, however, faces several challenges. Frequently occurring hazards such as floods, glacial lake outburst floods (GLOFs), erosion and sedimentation have been regularly impacting the irrigation system and have reduced its capacity. Climate change, on the other hand, has had a significant impact on the glacier and snow ecosystem, affecting freshwater flows and severely impacting water supply and irrigation (Shaheen *et al*., 2013), leading to dwindling irrigation water supplies and seasonal shifts. For example, flash floods, landslides and subsidence of moraine areas due to increased glacial melt have frequently disrupted the vital irrigation infrastructure and reduced irrigation water supplies in the Hunza valley (Sidky, 1993; Parveen *et al*., 2015). Moreover, the magnitude and frequency of extreme events are projected to increase in the future (Lutz *et al*., 2016; Wijngaard *et al*., 2017), which would likely threaten agriculture-dependent livelihoods in the UIB.

Limited arable land (~2%) and small landholdings (<0.73 ha) dominated by subsistence-based agriculture, labour shortages due to higher male outmigration (41%), insufficient research and development, a complex (labour and capital intensive) irrigation network, government subsidies and poor market linkages, population growth, increased demand, a complex geographical location and human-induced activities (Hashmi and Shafiullah, 2003; Viviroli *et al*., 2003; Kreutzmann, 2012; Parveen *et al*., 2015) are other challenges which have created stress on mountain irrigation. For instance, the position of the irrigation channels and the settlement location expose the irrigation system to a certain degree of risk in Hunza (Parveen *et al*., 2015) and Gilgit-Baltistan has only about 1.2% cultivated area, which is less than the available arable land. This is likely due to the poor accessibility of irrigation water and its location which is much higher or lower than the water sources. Around 2% of the area of Gilgit-Baltistan is cultivable wasteland that can be brought under cultivation with advanced irrigation measures (International Fund for Agricultural Development (IFAD), 2015). Moreover, inefficient water management activities comprising unlined water conveyance and distribution canals cause water loss, thereby lowering yields. Subsequently, improvement of the economic corridor of the Karakoram Highway leading to increased opportunities for non-farm activities such as labour and markets, and other external development (Parveen *et al*., 2015), reduce the communities' interest in local irrigation activities.

To cope with the challenges, communities have been adopting different measures both structural and non-structural depending on the location, the majority of which are ad hoc. Water management activities integrate local knowledge and culture and have been adjusting to harsh conditions reflecting the social and communal structure (Kreutzmann, 2012). To address the challenges in supplying undisturbed irrigation water, the International Centre for Integrated Mountain Development (ICIMOD) along with partners carried out an in-depth study on agricultural water management in two selected villages of the Hunza River basin. This innovative intervention was demonstrated as an alternative way of sustaining irrigation water supplies in face of the challenges the region is facing. This was carried out as part of a project entitled 'Agricultural Water, Energy, and Hazard Management in the Upper Indus Basin for Improved Livelihoods and Resilience'. Prior to the intervention, agriculture water management strategies in these villages were comprehensively analysed, focusing on irrigation history, glacio-hydrological hazards and their impact on irrigation water supply systems, and methods of water management, distribution and possible efficient use options. A baseline survey was conducted to discover communities' preference for alternative irrigation water management to improve local livelihoods. After establishment of the intervention, a midline survey was conducted to assess the economic viability of the demonstrated intervention.

1.1 | Study area

The Hunza valley is one of the 10 districts of Gilgit-Baltistan Province, located at an altitude between 1391 and 7850 m (Qureshi *et al*., 2017), with 90% of the area lying in the rain shadow of the Himalayas (Shrestha *et al*., 2015). The valley has a total catchment area of about 13 700 km^2 (Ali *et al*., 2015), of which glaciers cover an area of 3930 km^2 (Immerzeel *et al.,* 2012). The valley is divided into two sub regions—Upper Hunza or Gojal valley and Lower Hunza (Baig, 2018), which also includes three major peaks (Mts SistaghilSar, BaturaSar and PassuSar) (Qureshi *et al*., 2017). The Gojal is a narrow watershed, framed by steep slopes, having a population predominantly inhabited by the Wakhi-speaking people, while the lower region of Shinaki is inhabited by Shina-speaking people with a considerable number of Brushaki speakers. The temperature in the village ranges from −11 to 29 ^{0}C, and receives 150-200 mm annual rainfall, hence it has an arid climate (Rehmat, 2006).

The study area covers two villages of Upper Hunza—Passu and Morkhun—as seen in Figure 1. Passu is the oldest Wakhi settlement located at an altitude of about 2500 m between the Batura and Passu glaciers (Kreutzmann, 2012) with a population of 1168, while Morkhun is located at an altitude of about 2711 m having a population of 653 individuals (baseline survey). These two villages were selected because of: (i) the availability of a large unirrigated arable riverbank on the main River Hunza; (ii) availability of communal land without any disputes; (iii) active community participation, with willingness and assurance to take care and maintain the system; (iv) their plan to use the pilot area for fruit orchard development and fodder fields. Both sites were claimed to be free from hazards based on the communities' and expert judgement. Both villages lie in a single cropping zone where wheat and potato are the main cash crops

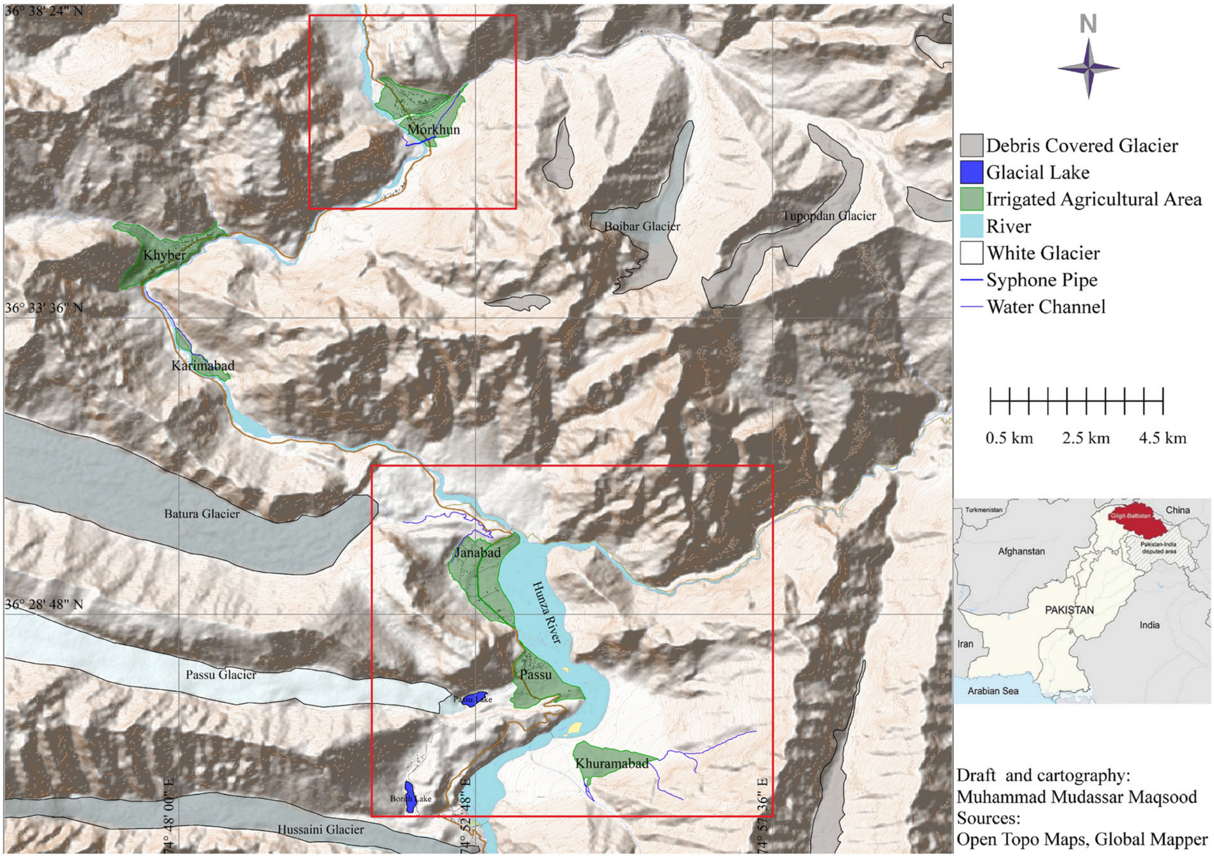

FIGURE 1 Upper Hunza River basin showing Passu and Morkhun villages

while maize and barley are grown as fodder crops. Orchards of apricots, mulberry, peach, apples, and poplar and sea buckthorn are available in these villages.

1.2 | Methodology

The study was carried out in three steps: situation assessment through baseline survey and secondary data; project intervention; and its assessment. Local organizations, mainly the Aga Khan Agency for Habitat (AKAH), were consulted to obtain disaster data and an intensive literature review was conducted for secondary information. A baseline household survey was conducted in the selected villages in 2016. Data were collected using a semi-structured questionnaire, for which sample size was determined using a 95% confidence interval considering a 5% of margin of error. The total number of households in Passu was 143 and 86 in Morkhun and the survey was conducted in 105 households in Passu and 71 in Morkhun. The data were then analysed using the Statistical Package for Social Sciences (SPSS) tool, and descriptive analysis (frequencies and percentages) was carried out. In addition, field visits and technical surveys were also conducted by the project team to assess the status of irrigation canals and historic hazards in the two villages. Based on this, a solar-powered pumping system with location-specific modification was piloted in these two villages.

In the final stage, the economic viability of the system was analysed based on net present value (NPV) (Equation 1) and benefit–cost ratio (BCR) (Equation 2) using the discounting cash flow method, pay-back period and internal rate of return (IRR) of the project:

$$\mathrm{NPV} = \sum\nolimits_{t=1}^{n} (B_t - C_t)/(1+i)^t \tag{1}$$

$$\mathrm{BCR} = \sum\nolimits_{t=1}^{n} B_t/(1+i)^t \Big/ \sum\nolimits_{t=1}^{n} \mathrm{C}_t/(1+i)^t \tag{2}$$

where
B_t = benefit in year t
C_t = cost in year t
$t = 1, 2, 3 \ldots \ldots \ldots n$
n = project life in years
i = discount rate or the assumed opportunity cost of the investment

The IRR was calculated to evaluate the economic efficiency of the solar pump because this tool does not depend on the application of an arbitrary discount (Asmon and Rothe, 2006). In IRR, the implied discount rate is measured in such a way that it equates the present value of benefits of the project to the present value of cost of the project, and thus the NPV becomes zero.

Therefore, NPV is a main project evaluation criterion which is widely used to determine the economic viability of a project and was formalized by Fisher (1907). This criterion works on the basis of all the foreseen discounted costs and revenue over the lifespan of the given project. Future cash flows are considered as deterministic under this measure, but many contributions devoted to the NPV measure are made on the assumption that those cash flows are uncertain as both benefits and costs of the project are related to future except initial cost of the project. In order to bring the uncertainty of future cash flow into account, several factors are considered in NPV calculation which include increasing the discount rate and comparing pessimistic and optimistic future cash flows (Gaspars-Wieloch, 2019).

This study calculated all the economic indicators of the project considering the uncertainty. The economic calculations were done considering the facts of the survival ratio of the fruit trees, wear and tear of the equipment, fruiting time of trees and changes in prices of fruit, labour cost and increasing the discount rate.

2 | RESULTS AND DISCUSSION

2.1 | Irrigation in the Hunza valley—a historical perspective

Irrigation in the Hunza Valley began at least from 1780, diverting water from the Batura Glacier to Zarkhon Passu (Parveen *et al.*, 2015). Hunza's geological and ecological setting, however, has several constraints. The difficult terrain of the valley was considered a major hurdle in constructing a complex hydraulic structure, which would require great number of human resources beyond the then capacity of an entire village. Initially, a localized irrigation system developed by farmers using locally available technology and resources existed in the valley (Velde, 1989). In central Hunza, historically a very small-scale irrigation network consisting of the Baltit-ill, Altit-gotsil and Hamachi which drained water to Baltit, Altit and Ganesh villages existed. Crops were cultivated by draining glacier and snow meltwater through a natural drainage system (Sidky, 1997). Later, the irrigation systems were established, upgraded and extended under several rulers. Rulers back then used to have rivalries with other princely states in Gilgit-Baltistan, and establishment of new settlements by the then rulers was seen as their strength. Hence, the irrigation development under the rulers of the princely states is basically linked with the political evolution in the history and focus of the rulers. For example, during the Mir Silim Khan regime (1790-1824) highly ambitious projects (e.g. Haligan-gotsil, Samarqand and Ahmadabad-gotsil) were initiated, diverting meltwater by canals to stone tanks and used to irrigate previously barren lands (Sidky, 1997).

During the Mir Silim regime, large-scale irrigation systems were successfully established because of his ability to mobilize a large number of people under his rule (Sidky, 1993). Moreover, he also initiated settlement expansion in the valley through establishment of new villages and constructing large-scale irrigation systems (Velde, 1989; Parveen *et al.*, 2015). The new villages were established at comparatively plain flood moraines on the periphery of glacial water resource. Later, Mir Salim's successors—Mir Ghazanfar (1841–1856) and Mir Ghazan Khan (1865–1886)—also continued the work on irrigation network development and establishment of new smallholder settlements. The Berbher canal was the largest channel serving central Hunza as a main water channel (Sidky, 1993).

Irrigation system development was, however, reduced after the arrival of the British-supported Dogra administration in 1890, and this continued until 1974. Later during the 1970s Z. A. Bhutto, the then Prime Minister of Pakistan, formally abolished the princely states in Gilgit-Baltistan (Velde, 1989). After this, several irrigation projects were initiated in the region by different institutions. For instance, the Bhutto government initiated an Integrated Rural Development Project in the early 1970s with the aim to improve farmers' income (Parveen *et al.*, 2015). Later, in the early 1980s, the Aga Khan Rural Support Programme (AKRSP) started about 166 irrigation projects to improve the old irrigation system and develop a new one. The AKRSP brought strong community participation, and the interventions integrated both indigenous knowledge and engineering technology in constructing a canal; this likely caused their projects to succeed (Velde, 1989).

Irrigation earlier was effected through small *kuhls*, constructed and maintained jointly by farmers and village officials, which carried meltwater through a crude intake structure (Velde, 1989). Equal distribution was then ensured through a traditional water management system by the village headman (*trangfa*) and canal supervisor (*darago*) (Sidky, 1997). Some 221 *kuhls* supplying irrigation water in the Gilgit district were identified by WAPDA, Pakistan, however information on their efficacy is lacking (Velde, 1989). They are built either of stone or mud, wherein the problems of water leakage and soil erosion exist. In the lower catchment of Gojal, meltwater from the Batura, Passu, Ghulkin and Ghulmit glaciers is diverted through a complex of irrigation canals to irrigate the cultivated lands of surrounding villages (Sidky, 1993; Parveen *et al.*, 2015).

3 | IRRIGATION SYSTEM IN THE PILOT VILLAGES

3.1 | Passu

In Passu, glacier melt from the Passu, Batura, Zarabad and Khuramabad glaciers is diverted through irrigation canals whose intakes are located at the terminus of the glaciers. There are five irrigation canals, namely Passu main nalah, Janabad, Lalzor, Khock and Murarabad, serving three community settlements, Passu, Jana Abad and Khuramabad (Figure 2). About 4 km^2 of land in the Passu village is irrigated by these irrigation canals (Table 1). Passu main nalah is considered the main canal, which supplies irrigated water to the Passu settlement from the Passu Glacier.

In Passu, of 92 households, 99% used glacial melt/stream, while only 1% extracted/pumped water from the river by electric motor for irrigation. Water is then diverted to the field using both gravity-fed water supply techniques and a pumping system.

Farmers in the village apply improved surface irrigation methods such as bed furrow or ridge furrow to irrigate cereal crops and vegetables, and flood irrigation to irrigate fodder crops, orchards and firewood plantations. Some 94% of households (n = 89) in Passu used improved surface irrigation methods to irrigate their cereal crops, while the remainder used the flood irrigation method. For orchards, 79% of households (n = 88) used flood irrigation methods, 16% used improved surface irrigation methods, and 5% used both irrigation methods.

The villagers, however, preferred bed furrow or ridge furrow methods over flood and basin irrigation as these were efficient in terms of water saving, workforce ease and crop productivity enhancement. Out of 85 respondents, 77% of households reported improved surface irrigation to be effective, while only 1 and 14% reported flood irrigation and basin irrigation respectively to be effective, and 8% of households responded that all three methods were efficient. The village lacked the use of any modern irrigation methods such as drip and sprinkler irrigation, likely due to the lack of awareness and knowledge of the benefits of such techniques. The survey also

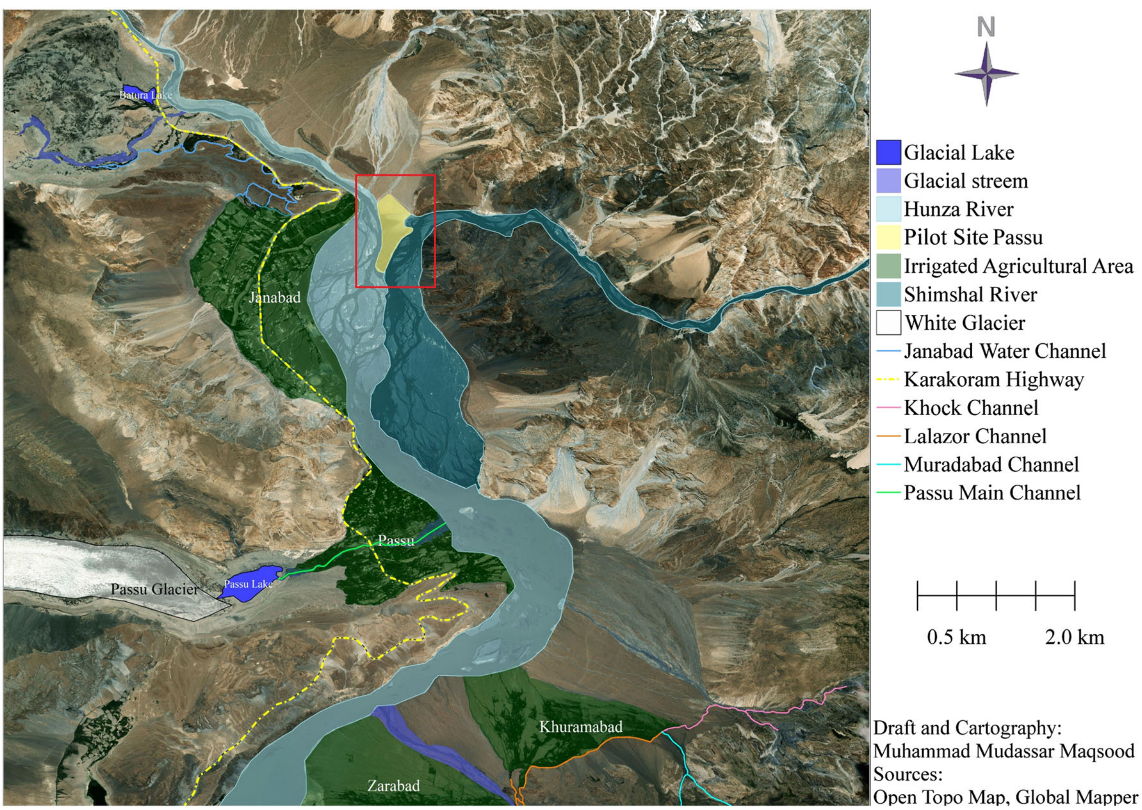

FIGURE 2 The irrigation canals serving three community settlements in Passu village

TABLE 1 Details of irrigation canals in Passu

Community settlement	Source of irrigation water	Irrigation canal name	Area under irrigation (km^2)
Passu	Passu Glacier	Passu main nalah	1.7
Jana Abad	Batura Glacier	Janabad	1.3
Khuramabad	Zarabad Glacier	Lalazor	0.5
Khuramabad	Khuramabad Glacier	Khock	0.4
Khuramabad	Khuramabad Glacier	Muradabad	0.1

Source: AKAH.

showed that water storage and conservation methods are not practised by 99% of households, whilst 1% use ponds to store water.

3.2 | Morkhun

In Morkhun water is diverted to irrigation canals from only one glacier—Tupopdon—through eight irrigation canals, namely Qalhabar, Yuur, Rech, Abjaat, Tanzeem, Chukul Ghar, Jomolabad and Sharshigduur (Figure 3), serving two community settlements, Morkhun and Jamal Abad. A perennial stream fed by the Tupopdan Glacier of Boiber valley is the major source for irrigation, including water extraction from the river. In the Morkhun and Jamal Abad community, about 1.35 and 1.21 km^2 of land respectively are irrigated through these canals (Table 2), using an unlined canal and syphon on the Khunjrab River. The syphon irrigated only 3.85 ha land on the right bank; likewise, the unlined canal is used for the left bank of the Khunjrab River. The baseline survey showed that 66% out of 67 households used glacial melt/stream, and the remainder extracted water from the river. And irrigated water was diverted to irrigable land by gravity.

Similar to Passu, in Morkhun both improved surface irrigation (bed furrow or ridge furrow) and flood irrigation methods are used to irrigate the cereal crops and orchards. A significant number of households, i.e. 68% (n = 63), reported the use of improved surface irrigation methods, while 16% used flood irrigation and 16% used

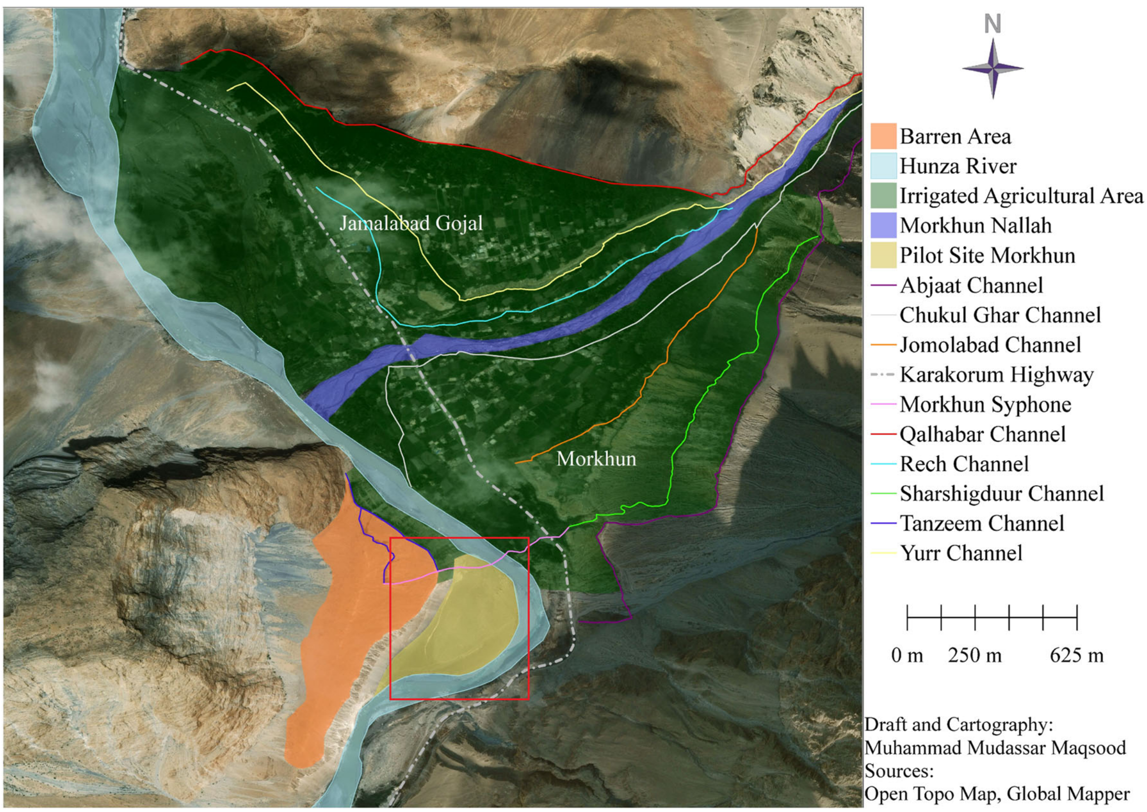

FIGURE 3 Irrigation canals serving two community settlements in Morkhun village

TABLE 2 Details of irrigation canals in Morkhun

Name of irrigation canals	Source of irrigation water	Community settlement	Area under irrigation (km^2)
1. Qalhabar	Tupopdon Glacier	Jamal Abad	1.2
2. Yuur			
3. Rech			
4. Abjaat		Morkhun	1.4
5. Tanzeem			
6. Chukul Ghar			
7. Jomolabad			
8. Sharshigduur			

Source: AKAH.

both methods. For orchards, 42% of households (n = 50) used flood irrigation, 16% improved surface irrigation and 42% both irrigation methods.

The effectiveness of these irrigation systems was similar to Passu; however, modern techniques were found to be operational. Some 55% of households (n = 66) thought that improved surface irrigation methods were more efficient in terms of their cost, with increased productivity and less labour intensive, while 14 and 17% claimed that flood and basin irrigation systems respectively were more efficient. Some 8% claimed that all three methods were efficient. However, about 6% of the respondents used modern techniques such as sprinkler and drip irrigation and reported them to be effective because of less water loss from evaporation, and they save time as manual watering of individual plants is not required.

Water storage and water conservation methods are not practised by the majority in the village; only 34% households (n = 64) used cement water storage tanks and traditionally built ponds in the village to store water for irrigation or drinking.

4 | IRRIGATION WATER DISTRIBUTION MECHANISMS

There is large fluctuation in seasonal water availability in these villages. For instance, from June to August there is a water surplus, while from May to July water demand is high. Hence, during the scarce period, irrigation water needs to be equally distributed, and is managed by a group of people forming awater users' association, which includes a diverse group of people (e.g. water users, irrigators and technical personnel of the water system). Conversely, it has been observed that other organizations have also been playing a prominent role in securing irrigation water through several interventions and financial help.

In both study areas, there exists a traditional water distribution mechanism, comprising different local committee representatives and a water distribution committee, regulated through the local *jirgah* system. There also exist some kinds of informal committees that regulate water distribution and manage other issues regarding irrigation water, including drinking water supply. When asked about the presence of a water users' association (WUA), 83% of 102 households in Passu reported the presence of a water users' group, while the remainder stated the absence of any such association. In Morkhun, 76% of 67 households reported the presence of water users' groups, while the remainder said that no water users' groups exist.

The main responsibilities of these groups are to resolve water issues, regulate equal water distribution and maintain the water conveyance system; however variation in their roles was observed in the two villages. In Passu, their major roles are to solve water issues and maintain the water conveyance system, while in Morkhun, allocation of equal water and its distribution, and maintenance of the water conveyance system are the prominent roles.

To validate the information obtained, we analysed people's perception on the same, and found out that 95% of the respondents in Passu mentioned the existence of such committees. Conversely, in Morkhun only 35% agreed on the presence of a traditional water distribution mechanism, which is regulated through community representatives, while the remainder disagreed on it (Table 3). On the other hand, the majority reported equal water distribution. The unequal distribution at Morkhun was likely due to maintenance of water distribution canals, larger size of farms and less water supply and scarcity of irrigation water.

TABLE 3 Opinion of local people about distribution of irrigation water

		Presence of traditional water distribution mechanism			Equitable water distribution	
Village	n	Agree (%)	Disagree (%)	n	Agree (%)	Disagree (%)
Passu	88	95	5	89	94	6
Murkhun	60	35	65	62	90	10

5 | PREFERRED POTENTIAL SOURCES OF IRRIGATION WATER SUPPLY IN FUTURE

To ensure a participatory approach when establishing the intervention, we collected information on the communities' preference for future irrigation sources and the system they want to have in these villages. Water lifting from the river and glacier was the major preference of the majority of households, i.e. 99% in Passu and 69% in Morkhun, the details of which are provided in Table 4. In Morkhun, 23% of respondents preferred to continue with the existing resources, while underground water extraction was mentioned by 3% and 5% of the respondents mentioned available rainfall in the future as a source of irrigation. However, the communities' preference for groundwater extraction might be technically feasible, as groundwater could be available along the riverbanks due to seepage of river water. In general, groundwater use for domestic water supply is not common in these areas except in the low-lying settlements in Gilgit town and a few riverside villages (Ahmed and Joyia, 2003).

6 | WATER-INDUCED HAZARDS AND THEIR IMPACT

The basin is prone to several hazards, which have been impacting on the lives and livelihoods of local communities over the course of several decades. Flash floods, landslides, riverbank erosion and sedimentation, and GLOFs are the most common hazards prevalent in the valley (Butz, 1989; Parveen *et al*., 2015; Hill, 2017), which have impacted on the irrigation-based agriculture in the region. The literature showed that several glacial impoundments and GLOFs have been recorded in the Karakoram (Hewitt and Liu, 2010), with the Hunza valley accounting for the greatest number of disastrous incidents (about 339) (Ashraf *et al*., 2012). It has also been seen that the basin has about 47 major glacial lakes (Ashraf *et al*., 2012), with one potentially dangerous lake. For instance, the catastrophic flooding in 1841 (Kreutzmann, 2012); ice dam burst of 1884, followed by similar events in 1893, 1905, 1906, 1927 and 1928 (Water Resources Research Institute (WRRI), 2008; Ashraf *et al*., 2012); Attabad Lake formation due to rockfall and flooding in 2010 (Zaidi *et al*., 2013); Batura Glacier advance in Zharkhon (Parveen *et al*., 2015) are a few of them. These events are said to be exacerbated by climate change, mainly in higher altitudes, as its impact is said to be more pronounced in the high-altitude mountains of the Hindu Kush Himalaya (Rajbhandari *et al*., 2014; Ali *et al*., 2015). Warming-induced melt, precipitation in the form of rainfall, and formation of potentially dangerous glacial lakes leading to floods and debris flow impact the downstream area (Eriksson *et al*., 2009). We therefore tried to identify the site-specific hazards prevalent in the pilot area as these are one of the major components in establishing any intervention and ensuring its effectiveness and sustainability.

6.1 | Passu

The inhabitants of Passu have been affected from several glacio-hydrological hazards as far back as 1873. Glacial advances and surges were reported to impact the cultivated land in 1905, 1910 and 1944 in the Shimshal Valley (Kreutzmann, 2012). This village is said to have been formed several times (i.e. four times); as a result of frequent erosion Passu has been frequently washed

TABLE 4 Preferred strategies to ensure irrigation water supply in future

Village	n	Lifting water from river and glacial lake (%)	Existing system (%)	Underground water (%)	Expecting rainfall (%)
Passu	91	99	1	–	–
Murkhun	65	69	23	3	5

Source: survey data.

away by glacial hazards (Hewitt and Liu, 2010; Kreutzmann, 2012) and this created water scarcity, either by destroying the irrigation canal or drying up the local water supply. The cultivated land mass was also reduced due to lateral undercutting of the riverbank (Kreutzmann, 2012).

In recent decades, disasters have increased in frequency due to the increased number of glacial lakes, the most significant being the 2007 and 2008 events (Din *et al.*, 2014). Five different GLOF events were recorded in the Ghulkin and Passu glaciers in 2008, creating a huge loss of infrastructure, settlement and cultivation land in Passu village. This destroyed the Passu main canal and the Murabadab canal and also affected irrigation-based agriculture in the village. Moreover, riverbank erosion was also found to be common in Passu; this has occurred since 1974, affecting agricultural land and irrigation canals. For example, riverbank erosion in 2009 destroyed the Janabad irrigation canal including productive land and trees, while in 2011, the Lalzor, Khock and Muradabad canals were destroyed, and 50 000 m^2 of productive land eroded.

6.2 | Morkhun

Morkhun village has also been experiencing several glacial fluctuations; however, not much information regarding their magnitude and impact on irrigation and agricultural land was available in the literature. Hence, AKAH was consulted about any recorded disasters, and they reported a few events of flood, debris flow and erosion. The most recent event (flood/debris flow/streamflow erosion), which took place in 2015, created great damage to irrigation canals and hydropower plants, and also eroded barren and cultivated land. All the irrigation canals were destroyed in the 2015 event. Unlike Passu, flash floods and landslides have also been identified in Morkhun together with GLOF and erosion. In last 5–10 years, flash floods have been the most common and prominent hazard, followed by landslides and riverbank erosion.

The major natural hazards that have occurred in Passu and Morkhun and their impact and the name of irrigation canals destroyed are summarized in Table 5 and shown in Figures 2 and 3.

7 | COMMUNITIES' ADAPTATION PRACTICES AND RESPONSES

The frequently occurring challenges have severely impacted irrigation- based agriculture in the region. The local communities have therefore developed a set of adaptation strategies to secure irrigation water by integrating suitable mechanisms and adjustment, such as

TABLE 5 Summary of hazards in Passu and Morkhun

S.No	Hazard	Year	Impact	Canals destroyed
Passu				
1.	River bank erosion	1974	Eroded productive and barren land, trees	Janabad
2.	GLOF/flood	1985–1986	Destroyed houses and cattle shed	Passu main canal, Muradabad
3.	GLOF/flood	1910	Destroyed houses, farm lands, orchards and potato and wheat fields	Janabad,
4.	GLOF/flood	2008	Destroyed cattle sheds, forest land and fruit trees	Passu main canal, Muradabad
5.	River bank erosion	2011	Eroded 50 000 m^2 productive land	Lalzor Khock Muradabad
6.	River bank erosion	2009	Destroyed productive land and trees	Janabad,
Morkhun				
7.	Flood/debris flow/erosion	2005	Eroded canal and damaged canal headworks	Qalhabar, Yuur, Rech, Abjat, Tanzeem, Chukul Ghar, Jomolabad, Sharshigduur
8.	Flood/debris flow/stream bank erosion	2010	Eroded barren and cultivated land, damaged canals, hydropower, electric poles, mill	Qalhabar, Yuur, Rech, Abjat, Tanzeem, Chukul Ghar, Jomolabad, Sharshigduur, Jomolabad
9.	Flood/debris flow/stream bank erosion	2014; 2015	Eroded barren and cultivated land, damaged irrigation canals, trees, hydropower, bridge	Qalhabar, Yuur, Rech, Abjaat, Tanzeen, Chukul Ghar, Jomolabad, Sharshigduur

Source: AKAH.

mobility, technological advances and crop replacement. In the valley, land-use practices and local adaptation have been developed because of several glacial fluctuations and hazards (Parveen *et al*., 2015). The adaptation strategies, however, vary among the villages in the Hunza Valley, based on their location. Back in 1857, people migrated to new places and started cultivation due to floods in the valley (Parveen *et al*., 2015). Migration was considered a popular strategy back then and was also practised during the 1960 flood, along with an attempt to restore abandoned land (Kreutzmann, 2012). However, migration was not practised fully as not everyone was able to migrate due to scarce resources (Ashraf *et al*., 2012).

A committee—*warabandi*—was also formed to allocate equal water. This committee ensures irrigation turns and farmers' contribution to annual canal maintenance either in the form of labour or products (Velde, 1989). However, the water allocation was considered inappropriate as locals were reluctant to follow the schedule because of their insistence that the ownership of the water lies with the original settlers (Parveen *et al*., 2015).

In addition, several structural measures were found to be operational in the valley for coping with several challenges. For example, since the 1960s relocation or cutting of irrigation canal intakes was carried out by villagers in the valley (Parveen *et al*., 2015). In Ghulkin village, the intake was shifted from the Ghulkin Glacier to the lake on Ghulmit Glacier during the Mir regime (1945–1974), and in Borith, canals were diverted across the lateral moraine by construction of a canal. Moreover, a syphon was used to lower the water level and drain the lake, posing the threat of a GLOF hazard in the Ghulkin Glacier (Ashraf *et al*., 2012). Sedimentation tanks or stilling basin were also built at the head of the main canals in the *kuhl* system for mitigating the sedimentation problem (Velde, 1989).

Moreover, during the peak irrigation season in Passu and Morkhun, the Water and Power Department closes the hydro-power stations from 7 am to 4 pm to regulate water in the irrigation canals. There also exist some forms of group called *yatkoin*, established for specific canals. These oversee the entire canal, repair minor leakages and inform the community about major damage or outbreaks for collective repair works. Sometimes, locals themselves also help to minimize water losses from the canals. For instance, PVC pipes are being used at vulnerable spots to reduce losses in the Imamabad and Karimabad canals (field survey).

Communities have been actively involved in securing irrigation water despite several challenges, however some of the strategies have failed to secure undisturbed water. For instance, intake relocation from the Ghulkin Glacier to Ghyper Zhui Lake failed because of the inaccessible location of the glacial fluvial outlet, and an attempt to restore the irrigation canal in Passu failed due to glacier down waste (Parveen *et al*., 2015). The effort to control the undercutting of riverbanks in Passu also failed due to the great number of natural hazards (Kreutzmann, 2012). Moreover, in 2013 the AKRSP-funded pipeline to source water from an ice cliff at an altitude of 2920 m.a.s.l. failed due to the unavailability of meltwater at the high altitude (Parveen *et al*., 2015). In Ganish village, the canal established by AKRSP was destroyed by floods in 1988/1989 and was not repaired. The diesel pump which was introduced in the village was not operational due to a dispute over landownership, and the high cost of fuel and maintenance of the pump (Parish, 1999). Beside these, other socio-economic factors such as conditions of poor livelihoods, complex terrain, resource constraints, poor management and lack of coordination could also exacerbate the strategies' ineffectiveness (Ashraf *et al*., 2012), including male migration which is prevalent in the Hunza valley. This leads to a lack of manpower in maintaining the irrigation systems and looking after agricultural fields, leading to increased barren land (Parveen *et al*., 2015). About 77% of households have migrants in Hunza and of them 99% are male. Male outmigration has changed the traditional division of labour, hence women have either to perform several tasks that were previously assigned to men or hire an external labour force to continue farming activities. Outmigration has also limited the ability of women to leave their villages to get essential services and items (Gioli *et al*., 2014) required for farming.

8 | PROJECT INTERVENTIONS AS AN ALTERNATIVE OPTION TO THE TRADITIONAL IRRIGATION SYSTEM

In line with the communities' preference, ICIMOD along with its partners demonstrated interventions for agricultural water management by a lifting technique using a solar pump in these two villages. To our knowledge, an innovative alternative to the conventional irrigation system—a solar lift pumping system with efficient drip irrigation—is the first of the kind in this area, and which has been established with several modifications. This was considered a potential option where glacier melt irrigation is not available, and an alternative option to inconsistent glacier meltwater supplies to bring uncultivated barren land under cultivation. This also allowed electricity dependency to be overcome as it uses clean renewable energy.

The technical specification of the installed pump is a DC submersible pump of 1 HP (∼745 W) capacity, operated with a 500 W solar panel, and pumping capacity of

7.5 l min^{1}. This is capable of lifting water vertically up to a height of 30.5 m (∼100 feet). A similar system has been used in the plains of Pakistan, however the solar pump installed on the pilot site was customized based on site characteristics, to minimize the impact of sediment load on the impellers. This would allow the system to be functional and sustainable. Initially, a sump (well) was constructed at the riverbank to trap the suspended sediment, however, excessive sediment load impacted the impellers and hampered their functionality. Consequently, a filter made from UPVC pipe (0.25 m diameter (10 inch), 4 m long (∼13 feet)) was attached to the outer layer of the pump with a fine-mesh green net to impede sediment entry. This was done differently in the two villages—bolted on in Passu and tightly bound in Morkhun, both of which were firmly tied to trees for safety. Then, the filter was placed transverse to the river flow direction. The lessons from the earlier failure and further modification meant it was successful in trapping the sediment and allowed water pumping.

The water was then efficiently distributed through a high-efficiency irrigation system (HEIS)—surface and pressure-compensating drip irrigation. A storage tank above the field was established in Morkhun (not in Passu) and water was applied to apple orchards as seen in Figure 4. Further to this, to increase moisture retention time and avoid weed production, mulch was used. This system proved to decrease the need for labour and minimize water losses during distribution and application, and benefited about 1200 people in the two villages. The locals have also shown a positive response in terms of ease of operation, hence it can be considered a suitable adaptation measure in locations with a similar geographical setting.

9 | ECONOMIC VIABILITY ASSESSMENT OF THE SOLAR PUMP

Economic indicators of the project considering future cash flow uncertainty were calculated in detailed discussions with the agricultural experts in the region. Wear and tear of the equipment, fruiting time and variation in fruit cost, survival ratio of the fruit trees, labour cost and increasing the discount rate were taken into consideration.

The total investment cost of the solar drip irrigation system is PKR4 640 000 (US$29 100 as at July 2019), which includes equipment cost and average annual operating cost. The average operating cost is assumed to be PKR10 000 (US$62.7) for the first 5 years, PKR20 000 (US $125) for 6–10 years, PKR30 000 (US$188) for 11–15 years and PKR40 000 (US$251) for 16–20 years, when a 20-year life cycle is considered. This also incorporated the amount for inflation and depreciation, and repair and labour costs. It was observed that the return on investment in irrigation for crop production was significantly influenced by the development of advanced agricultural technology because drip irrigation offers economic and agro-technical advantages.

The analysed economic parameters showed that the system is economically feasible. The NPV was found to be PKR20 900 000 (US$131 000) which is positive, indicating economic viability since the discounted benefits of the solar drip irrigation projects exceed the discounted cost of the projects. Likewise, BCR with a 12.3% discount

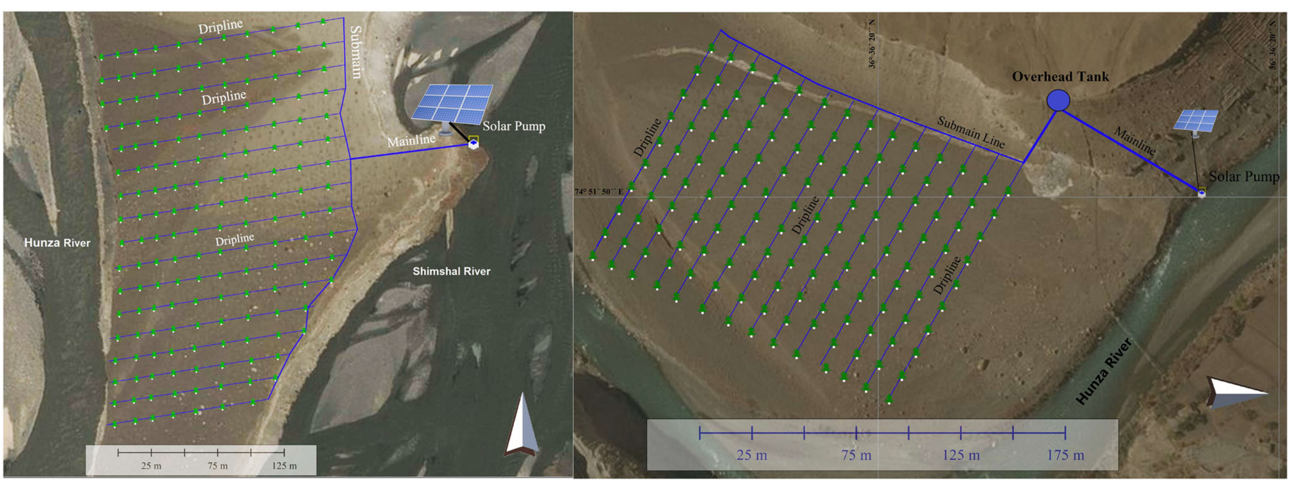

FIGURE 4 Illustration of solar-powered pump and drip to irrigate barren land: Passu on the left and Morkhun on the right

TABLE 6 Economic viability of drip irrigation system

Parameter	Value
NPV (US$)	131 000
IRR	31%
BCR	4.96
Payback period (years)	10.9

rate was found to be 4.96, and the IRR of the system was found to be 31%, higher than the discounting factor 12.3% (Table 6). The findings suggested that the system is economically viable, and the investment should be encouraged. Furthermore, it was calculated that the initial investment cost would be fully recovered in 10.9 years, the payback period therefore is around 11 years, and repayment of the investment would start from the eighth year.

It would therefore be beneficial to inform the community about the economic and environmental benefits of this technology. This system can be considered as climate change resilient, as it uses clean renewable energy and is simple to operate. Hence, it could be replicated in other places with location-specific modifications as demonstrated in the pilot site. Despite its benefits, the huge capital cost/investment is difficult for small farmers to afford, therefore it would be promising if government could take the initiative in providing either financial support or subsidy to implement the system. Local government could also play a significant role in carrying out research activities and introduce this system through its mega programmes. Likewise, financial institutions could also contribute by providing low-interest rate loans to the community. On the other hand, the maintenance cost, and lack of local capacity in repairing and maintaining the system, need to be taken into consideration when upscaling, together with the climate of the area, the crops to be irrigated and the location of the cultivable land. In our intervention, since the local community and agricultural experts argued that the project locations are not highly vulnerable to hazards such as landslide and floods, the hazard aspect was not considered.

10 | CONCLUSION

Glacier meltwater is the major source of irrigation in the Hunza River basin, which started back in 1780 by diverting water from the Batura Glacier. This was later upgraded and extended under several rulers and by various institutions/organizations. These systems faced several challenges in terms of location, climate, natural hazards and other socio-economic issues. Challenges were addressed by several adaptation measures such as migration, intake relocation and canal restoration, some of which however were not successful.

ICIMOD, with its partners through a consultative process and active involvement of the community, demonstrated an innovative solar lifting package to irrigate barren land. This system could be considered an alternative technological package to existing/traditional systems, being energy and water efficient and with a capacity to irrigate barren land through a water-lifting technique. Being environmentally and economically feasible, and technically manageable, it could be replicated in other geographical regions similar to Gilgit-Baltistan. The solar pump has flexibility of modification based on the requirements of locations, as seen from the project site. The modified system worked well in a river containing a higher silt and sediment load. The technological package is also less labour intensive; for example, the drip system reduces the time needed for irrigation as plant to plant attention is not required, and it is particularly useful for the Hunza valley where male outmigration is very high.

However, the high initial investment and longer payback period are major factors that seem to hinder replication of the system. To overcome this, both local and provincial governments and financial institutions could provide financial incentives or subsidies to the community for implementing the system. Developmental organizations could also support the initiative and incentivize farmers to adopt the technologies to irrigate their barren lands, which are otherwise not possible to irrigate. An important step in minimizing the potential risk and ensuring sustainability could be taken by providing local ownership through a strong participatory approach, capacity building of local communities and encouraging group farming and establishing cost–benefit sharing mechanisms in a group rather than individually.

As of today, this system has been able to capture the interest of people as well as nodal agencies. The United Nations Development Programme (UNDP) with the World Wildlife Fund (WWF) has outscaled solar pumps in 10 different sites in Gilgit-Baltistan. The federal government through the Federal Water Management Cell of the Ministry of Food Security and Research through its national programme for Enhancing the Command Area of Small and Mini Dams in Barani Areas of Pakistan (Gilgit-Baltistan component) has a plan to install 150 solar-powered irrigation pumps in 10 districts costing 120 million Pakistani rupees (based on personal communication with WWF-Gilgit). If the projects are successfully established and operated, a majority of households are said to benefit and can enhance their livelihood activities through economic generation activities through increased crop yield.

ACKNOWLEDGEMENTS

The authors would like to thank the Indus Basin Initiative team of ICIMOD, the WWF Gilgit team, the Pakistan Council of Research in Water Resources (PCRWR)—Pakistan team, and the AKAH team for their support during field implementation of the technological package and completing the study. Special thanks go to the communities of Passu and Morkhun villages for sharing their knowledge with us during field visits and surveys.

This study was undertaken under the Indus Basin Initiative of ICIMOD, which contributes to the Sustainable Development Investment Portfolio and is supported by Australian aid. The study was partially supported by core funds of ICIMOD contributed by the governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland and the United Kingdom).

DISCLAIMER

The views and interpretations in this publication are those of the authors. They are not necessarily attributable to their organizations.

ORCID

Amjad Ali https://orcid.org/0000-0002-5840-8848

REFERENCES

Ahmed, S. and Joyia, M.F. (2003) *Northern areas strategy for sustainable development*. International Union for Conservation of Nature and Natural Resources, Background Paper: Water—Pakistan, Northern Areas Programme, ***Gilgit, Pakistan*** 67.

Ali, S., Li, D., Congbin, F. and Khan, F. (2015) Twenty first century climatic and hydrological changes over Upper Indus Basin of Himalayan region of Pakistan. *Environmental Research Letters*, 10(1), 014007. https://doi.org/10.1088/1748-9326/10/1/014007

Ashraf, A., Naz, R. and Roohi, R. (2012) Glacial lake outburst flood hazards in Hindukush, Karakoram and Himalayan ranges of Pakistan: Implications and risk analysis. *Geomatics, Natural Hazards and Risk*, 3(2), 113–132. https://doi.org/10.1080/19475705.2011.615344

Asmon, I. and Rothe, R. (2006) *The economic feasibility of drip Irrigation in Afghanistan*. Alternative livelihoods project – south (alp/s). https://afghanag.ucdavis.edu/irrigation-natural-resource/files/irrigation-feasibility.pdf

Baig, S.U. (2018) Spatio-temporal analysis of glacial ice area distribution of Hunza River Basin, Karakoram region of Pakistan. *Hydrological Processes*, 32(10), 1–11. https://doi.org/10.1002/hyp.11508

Butz, D. (1989) The agricultural use of melt water in hopar settlement. *Pakistan. Annals of Glaciology*, 13, 35–49.

Din, K., Tariq, S., Mahmood, A. and Rasul, G. (2014) Temperature and precipitation: GLOF triggering indicators in Gilgit-Baltistan, Pakistan. *Pakistan Journal of Meteorology*, 10(20), 39–56.

Eriksson, M., Jianch, X., Shrestha, A.B., Vaidya, R.A. and Nepal, S. (2009) Perspectives on water and climate change adaptation: The changing Himalayas – Impact of climate change on water resources and livelihoods in the Greater Himalayas. *International Center for Integrated Mountain Development*, 1–22. https://doi.org/10.1144/SP312.3

Fisher, I. (1907) *The rate of interest. McMaster University for the History of Economic Thought*. New York, USA: Macmillan.

Gaspars-Wieloch, H. (2019) Project Net Present Value estimation under uncertainty. *Central European Journal of Operations Research*, 27, 179–197.

Gioli, G., Khan, T., Bisht, S. and Scheffran, J. (2014) Migration as an adaptation strategy and its gendered implications: A case study from the Upper Indus Basin. *Mountain Research and Development*, 34(3), 255–265.

Hashmi, A. A, and Shafiullah, A. (2003) *Northern areas strategy for sustainable development*. International Union for Conservation of Nature and Natural Resources, Background Paper: Agriculture and Food Security—Pakistan. ***Gilgit, Pakistan***.

Hewitt, K. (2011) Glacier Change, Concentration, and Elevation Effects in the Karakoram Himalaya, Upper Indus Basin. *Mountain Research and Development*, 31(3), 188–200. https://doi.org/10.1659/MRD-JOURNAL-D-11-00020.1

Hewitt, K. and Liu, J. (2010) Ice-Dammed Lakes and Outburst Floods, Karakoram Himalaya: Historical Perspectives on Emerging Threats. *Physical Geography*, 31(6), 528–551. https://doi.org/10.2747/0272-3646.31.6.528

Hill, J.K.W. (2017) Supporting farmer-managed irrigation systems in the Shigar valley, Karakorum: role of the government and Aga Khan rural support programme. *Journal of Mountain Science*, 14(10), 2064–2081. https://doi.org/10.1007/s11629-017-4496-7

Immerzeel, W.W., Pellicciotti, F. and Shrestha, A.B. (2012) Glaciers as a proxy to quantify the spatial distribution of precipitation in the Hunza Basin. *Mountain Research and Development*, 32(1), 30–38. https://doi.org/10.1659/MRD-JOURNAL-D-11-00097.1

International Fund for Agricultural Development (IFAD). (2015) *Economic Transformation Initiative Gilgit-Baltistan Programme, Islamic Republic of Pakistan* Design Report. https://www.ifad.org/en/document-detail/asset/40143518

Khan, R.N.A. (2013) *Chapter - 3 Geographical Profile of Indus Basin*. 47-70. http://shodhganga.inflibnet.ac.in/bitstream/10603/14384/7/chapter_3.pdf

Kreutzmann, H. (2012) After the flood. Mobility as an adaptation strategy in high Mountain Oases. The case of Pasu in Gojal, Hunza valley, Karakoram. *Die Erde*, 143(1–2), 49–73.

Lutz, A.F., Immerzeel, W.W., Kraaijenbrink, P.D.A., Shrestha, A.B. and Bierkens, M.F.P. (2016) Climate change impacts on the Upper Indus Hydrology: sources, shifts and extremes. *PLoS ONE*, 11(11), 1–33. https://doi.org/10.1371/journal.pone.0165630

Nüsser, M. (2017) Socio-hydrology: a new perspective on mountain waterscapes at the nexus of natural and social processes. *Mountain Research and Development*, 37(4), 518–520. https://doi.org/10.1659/MRD-JOURNAL-D-17-00101.1

Parish, R. (1999) The unseen, unknown and misunderstood: complexities of development in Hunza, Pakistan. *International Journal of Sustainable Development and World Ecology*, 6(1), 1–16. https://doi.org/10.1080/13504509.1999.9728438

Parveen, S., Winiger, M., Schmidt, S. and Nüsser, M. (2015) Irrigation in Upper Hunza: evolution of socio-hydrological interactions in the Karakoram, northern Pakistan. *Erdkunde*, 69(1), 69–85. https://doi.org/10.3112/erdkunde.2015.01.05

Qureshi, M.A., Yi, C., Xu, X. and Li, Y. (2017) Glacier status during the period 1973–2014 in the Hunza Basin, Western Karakoram. *Quaternary International*, 444, 125–136. https://doi.org/10.1016/j.quaint.2016.08.029

Rajbhandari, R., Shrestha, A.B., Kulkarni, A., Patwardhan, S.K. and Bajracharya, S.R. (2014) Projected changes in climate over the Indus river basin using a high resolution regional climate model (PRECIS). *Climate Dynamics*, 44(1–2), 339–357. https://doi.org/10.1007/s00382-014-2183-8

Rehmat, A. (2006) Socio-Geographical Study of Hussaini Village-Hunza. *Journal of Pakistan Society of Geographic Information Systems MSGIS*.

Shaheen, F.A., Wani, M.H., Wani, S.A. and Norphel, C. (2013) Climate change impact in cold arid desert of north – western Himalaya: community based adaptations and mitigations. In: Nautiyal, S., Rao, K., Kaechele, H., Raju, K. and Schaldach, R. (Eds.) *Knowledge Systems of Societies for Adaptation and Mitigation of Impacts of Climate Change*. Environmental Science and Engineering. Berlin, Heidelberg: Springer, pp. 239–256. https://doi.org/10.1007/978-3-642-36143-2_15

Shrestha, M., Koike, T., Hirabayashi, Y., Xue, Y., Wang, L., Rasul, G. and Ahmad, B. (2015) Integrated simulation of snow and glacier melt in water and energy balance-based, distributed hydrological modeling framework at Hunza river basin of Pakistan Karakoram region. *Journal of Geophysical Research*, 120(10), 4889–4919. https://doi.org/10.1002/2014JD022666

Sidky, M.H. (1993) Irrigation and the political evolution of the high-mountain kingdom of Hunza. *Asian Affairs*, 24, 131–144. https://doi.org/10.1080/714041207

Sidky, H. (1997) Irrigation and the Rise of the State in Hunza: A Case for the Hydraulic Hypothesis. *Modern Asian Studies*, 31 (4), 995. https://doi.org/10.1017/S0026749X00017236

Velde, E.J.V. (1989) *Irrigation Management in Pakistan Mountain Environment*. IWMI Books, Reports H005715, International Irrigation Management Institute. Country paper- Pakistan no. 3.Colombo, *Sri Lanka*.

Viviroli, D., Weingartner, R. and Messerli, B. (2003) Assessing the hydrological significance of the world's mountains. *Mountain Research and Development*, 23(1), 32–40.

Water Resources Research Institute (WRRI). (2008) *Community Based Survey for Assessment of Glacial Lake Outburst Flood Hazards (GLOFs) in Hunza River Basin*. Islamabad, Pakistan: National Agricultural Research Centre.

Wijngaard, R.R., Lutz, A.F., Nepal, S., Khanal, S., Pradhananga, S., Shrestha, A.B. and Immerzeel, W.W. (2017) Future Changes in Hydro-climatogical Extremes in the Upper Indus, Ganges, and Brahmaputra River Basins. *PLoS ONE*, 12(12), 1–26. https://doi.org/10.1371/journal.pone.0190224

World Bank. (2010) *Pakistan, Gilgit-Baltistan Economic Report, Broadening the Transformation*. World Bank. Retrieved from: http://documents.worldbank.org/curated/en/939151468062972670/Pakistan-Gilgit-Baltistan-economic-report-broadening-the-transformation

Zaidi, A. Z., Yasmeen, Z. and Siddiqui, M.D. (2013) *Glacial Lake Outburst Flood (GLOF) risk mapping in Hunza River Basin (Pakistan) using geospatial techniques*. RAST 2013 - Proceedings of 6th International Conference on Recent Advances in Space Technologies, 191–195. https://doi.org/10.1109/RAST.2013.6581198

How to cite this article: Dhakal MP, Ali A, Khan MZ, et al. Agricultural water management challenges in the Hunza River Basin: Is a solar water pump an alternative option? *Irrig. and Drain*. 2021;1–15. https://doi.org/10.1002/ird.2563