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Cryosphere-Fed Irrigation Networks in the Northwestern Himalaya: Precarious Livelihoods and Adaptation Strategies Under the Impact of Climate Change

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Irrigated agriculture is crucial for the livelihood security of mountain communities in the northwestern part of the Himalayan arc and adjoining regions of the Karakoram, Hindu Kush,

and Trans-Himalaya. Using meltwater from glaciers, snow, and permafrost, mountain dwellers have developed sophisticated techniques to cope with recurrent water scarcity caused by glacier retreat, glacier thinning, and seasonal snow-cover dynamics. Based on case studies from the Nanga Parbat region, Hunza-Karakoram, and Ladakh, this paper seeks to identify general patterns and site-specific characteristics of agrarian practices and adaptation strategies in the face of climate change. The comparative case study approach reveals differing responses to water scarcity, which depend on local conditions and include the construction of new irrigation channels,

installation of pipes, and building of artificial ice reservoirs. The biophysical investigation is supplemented by an exploration of socioeconomic factors and is based on long-term research in the 3 study areas. The methods used include multitemporal remote sensing analysis, mapping of natural water storage components and irrigation infrastructure, and interviews. Taking into consideration social factors such as the expansion of off-farm income opportunities and market integration, we identify key variables that affect the sustainability and resilience of land use systems. Outcomes are diverse, ranging from the intensification and extension of irrigated mountain agriculture to the abandonment of irrigated areas, depending on local sociohydrological settings.

Keywords: Cryosphere dynamics; irrigation networks; adaptation strategies; sociohydrology; Himalaya; India; Pakistan.

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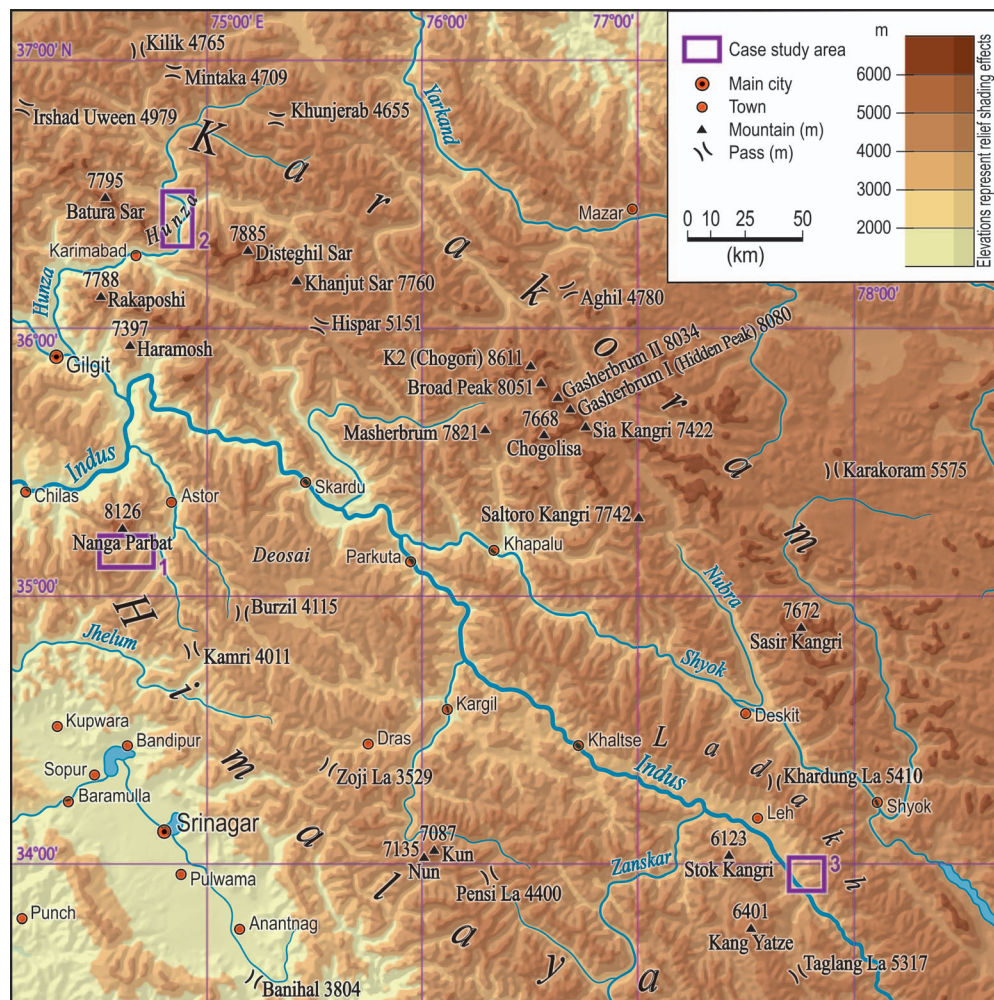
Introduction

Irrigated agriculture is crucial for the livelihood security of local communities in the mountain deserts of the upper Indus Basin (Kreutzmann 2000, 2011). Relying on meltwater from glaciers, snow, and permafrost, villagers in the northwestern part of the Himalayan arc, the Karakoram, and the Hindu Kush, have developed sophisticated irrigation techniques and infrastructure to cope with recurrent water scarcity (Ashraf and Iqbal 2018). These irrigation networks and management systems are situated at the interface between cryosphere dynamics and socioeconomic development processes. Cryosphere-fed irrigation networks in arid mountain regions have been framed as “sociohydrological interactions” (Nüsser et al 2012) to emphasize the interconnectedness of

cryosphere dynamics, glaciofluvial runoff, water distribution, socioeconomic conditions, institutional arrangements, development interventions, and historical trajectories. In general, changes in water availability coevolve with land use transitions, local environmental knowledge, and external development interventions.

Research has primarily focused on the larger scale of the entire Indus Basin with its striking dependence on meltwater and the expected adverse consequences of climate change for downstream populations (Archer et al 2010; Kaser et al 2010; Ali et al 2015; Lutz et al 2016; Pritchard 2017) or on political aspects of water management and water-sharing issues between India and Pakistan (Adeel and Wirsing 2017; Hill 2017). The effect of cryosphere change on local meltwater-dependent irrigation practices has received much less attention

FIGURE 1 Location of case study areas. 1: Rupal Valley in the northwestern Himalaya; 2: Upper Hunza Valley in the western Karakoram; 3: Igloo catchment in the Trans-Himalaya of Ladakh. (Map by the authors)



(Kreutzmann 1998), even though dependence on glacier meltwater and vulnerability to cryosphere dynamics are of serious concern in all mountain areas. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2014) states that linkages between local livelihoods, environmental dynamics, and land resources are poorly understood. All of that report's scenarios project that glaciers will continue to shrink even without further temperature increase, which reinforces the urgency of understanding adaptation to glacier meltwater dynamics.

Continuity and change in irrigation networks have been analyzed in the context of mountain agriculture, land use and land cover change, livelihood strategies, socioeconomic transformation, and political institutions for various locations in the upper Indus Basin (Kreutzmann 1993; Nüsser 2001; Dame and Mankelov 2010; Hill 2017). Besides commonalities of gravity-fed canal transfer of meltwater to the cultivated fields, these studies confirm site-specific characteristics of water

diversion and irrigation networks and practices. Spatially and temporally differentiated and localized cryosphere responses to climate change across the region include glacier surges, glacier lake outburst floods (GLOFs), glacier retreat, and downwasting.

Agrarian strategies to adapt to uncertain water availability from cryosphere components are quite diverse, depending on environmental, socioeconomic, and political conditions (Kreutzmann 2011). This article draws on 3 case studies from the upper Indus Basin: the first from the Nanga Parbat region in the northwestern Himalaya, the second from the Hunza Valley in the western Karakoram, and the third from the Trans-Himalaya of Ladakh (Figure 1). The first 2 study areas are located in Gilgit-Baltistan, Pakistan, and the third in the Indian state of Jammu and Kashmir. For each of these studies, cryosphere dynamics and water availability are contextualized against changing water management and adaptation strategies to enable a comparative analysis. In this article, we highlight only a limited subset of social

factors that are directly related to cryosphere dynamics, with the aim of contributing to the forthcoming Intergovernmental Panel on Climate Change Assessment Report on strategies to adapt to climate change in high mountain areas.

Material and methods

We used an integrated approach to analyze glaciohydrological and socioeconomic data. Glacier changes were detected using multitemporal satellite imagery with data from the 1960s (Corona), from around 2000 (Landsat), and from 2018 (Sentinel-2). High-resolution data (QuickBird, KOMPSAT, GeoEye) were used for mapping of irrigation networks, further validated by field visits for ground truthing. Information on the evolution of irrigated agriculture and primary socioeconomic data were collected in successive field surveys for the 3 case studies. In this context, the role of irrigated agriculture for livelihood security and the relevance of local environmental knowledge in the development process were examined by interviews with smallholder farmers, community water managers, representatives of nongovernmental organizations (NGOs), and government officials. As few written records exist, information about socioeconomic and environmental conditions was based on oral history.

To allow for a comparative perspective of site-specific differences in adaptation strategies, evidence from the 3 local case studies was collated according to a set of criteria including physical and hydrological conditions, cryosphere dynamics including relative positions of glacier fronts to agricultural fields, socioeconomic conditions, development processes, and institutional arrangements in water management. Comparative data for the case study areas draw on earlier research (Parveen et al 2015; Nüsser and Schmidt 2017; Nüsser et al 2019) and updated satellite imagery.

Case studies of local irrigation systems

The Rupal Valley in the northwestern Himalaya

Located south of the main ridge of Nanga Parbat (8126 m), the upper portion of the Rupal Valley is covered by several glaciers. The stream forms an affluent of the Astore River, a tributary of the upper Indus River. As more than 75% of the total annual runoff in the Astore Basin depends on meltwater produced by glaciers and seasonal snow cover (Farhan et al 2015), irrigated agriculture in the Rupal Valley is dominantly cryosphere-fed. Cultivated fields are mostly located on isolated plateaus of basal moraine and debris fans, towering some 50 m above the stream. Due to this topographic setting, resulting from fluvial dissection and incision, irrigation networks are completely decoupled from glaciers in the

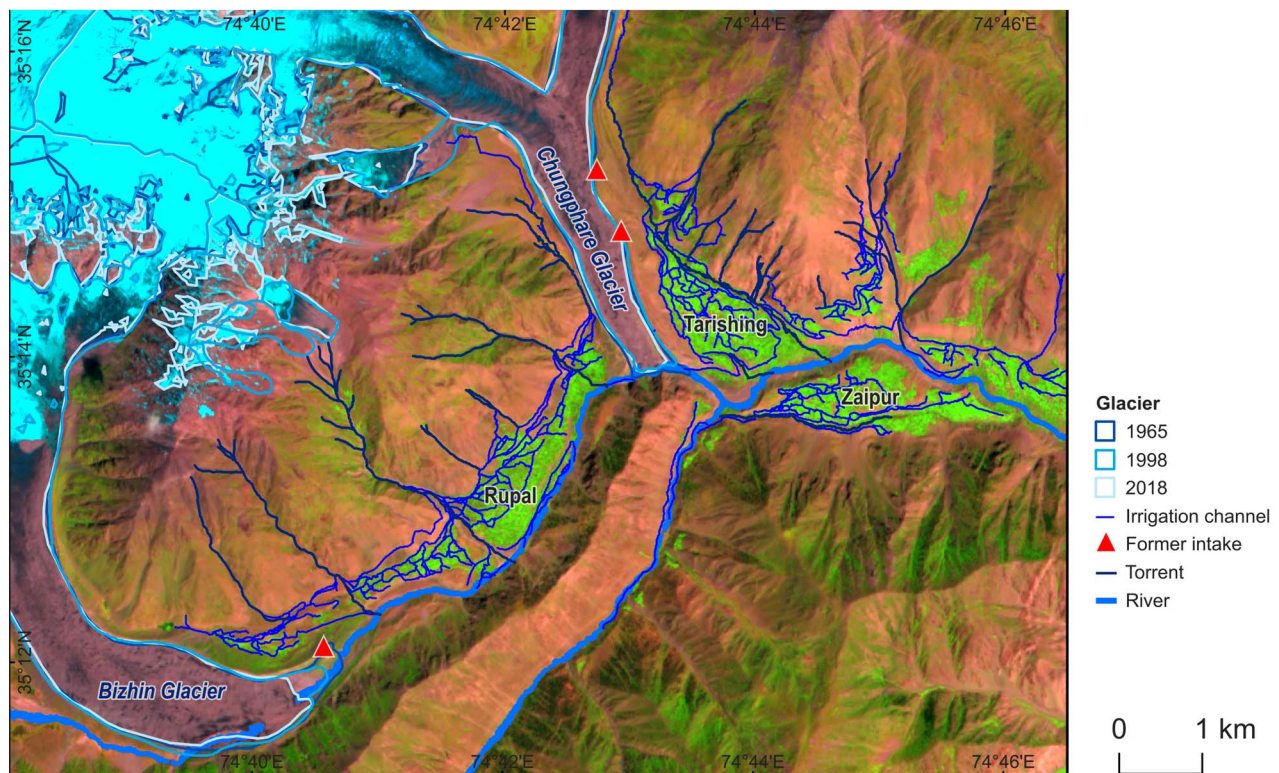
upper valley. Chungphare Glacier covers an area of 27.3 km² over a length of 11.6 km to the lowest tongue position in the valley, terminating at an elevation of 2850 m in 2018. The glacier front receded by 390 m between 1965 and 2018. Cultivated fields of the 2 adjoining villages Tarishing and Rupal are located high above the glacier tongue; therefore the main meltwater outlet of Chungphare Glacier cannot be tapped for gravity-fed water transfer.

Historical reports and maps provide evidence of earlier water abstraction from higher parts of Chungphare Glacier at least until the 1930s, as can be reconstructed from 2 former intakes on the lateral moraine and fragments of water diversion structures (Figure 2). However, due to downwasting, the debris-covered glacier surface is located too far below the lateral moraines that need to be crossed by water canals. The Aga Khan Rural Support Programme (AKRSP) initiated efforts to lead meltwater through flexible pipes from the upper glacier to irrigated fields in the 1990s. However, due to glacier movement, the inlets were often damaged and the pipes broke frequently. Meltwater from Chungphare Glacier no longer contributes to local irrigation, and so the channel intakes of Tarishing and Rupal are constructed on cryosphere-fed torrents of different sizes along the south-facing slopes of Nanga Parbat (Nüsser and Schmidt 2017). The role of permafrost thaw is unquantifiable but possibly significant.

Land use change in the Rupal Valley can be traced back to the colonial period and is characterized by the expansion of villages and cultivated areas, an increase in individual field numbers, and a reduction in average field size (Nüsser 2000; Nüsser and Schmidt 2017). The permanent settlements are located at elevations between 2630 and 2910 m (Figure 3), while agricultural fields with wheat and barley as dominant crops—often cultivated together with potatoes, vegetables, and fodder—reach an upper limit of 3350 m (Nüsser and Clemens 1996). The production of potatoes, largely as a cash crop, has shown the largest increase over the past 20 years. Depending on elevation, cultivation of fields begins in April and May with irrigation intervals of 7 to 12 days until the crops are harvested and threshed in September. Together with seasonal pastoral migration, these practices shape the spatial and temporal organization of combined mountain agriculture in the valley, where the debris-covered glacier tongues of Chungphare and Bizhin are frequently crossed by local transports between settlements and by animal herds during seasonal pastoral migration (Clemens and Nüsser 2000).

Labor-intensive construction, maintenance, and restoration of gravity-dependent irrigation channels are generally managed by community institutions, arranged between households, neighborhoods, and villages. These institutional arrangements demonstrate the adaptive capacity and flexibility of local mountain dwellers. They

FIGURE 2 Glaciers and villages in the Rupal Valley. (Map by the authors)



Draft and Cartography: S. Schmidt

Data Source: Corona 1965-10-08 (USGS), Landsat 5 1998-08-29 (USGS), Sentinel 2 2018-08-04 (ESA), QuickBird 2003-07-19 (Digital Globe)

Background: Sentinel 2 2018-08-04 SWIR1-NIR-R

enable residents to cope with water scarcity and channel destruction due to natural hazards, such as torrential rains in 1992, 1997, and 2010. At the same time, they help compensate for labor shortages resulting from the availability of nonfarm income sources and the requirements of multilocal agricultural with widely distributed landholdings and grazing grounds. However, agricultural production in the Rupal Valley has never been able to meet subsistence needs, and additional food supplies had to be purchased in the lowlands of Pakistan before subsidized government programs were implemented in the 1970s (Nüsser and Clemens 1996), which remain relevant for local livelihoods today. Despite an increase in off-farm income through government jobs, mountain tourism, and remittances from migrating household members as complementary components of livelihood security, irrigated agriculture and livestock remain important sources of food security in the Rupal Valley.

The upper Hunza Valley in the western Karakoram

To the east of the Batura ridge, culminating in Batura Sar (7795 m), 4 large valley glaciers flow toward the Hunza

River, the northernmost tributary of the Indus Basin (Figure 4). In this section of the upper Hunza Valley, the river forms a braided streambed, frequently flooded by glacial lake outbursts in the upper tributaries (Kreutzmann 2012). With a glaciated area of 342 km² and a length of 56.6 km, Batura Glacier is the largest, followed by Passu (64 km² and 27.2 km), Ghulkin (34 km² and 19.5 km), and Gulmit (14 km² and roughly 10 km). Their tongues terminate at elevations between 2610 m (Batura) and 2495 m (Ghulkin). Batura Glacier is characterized by substantial fluctuations, recorded in historical reports and oral history as well as recent investigations (Iturrizaga 2011; Hewitt 2014), with a relatively small negative mass balance (Bolch et al 2017). In contrast to investigations by Shafique et al (2018), our own multitemporal remote-sensing analysis of Batura Glacier indicates fluctuating front positions with an advance of 427 m between 1998 and 2018, but a net retreat of 680 m over the 53 years between 1965 and 2018. Passu Glacier shows a front retreat of 774 m over the same period, with the formation of a proglacial lake. Whereas Ghulkin Glacier retreated 238 m between 1965 and 1992, surge events since 2008 have compensated for the lost glacier length, so that the

FIGURE 3 The cultivated fields of Rupal Valley receive irrigation water from torrents (visible in the background) along the south-facing slopes of Nanga Parbat. (Photo by Marcus Nüsser, 5 September 2010)



frontal position in 2018 is located at almost exactly the same position as in 1965. Gulmit Glacier shows a frontal retreat of 330 m between 1965 and 2018; however, fluctuations with an advance of 55 m between 1992 and 2001 and a retreat of 45 m between 2001 and 2018 are evident from satellite imagery.

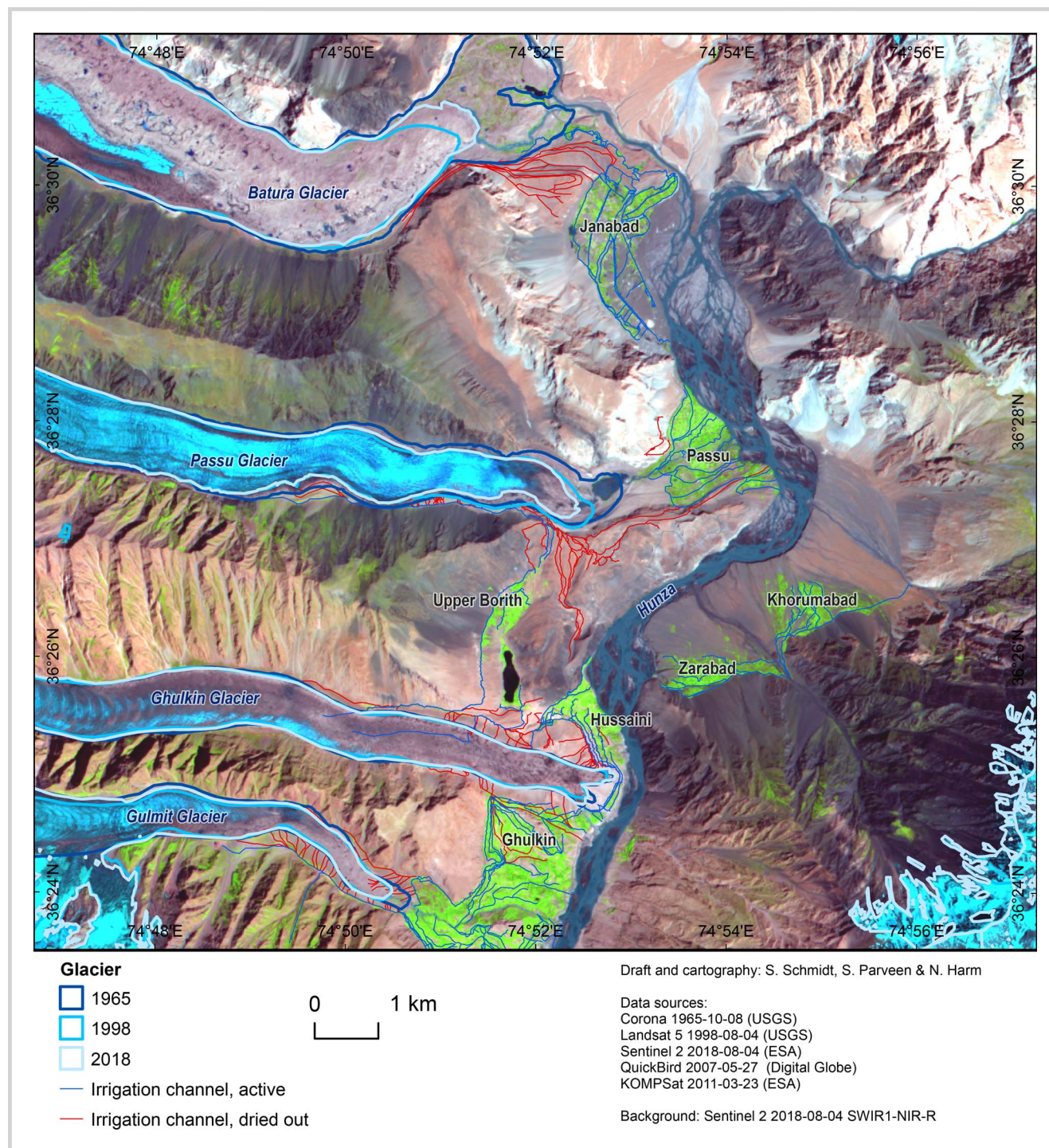
The permanent settlements between Batura Glacier in the north and Gulmit Glacier in the south are located in the vicinity of the glacier tongues on fluvial terraces and basal moraines at elevations between 2400 and 2800 m. Due to the deep incision of the Hunza River, discharge from the main stream is not used for irrigation, and meltwater from tributaries is the most important source of irrigation. Despite the size and the relatively low front elevations of the 4 glaciers, which make meltwater available right from the onset of the growing season, villages in the upper Hunza Valley regularly experience water scarcity resulting from glacier dynamics in several ways: Advances in frontal positions may result in the destruction of water channels and intake infrastructure, as reported for Passu village (Parveen et al 2015). In contrast, in the case of Batura Glacier, irrigation of new land on the fluvial terrace of Janabad—supported by AKRSP in the 1980s—was possible only after the shift of

the glaciofluvial drainage line to the south. A northward shift of the Batura Glacier outlet can be detected on satellite imagery from 2018, which could imperil future water supply for Janabad.

Furthermore, meltwater diversion channels across the lateral moraines to cultivate fields located on terraces above the glacier tongue have been constructed (Figure 5). Even small downwasting rates can severely hamper the functionality of such water transfer schemes, as large gaps open up between glacier surfaces and channel intakes. Lowering of the glacier surface requires constant structural modifications to the intake and its channel. However, many intakes and channels are dried out, and therefore some hamlets, scattered parts of villages, had to be abandoned in the southern vicinity of Passu Glacier. Moreover, GLOFs frequently destroy channels and fields (Ashraf et al 2012; Ashraf et al 2014), and glacier surges destroy channels and intakes, as reported for a historical settlement in the southern vicinity of the Batura Valley.

Continual efforts to readjust irrigation networks according to glacial fluctuations and glaciofluvial hazards shape land use practices in the upper Hunza Valley. Local strategies to adapt to cryosphere dynamics and resulting variations in meltwater supply range from daily

FIGURE 4 | Glaciers and villages in the upper Hunza Valley. (Map by the authors)



excavation work to align intakes and channels to complete restructuring of the irrigation system in response to ever-changing glacier tongues, glacier surface, and supraglacial lakes.

Until the 1980s, livelihoods in upper Hunza (also known as Gojal) were largely characterized by subsistence-oriented mountain agriculture supplemented by limited off-farm income opportunities, for example, through

FIGURE 5 Deeply indented channel crossing the northern lateral moraine of Ghulkin Glacier. (Photo by Sitara Parveen, 25 June 2016)



outmigration or employment with the armed forces, government schools, or the construction sector. Since then, cash-crop production and marketing have been introduced to the upper Hunza Valley, supported by the government of Pakistan, international donors, and the AKRSP (Benz 2014). Nowadays, wheat and potatoes are the dominant crops, and apricot, apple, and cherry trees are cultivated in orchards, intercropped with vegetables. Furthermore, the area of cultivated land has been expanded to replace fields lost to GLOFs in Passu (Kreutzmann 2012; Mizushima 2016).

Over the last decades of hereditary rule, ending in 1974, the expansion of the irrigation systems had already decreased, and some hamlets of Borith, a small settlement located near the frontal position of Passu Glacier above Hussaini, had to be abandoned due to water scarcity. Following the abolishment of feudal rule, the village water management committees struggled to secure water (Kreutzmann 2000); however, their ability to mobilize neighboring communities to construct new irrigation channels remained limited. Around a decade later, AKRSP started several projects to improve water availability and irrigation networks. Due to new income opportunities, especially after completion of the

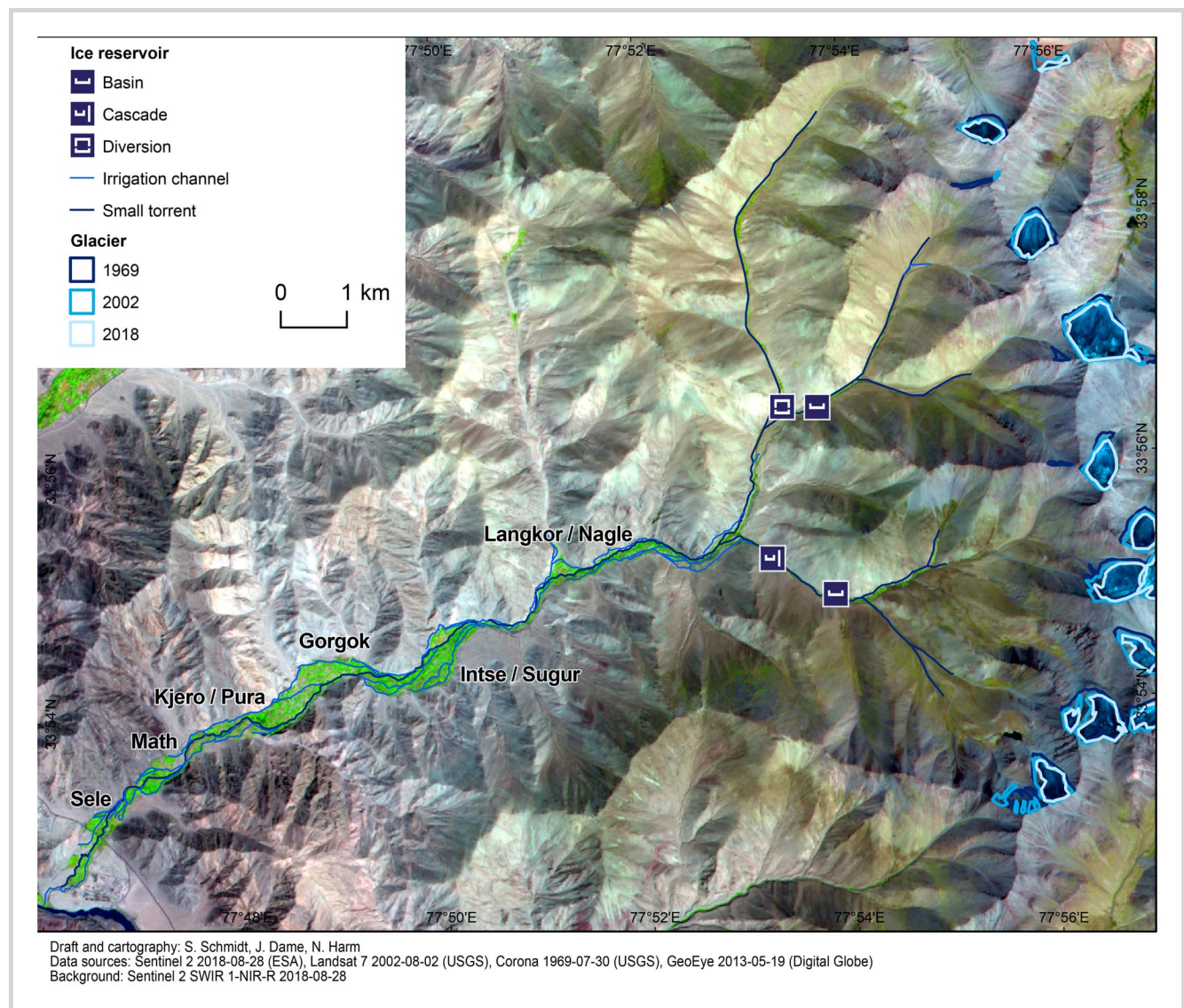
Karakoram Highway in 1978 (Kreutzmann 1991; Benz 2016), the villages often lacked sufficient labor to maintain irrigation networks and agricultural fields. As a consequence, many channels have been dried out and fields abandoned.

Especially after GLOFs, limited local capacity results in considerable time lags before irrigation systems can be reestablished. In the case of Ghulkin, changes in the irrigation system owing to glacial downwasting reignited historical disputes between 2 neighboring settlements, highlighting the importance of appropriate institutional regulations to manage equitable water sharing.

The Igoo catchment in the Trans-Himalaya of Ladakh

The southwest-facing Igoo catchment occupies approximately 120 km² in the eastern part of the central Ladakh Range and drains several high-elevation glaciers to the Indus River. These glaciers are small with high terminal positions exceeding 5370 m. A general glacier decrease is evident for the Trans-Himalaya of Ladakh between 1969 and 2016, with glaciated area reduction ranging from 0.2 to 0.9% per year across different watersheds (Schmidt and Nüsser 2017). Under local

FIGURE 6 Glaciers and villages in the Igoo catchment. (Map by the authors)



conditions of frequent freeze-thaw cycles, icing regularly occurs on frozen ground in the broad upper valley. Due to the glaciers' high elevation, low temperatures, and considerable variability of seasonal snow cover, a sufficient and reliable supply of meltwater for irrigation becomes available only about 6 weeks after the onset of the agricultural season. With a total population of 1103, Igoo has 9 hamlets, ranging in elevation from 3450 to 4100 m over the length of the valley (Figure 6). The irrigated area along the stream covers 3.07 km² and reaches its upper limit at 4370 m. Because of the length of the Igoo catchment, 3 water managers (*chudpon*) are responsible for water allocation on a rotational basis and for organizing maintenance of irrigation infrastructure together with the

community. Barley, peas, mustard, and potatoes are the main irrigated crops. Field structures are generally highly persistent, though some terraces have not been repaired since they were damaged by floods in 2006 and 2010, due to lack of labor and financing.

The cryosphere-fed irrigation network in the cold, arid region of Ladakh has always been prone to water scarcity in spring (Labbal 2000; Dame and Mankelaw 2010). To cope during this critical period, different types of ice reservoirs, commonly called artificial glaciers, have been introduced as adaptive strategies in different catchments in Ladakh. The classical type consists of a cascading series of rock walls in the river beds to reduce runoff velocity and to facilitate the process of icing under conditions of

FIGURE 7 Efficient ice accumulation in a cascade-type reservoir in the Igloo catchment. The entire riverbed is filled with ice, and the cascades are completely iced over. (Photo by Marcus Nüsser, 25 February 2014)



frequent freeze-thaw cycles. Other ice reservoir types include basins or water diversion structures for seasonal ice accumulation. All of these man-made structures are located at elevations below the glaciers and above agricultural fields (Nüsser et al 2019).

While the first ice reservoirs were built by government agencies in the late 1980s, most were built after 1995 under the aegis of the national Watershed Development Programme, with NGOs, such as the Leh Nutrition Project, serving as project implementing agencies. More recent constructions have been partly funded by the Sadbhavana (Goodwill) program of the Indian Army in 2008/2009 and the Tata Trust since 2015. Under such funding schemes, 4 ice reservoirs have been built in the Igloo catchment at elevations between 4230 and 4570 m. All are subject to high interannual variability of ice accumulation. While the cascade and basin types have proved successful (Figure 7), one diversion structure funded under the Sadbhavana scheme is not functional because inflow has regularly been blocked by frozen pipes. Other traditional water storage techniques include small barrier walls for “snow harvesting” on the uppermost

slopes. These structures serve to capture wind-blown snow at specific locations to prevent aeolian transport to areas outside the catchment.

Participation of local villagers in building and maintenance is crucial to the success of ice reservoirs. In Igloo, reconstruction of the reservoirs following the 2010 floods was made possible only by 275 residents donating their labor over a week in October 2013. The lack of monetary incentives makes local villagers reluctant to contribute their labor for maintenance and repair of these structures, even though willows and poplars are now being planted as community forests, increasing the demand for irrigation. As an income-generating activity, tree plantations and cash crop production, especially of potatoes and peas, provide valuable incentives for communities. Agrarian livelihood strategies in Igloo are regularly supplemented by off-farm work. Apparently, lack of an agrarian workforce, partly compensated by engaging hired laborers, is responsible for an increase in fallow land from 11.2 to 21.6% between 2009 and 2015. Food security has been improved by subsidized government schemes (Dame and Nüsser 2011).

Conclusions

These 3 case studies from the upper Indus Basin show high diversity in cryosphere-fed irrigation networks depending on environmental conditions and local adaptation measures. The integrated research framework of sociohydrological interactions is useful for analyzing glacier dynamics and local irrigation networks, including site-specific particularities, in a comparative way.

Whereas changes in glaciated area and variability in seasonal snow cover can be detected using remote sensing data, permafrost thaw as the “invisible” cryosphere component remains difficult to quantify, although a considerable contribution to meltwater discharge in periglacial environments must be assumed. Likewise, the hydrological importance of icing processes needs to be further explored, as in the case study from the Igoo catchment in the Trans-Himalaya of Ladakh. Highly complex and variable climatic and environmental conditions require flexible responses and continuous adaptation. Against this background, site-specific environmental knowledge and the ingenuity of mountain residents are of particular interest.

Adaptation strategies across the study area vary and include the construction of new irrigation channels and installation of water pipes and artificial ice reservoirs. Despite these enhancements in irrigation infrastructure, abandonment of fields can be witnessed in all study villages, mainly due to increased off-farm opportunities and outmigration from the rural mountain areas. Moreover, adaptive strategies often fail in the face of unpredictable environmental processes and glaciofluvial hazards, including GLOFs, flash floods, landslides, and

rockfall (Cook and Butz 2013; Ziegler et al 2016). At the same time, farmers opt to maintain agricultural land use or even expand irrigated areas to cultivate cash crops. In all 3 case studies, water management faces considerable labor constraints, which affect community capacity to establish successful adaptation strategies. Cryosphere change and resulting water scarcity require constant efforts to maintain irrigation infrastructure, including by constructing new irrigation channels (in the Rupal and upper Hunza Valleys) or artificial ice reservoirs (in the Igoo catchment). Effective institutional arrangements between participating households and locally accepted external development interventions are crucial for successful adaptation strategies.

As construction, maintenance, and repair of irrigation infrastructure require active participation by community members, responsive adaptation strategies can be analyzed only in the broader context of socioeconomic development. Factors such as alternative employment opportunities, migration, governmental welfare schemes, external development interventions, and changing food habits are key variables of socioeconomic trajectories. In the context of changing livelihood strategies, factors such as increased road accessibility and regional integration need to be considered. In all case studies, community water institutions face considerable labor shortages, which affect community capacity to establish successful adaptation strategies. The array of relevant glaciohydrological and socioeconomic factors needs to be explored in order to better understand site-specific climate change adaptation practices and development options.

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