



# Socio-hydrology of “artificial glaciers” in Ladakh, India: assessing adaptive strategies in a changing cryosphere

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## Abstract

The consequences of even small glacier decrease and changes of seasonal snow cover are critical for the functioning of meltwater-dependent mountain agriculture. In order to deal with recurrent water scarcity, different types of ice reservoirs, commonly called “artificial glaciers,” have been introduced in Ladakh and promoted as appropriate adaptive strategies to cope with changes in the cryosphere. The resulting seasonal ice reservoirs increase meltwater availability during the critical period of water scarcity in spring. We examine the efficacy of 14 ice reservoirs through a long-term analysis of their functioning within the environmental and socioeconomic context of Ladakh. Using multi-temporal satellite data (1969–2017), close range photogrammetry, and repeat field measurements (2014 and 2015), we provide an inventory and typology of these ice reservoirs and estimate storage volume of one selected structure, which ranges from 1010 to 3220 m<sup>3</sup> of water. We extrapolate this volume to all ice reservoirs and estimate potential irrigation cycles of cropped areas, which vary between less than 0.1 in unfavorable cases and almost 3 in optimal cases and years. Based on interviews and field surveys (2007–2017), we discuss the benefits perceived by local smallholders, such as the reduction of seasonal water scarcity and resulting crop failure risks together with the possibility of growing cash crops. We argue that “artificial glaciers” are remarkably suited to the physical environment. However, their usefulness as a climate change adaptation strategy is questionable because climatic variability, natural hazards, and an incomplete integration into the local socioeconomic setting significantly reduce their efficacy.

**Keywords** Climate change adaptation · Cold-arid region · Ice reservoirs · Irrigated agriculture · Water conservation · Socio-hydrology

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## Introduction

Meltwater from glaciers, snowfields, and permafrost is the most important source of irrigated agriculture in cold-arid mountain regions all over the world. In order to cope with insufficient or seasonally unreliable availability of water, adaptive techniques and sophisticated designs for water management and distribution have been established in diverse regional contexts (Kreutzmann 2011; Carey et al. 2017; Mark et al. 2017). The necessity of including socioeconomic dynamics in studying the evolution of human-water interactions has been stressed in the current discussion on socio-hydrology (Sivapalan et al. 2012; Wesselink et al. 2017; Nüsser 2017). Conceptual approaches under this umbrella term have the shared premise that human-water interactions are characterized by co-evolution of natural and social systems entangled in diverse feedback loops.

There is a long tradition of research on human-water relations in the upper Indus Basin, in both Ladakh, northern India (Labbal 2000; Nüsser et al. 2012) and various locations in northern Pakistan (Kreutzmann 2011; Nüsser 2001; Parveen et al. 2015; Nüsser and Schmidt 2017). Our study extends the socio-hydrological discussion to water harvesting structures in Ladakh, commonly called “artificial glaciers,” which have been framed as adaptive strategies to climate change (Bagla 1998; Vince 2009; Clouse 2014). Land use in the cold-arid region of Ladakh has always been prone to seasonal water scarcity, affecting irrigation and domestic water supply (Dame and Mankelov 2010; Nüsser and Baghel 2016). Due to low temperatures and the high variability of seasonal snow cover (Mukhopadhyay and Khan 2015), there is a typical shortage of water at the onset of the agricultural season for about 2 months until a sufficient and reliable supply of meltwater from high-altitude glaciers becomes available. “Artificial glaciers,” located at much lower altitudes than the naturally occurring glaciers above 5200 m a.s.l. (Schmidt and Nüsser 2017), serve to bridge the critical gap in

water availability by providing ice reservoirs that melt earlier in the agricultural season. Such ice reservoirs have been constructed in several tributaries of central Ladakh over the past three decades (Fig. 1). In spite of the popularity of the term “artificial glacier,” the term “ice reservoir” conveys their character and function more accurately because the ice bodies only exist for a few months, unlike glaciers in the strict sense, which are defined as perennial, moving ice bodies with distinct accumulation and ablation zones.

Such ice reservoirs utilize the hydrological process of icing under local conditions of frequent freeze-thaw cycles to capture water for seasonal storage. They are not water storage structures that freeze from the top down, rather they are produced through sequential, freezing of thin layers of water creating superimposed sheets of ice. These ice reservoirs are maintained as communal infrastructure reliant on local institutions and external technological interventions. Published quantifications of their ice storage capacity differ between 17,000 and 23,500 m<sup>3</sup> (Bagla 1998; Norphel and Tashi

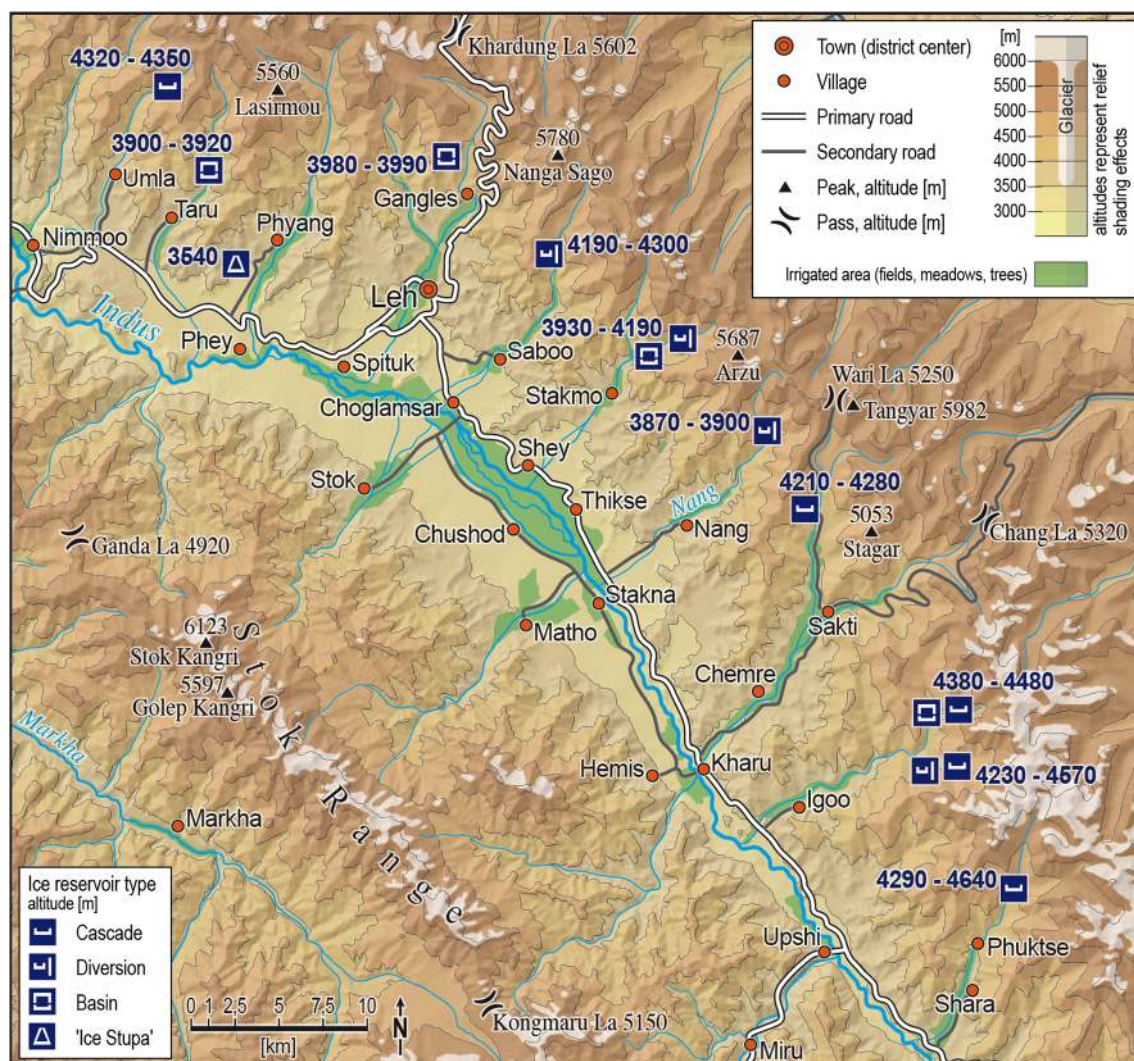


Fig. 1 Ice reservoirs in central Ladakh

2015). Recent research has called for an examination of their long-term efficacy and their usefulness as climate change adaptation strategies (Clouse et al. 2017). We attempt to address this gap through a longitudinal study that takes into account their functioning as supplementary irrigation, as interventions to foster sustainable development, and their usefulness as adaptation strategies to global climate change. Based on multi-temporal satellite data (1969–2017), close range photogrammetry, and repeat field measurements (2014 and 2015), we provide an inventory and typology of these ice reservoirs and estimate storage volume of one selected structure. The extrapolation to other ice reservoirs allows to estimate the number of potential irrigation cycles. Between 2007 and 2017, empirical social research methods were employed to investigate the nexus of glacio-hydrological processes and local mountain livelihoods. This study from a cold-arid mountain region can inform evaluations of the efficacy and transferability of climate change adaptation strategies and stresses the importance of site-specific socio-hydrological interactions.

## Material and methods

An integrated approach, based on remote sensing analyses and socioeconomic surveys, was used to examine the functioning of ice reservoirs in central Ladakh. Ice reservoirs were identified and mapped on high spatial resolution satellite imagery in ArcMap (ESRI). Corona data from 1969 were used to identify conditions existing prior to the first reported construction in Ladakh, explicitly identified as an “artificial glacier” in 1987. Time series of all available Landsat imagery from 1989 to 2017 available at the USGS archive, with cloud cover of less than 30% were used to classify sites as ice filled, snow covered, free of snow and ice, or cloud covered, in order to evaluate the functioning of the structures. Visual interpretation and manual classification were carried out for all sites, based on the months of April and May as proxies for the extent of ice formation at the onset of the agricultural season and the period between November and March for the extent in winter months. In case of differences in ice formation between images taken in April and May, the greater extent was selected where data for both months were available. The elevations of different ice reservoirs were derived from ALOS Digital Surface Model.

Functioning of ice reservoirs was further verified using repeat photography, conducted in February and October 2014. The volume of one selected ice reservoir was estimated using a structure from motion (SfM) photogrammetry approach (Westoby et al. 2012; Fonstad et al. 2013; Smith et al. 2016) with two fine-grained DEMs ( $0.1 \times 0.1 \text{ m}^2$ ), generated from several hundred photos using the photogrammetry software PhotoScan (Agisoft). Ice volume of the test site (Nang reservoir) was determined based on the difference

between winter and summer DEMs in 2015 (online supplement). Volumes of ice reservoirs were calculated from this example using surface-area-to-volume ratio and multiplied by 3 to denote inter-annual variability between optimal and unfavorable years. Potential irrigation cycles of cropped areas were calculated based on field observations and estimations by Norphel and Tashi (2015) that irrigated plots are flooded with 2–5 cm of water.

To determine reservoir locations in relation to glaciated and irrigated areas, Sentinel 2 imagery from 2017 was classified. Furthermore, the snow line elevation (SLE) was delineated using MODIS data products (2000–2018). Ground truthing of the results from remote sensing analyses was conducted during repeat field surveys (2007–2017). The role of ice reservoirs in the local socioeconomic setting was investigated by interviews with community water managers (*chudpon*), small-holder farmers, representatives of non-governmental organizations (NGOs), government officials, and selected key informants associated with the construction and promotion of “artificial glaciers.”

## Study area

### Physical setting and the cryosphere

The upper Indus Basin of Ladakh is a high-altitude desert, situated between the Greater Himalayan Range to the south and the Karakoram Range to the north. It forms the western-most part of the Tibetan Plateau at an altitude of over 3000 m, with surrounding mountain ranges exceeding altitudes of 5500 m. Due to its location in the rain shadow of the Himalayan and Karakoram ranges, the region is characterized by cold-arid conditions with an average annual precipitation of approximately 100 mm in Leh (India Meteorological Department 2011) and with occasional torrential rainstorms, such as the extreme cloudburst in August 2010 (Thayyen et al. 2013). Most precipitation falls during the monsoon period with regular summer snowfall at altitudes above 5000 m, but the influence of western disturbances causes a secondary maximum during winter and pre-monsoon (Chevuturi et al. 2018). Seasonal snow cover characterized by uneven distribution and duration contributes significantly to runoff in spring (Mukhopadhyay and Khan 2015; Gurung et al. 2017).

Taking into account the sparsity of weather stations and lack of detailed historical data for the region, the period after 1995 is characterized by a decreasing trend of average precipitation amounts (Chevuturi et al. 2018). Mean monthly temperature values in Leh show a high seasonal variation of around 25 °C between January (−7.2 °C) and August (17.5 °C) (India Meteorological Department 2011), reflecting the typical glacio-hydrological regime of a cold-arid catchment (Thayyen and Gergan 2010). Temperatures in Leh show



a slight increase between 1901 and 1979, followed by a short cooling period from 1979 to 1991, and a steep increase from 1991 to 2013 (Chevuturi et al. 2018). However, the inverse relationship between general trends in temperature and precipitation changes is more complex due to high inter-annual variability.

The specific combination of topography and climate contributes to the small size and high altitude of glaciers, almost all of which terminate above 5200 m. While the glaciated area of central Ladakh totals 997 km<sup>2</sup> with more than 1800 glaciers, 79% of them are smaller than 0.75 km<sup>2</sup>. A general glacier decrease is evident for the time period between 1969 and 2016, with a high variability across different watersheds, with glaciated area reduction ranging from 0.2 to 0.9% year<sup>-1</sup> (Schmidt and Nüsser 2017). These results correspond with a study by Chudley et al. (2017) who estimate total retreat of 12.8% for 657 glaciers between 1991 and 2014. Although glacier decrease is not as pronounced as in other Himalayan regions, even small climatic shifts influence water storage and runoff in cold-arid regions, crucial for the functioning of irrigation systems (Barnett et al. 2005; Parveen et al. 2015). Despite their small size, meltwater from these glaciers determines the potential for irrigated crop cultivation. Consequently, tributaries without glaciated valley heads are especially susceptible to water scarcity in summer when seasonal snow cover has melted. Permafrost occurrence can be assumed in the upper catchments (Gruber et al. 2017); however, the actual contribution of local permafrost thaw to runoff remains uncertain.

### Socioeconomic setting and irrigation practices

Located in the Indian State of Jammu and Kashmir, Ladakh is sparsely populated and has a total of about 274,300 inhabitants (Leh and Kargil districts), with the registered population expanding by 1.5% annually between 2001 and 2011 (Census of India 2011). However, this does not include the large but uncertain number of army personnel and seasonal migrants to the region. Ladakh is a geopolitically sensitive region with contested boundaries and heavy military presence (Baghel and Nüsser 2015; Gagné 2017). The Indian Army and associated institutions are major economic actors, providing employment, maintaining transport infrastructure, health services, and bringing in food supply. Irrigated agriculture continues to be a major, albeit declining, source of livelihood and food security (Dame and Nüsser 2011). Irrigated areas and scattered settlements in central Ladakh are only found along the Indus, on alluvial fans, or tributary valleys between 3200 and 4370 m. Due to the short growing period, central Ladakh is a single-cropping area with barley and wheat as important staples, complemented by vegetables, pulses, and oil seeds. Potatoes, having a slightly longer growing period and higher water demand, are cultivated for household consumption and

increasingly as cash crops in recent years. Depending on altitudinal position, irrigation with complete flooding of fields (approximately 2–5 cm water column) starts between March and April prior to the melting of high-altitude glaciers, with additional delay following extended cloudy periods. Further, the unreliability and the foreseen decrease of seasonal snow cover (Chevuturi et al. 2018) increase the precariousness of the water storage function of the cryosphere, especially in spring. In order to cope with recurrent water scarcity, water harvesting technologies and community arrangements have been developed. These include the *zing*, which are small ponds in close proximity to the cultivated fields, where water is collected temporarily for irrigation. Other traditional water storage techniques include small barrier walls for “snow harvesting” in the upper catchments (Dawa et al. 2000). Distribution of meltwater and maintenance of infrastructure is supervised by a *chudpon*.

## Results

### Types of ice reservoirs

Over the past 30 years, 14 seasonal ice reservoirs have been constructed in central Ladakh, located in tributary valleys north of the Indus (Fig. 1). Usually situated around 1100 m below the glaciers at elevations where snowmelt starts end of March, these structures facilitate the freezing of stream water during winter at selected sites, usually shaded by surrounding mountains. However, three of these structures are located in watersheds without glaciated valley heads (Table 1). There are four distinct types of ice reservoirs with site-specific modifications: the first type is built as cascades on perennial streams. A series of loose rock walls in the river bed reduces flow velocity, but still lets water pass through. Such cascades allow flowing water to freeze on exposed surfaces and form superimposed ice layers when temperatures drop (Fig. 2). This design was used for the oldest structure explicitly called “artificial glacier” in Ladakh, built in 1987 at a favorable location between 4290 and 4640 m in Phuktse. However, according to oral history and Corona imagery from 1969, the first ice reservoirs of this design type are older than 50 years and can be found in Phuktse and Igoo. In February 2014, Phuktse was a successful cascade with an almost complete continuous stretch of ice, with no dry or empty areas (Fig. 3).

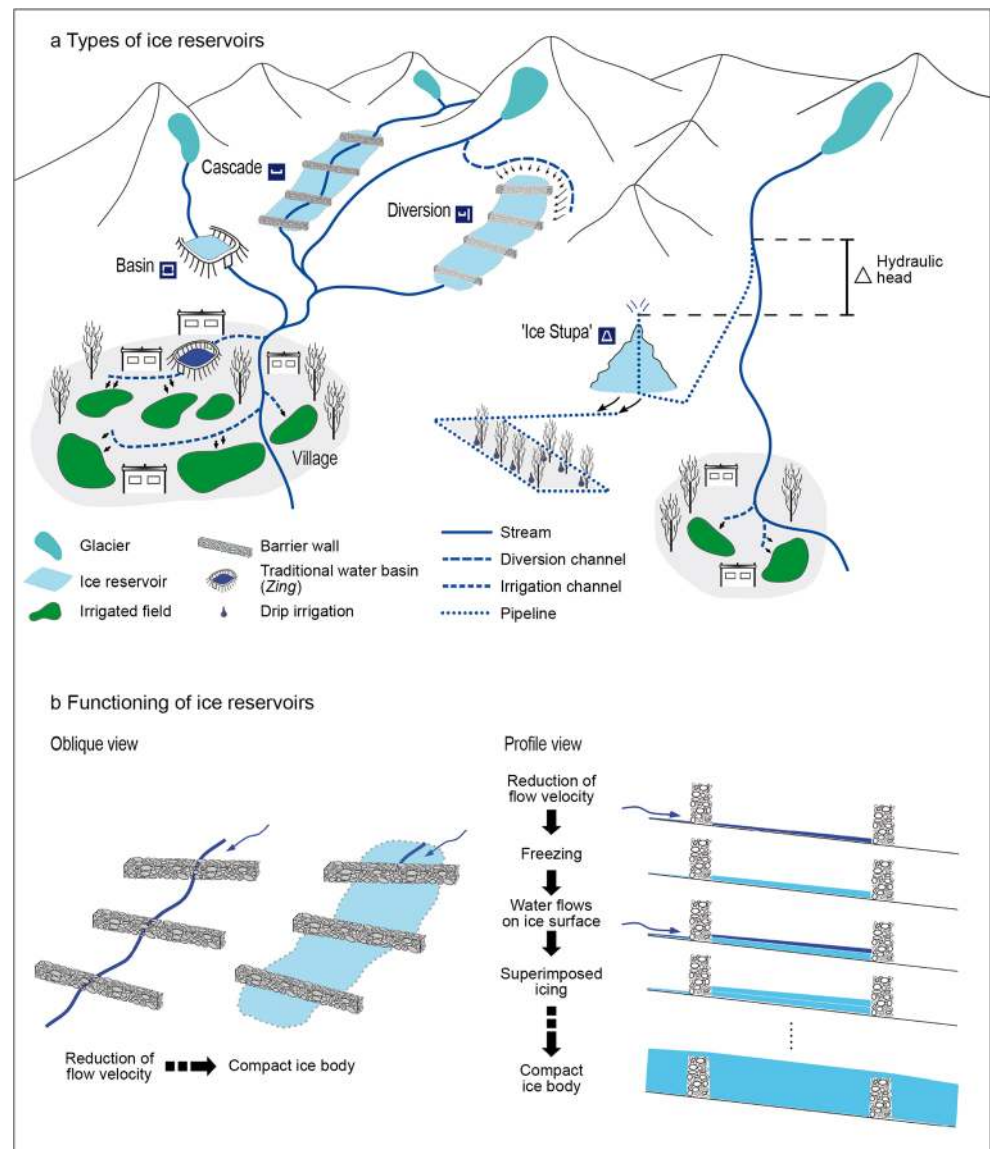
The second type diverts water from streams with higher flow velocity to small side valleys, shaded by surrounding mountains. This design allows to integrate higher slope positions for additional ice formation such as the ice reservoir above Nang, completed in 1999 (Fig. 4). It consists of a series of six partially cemented stone walls across the stream bed measuring approximately 3 m in height and 1 m in width.

**Table 1** Ice reservoir parameters with population, irrigated area, glaciated area, and snow line elevation (SLE) in spring

Village	Pop. <sup>a</sup>	Ice reservoir			Irrigated area			SLE <sup>g</sup>			Glaciated area		Watershed
		Type <sup>b</sup>	Elevation range (m a.s.l.) <sup>c</sup>	Area (km <sup>2</sup> )	Volume (m <sup>3</sup> ) <sup>d</sup> normal / optimal	Cropped area (km <sup>2</sup> ) <sup>a</sup>	Total area (km <sup>2</sup> ) <sup>e</sup>	Maximum elevation (m a.s.l.) <sup>c</sup>	Potential irrigation cycles by ice reservoirs <sup>f</sup>	8 March 8 April 16 April (m a.s.l.)	Total area (km <sup>2</sup> ) <sup>e</sup>	Minimum elevation (m a.s.l.) <sup>e</sup>	
Phuktse, Shara	905	D	4290–4640	0.151	25,420 / 81,040	1.65	3.25	4350	0.31–0.77 0.98–2.45	4310 4520 4875	2.97	5400	84.34
Igoo	1103	BCCD	4230–4570	0.137	29,560 / 88,810	1.51	3.07	4370	0.39–0.98 1.18–2.94	4021 4353 4553	0.82	5370	119.68
Sakti, Chemre	7940	C	4210–4280	0.026	4380 / 13,950	4.63	9.97	4160	0.02–0.05 0.06–0.15	3877 4166 4514	0.61	5430	195.73
Nang	341	D	3870–3900	0.006	1010 / 3220	0.53	1.21	3880	0.04–0.1 0.12–0.3	3778 4266 4437	—	—	50.41
Stakmo	no data	BD	3930–4190	0.001	6630 / 10,820	n.d.	1.41	3850	0.31–0.77** 0.98–2.46**	3804 4088 4329	0.03	5350	62.09
Saboo	1233	D	4190–4300	0.051	8590 / 27,370	1.33	2.81	4120	0.13–0.32 0.41–1.03	3800 4131 4392	0.33	5410	70.72
Leh (Gangles)	30870	B	3980–3990	0.004	3660 / 9160	n.d.	7.36	3940	0.02–0.05** 0.05–0.12**	3794 4129 4351	1.03	5330	142.00
Phyang, Phey	2367	I	3570	<0.001	150*	2.54	5.41	4100	no data	3848 4184 4354	1.96	5250	114.85
Taru	442	B	3900–3920	0.005	4950 / 12,370	0.6	0.92	3900	0.16–0.41 0.27–1.03	3800 4215 4492	—	—	55.11
Umla	99	C	4320–4350	0.003	510 / 1610	0.12	0.33	4010	0.08–0.21 0.27–0.67	3585 <sup>u</sup> 4294 4465	—	—	31.84

<sup>a</sup> Population data according to Government of Jammu and Kashmir - Ladakh Autonomous Hill Development Council Leh. 2015. Blockwise Village Amenity Directory 2014–2015 (unpublished)<sup>b</sup> Ice reservoir types: *B* basin, *C* cascade, *D* diversion, *I* ice stupa<sup>c</sup> Elevation and watershed area derived from ALOS/DSM (© JAXA)<sup>d</sup> Volume of water storage in ice reservoirs modeled from field measurements; \*in case of the ice stupa: information by Sonam Wangchuk; in case of basin structures: assumption of ice fill heights between 1 and 2.5 m<sup>e</sup> Area derived from Sentinel 2A-data (2017–08–28)<sup>f</sup> Potential irrigation cycles by ice reservoir volume: assuming that fields are flooded with 2–5 cm of water; upper range represents unfavorable years and cases, lower range represents optimal conditions; \*\*calculated by mean average ratio irrigated to cropped area<sup>g</sup> Snow line elevation (SLE) derived from MOD10A2 product and ALOS/DSM (© JAXA)

**Fig. 2** Ice reservoirs. **a** Different types. **b** The process of ice accumulation



Their length varies between 7 and 17 m. The water for the ice reservoir is obtained through a 1 km long diversion channel, prone to recurring problems of sedimentation, erosion, and frequent freezing in winter, which prevents regular water flow.

The third ice reservoir type is a basin structure, resembling the traditional *zing* form of water storage, but located above the cultivated fields. An early example can be found at Igoo, where embankments already existed in 1969, as witnessed by satellite imagery and interviews. This ice reservoir was further expanded after 2000 and completed in 2013. Another such structure in Gangles, along the road to Khardung La, is of importance for the urban agglomeration of Leh. Completed in 2016, it comprises a basin with controls for inflow and outflow, adjacent to a stream which is allowed to flow during the summer but whose water is diverted to the basin in autumn. The structure consists of stone walls of approximately

2.5 m height, stabilized by gabions (wire cages) and concrete pillars.

The fourth and the newest type of ice reservoirs is the vertical “ice stupa” in Phyang, initiated in 2015, whose name refers to the conical form of Buddhist stupas. High-density plastic pipes, buried in earth to prevent freezing, divert water by gravity from the upper stream area to preferred locations, using the hydraulic head, produced by the altitudinal difference between intake and outflow. There, a narrower vertical pipe with a sprinkler fixed on top sprays out a fountain of water due to hydrostatic pressure which freezes on contact with cold air. The ground is previously plastered with clay to reduce its permeability and to prevent rapid seepage during the melting phase in spring. Branches of seabuckthorn and barbed wire are laid around the initial structure to provide additional surfaces for ice aggregation. One advantage of this ice reservoir type is that its conical shape reduces the surface

**Fig. 3** Ice reservoir of Phuktse, viewpoint 4430 m. **a** February 2014. **b** October 2014



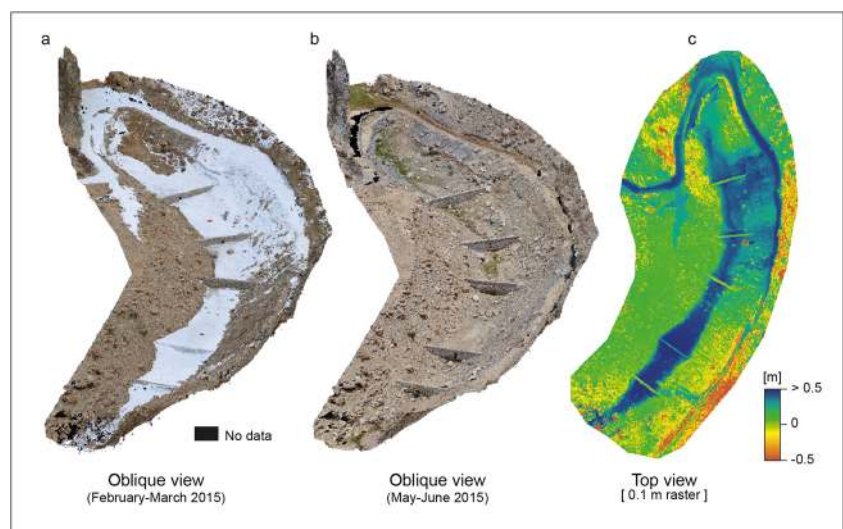
receiving direct solar radiation, thereby slowing down the melting process.

### Efficacy of ice reservoirs

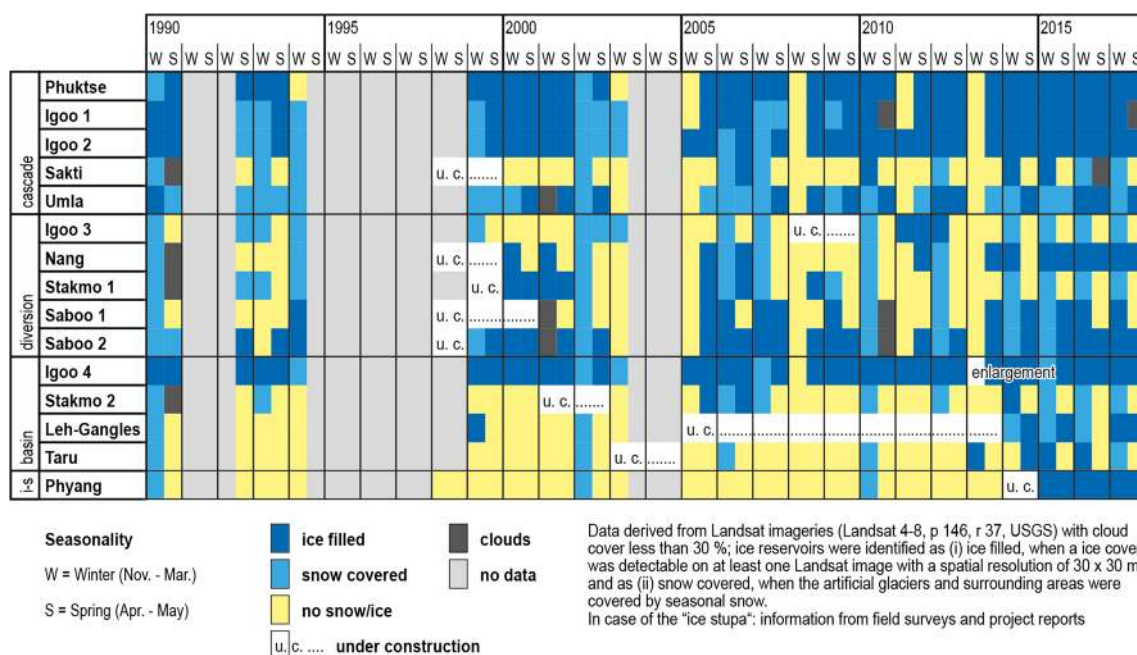
High inter-annual climatic variability, frequency, and duration of freeze-thaw cycles together with variances in design result in great differences in ice accumulation among investigated structures (Fig. 5). Flash floods, landslides, erosion, and sedimentation are recurrent problems, so that many ice reservoirs are frequently dysfunctional, like those in Igoo and Saboo after the 2010-flood. Whereas ice accumulation occurred in most years in the cascading reservoirs above Phuktse and Igoo, the structure above Sakti was less efficient in producing a reliable

store of ice. In the latter case, ice accumulation in winter often did not last until spring during the observation period (1990–2017). The majority of diversion-type reservoirs which are generally prone to early or untimely freezing of channels or pipes showed only fragmented ice accumulation and snow cover, whereas one above Saboo exhibited successful ice accumulation in most years. The ice reservoir above Nang, being in use since winter 1999/2000, showed regular ice formation only after 2014. While imagery from 2014 and 2015 indicates ice formation, ground surveys and repeat photography reveal large differences in ice volume. According to SfM photogrammetry, the ice volume in winter 2014/15 reached only about 1100 m<sup>3</sup>. This estimation is considered as an example of unfavorable ice formation, as the potential storage volume is

**Fig. 4** Ice reservoir of Nang based on structure from motion (SfM)-data taken in 2015. **a** Winter, **b** summer, and **c** difference (winter minus summer) model







**Fig. 5** Efficacy of ice reservoirs in central Ladakh from 1990 to 2017. November is the time when ice starts filling in and spring, when it is required for addressing seasonal water scarcity

estimated to be about three times more (Fig. 4, online supplement). During a field visit in February 2014, the extent of ice formation in this as well as in other reservoirs was almost optimal. The basin structure above Igoo, the oldest of its kind, also proved to be successful over the entire observation period. Likewise, the Gangles basin, a basin structure with diversion, was effective in the last few winters. The derived irrigation cycles show a large variation between catchments. Only under optimal conditions, all fields can be irrigated with runoff from ice reservoirs in five catchments. In Igoo, where four reservoirs cover a total area of 0.137 km<sup>2</sup>, 1.18–2.94 additional irrigation cycles are possible. In contrast to this, even under optimal conditions less than 30% of cropped area can be irrigated in Nang, Sakti, and Leh (Table 1).

In the case of the vertical “ice stupa” in Phyang, ice formation could be accomplished, although not always with the desired volume. After a prototype study in winter 2013/2014, a larger “ice stupa” was created in 2015, where the ice body reached a maximum height of about 19 m by the end of March. In 2016, only reduced ice formation was possible due to frozen pipes preventing constant water flow. Water stored in this ice reservoir is used for irrigation of barren land, where a forest of 5000 poplars was planted. The decentralized character of this design type with flexible installations, little space requirement and locations in close vicinity to settlements and fields are further advantages. The designer, Sonam Wangchuk, estimates a volume equivalent to 150 m<sup>3</sup> of water could be stored as ice. However, the lack of irrigation later in the year once the ice reservoirs have melted is likely to be problematic for long-term success of forest plantation.

### Support, participation, and perceived benefits

Availability of funding and actor constellations have a great influence on the location and type of ice reservoirs. The ice reservoir in Phuktse was designed in 1987 by Chewang Norphel, a civil engineer, who as the “Glacier man” (Vince 2009) became central in the framing of “artificial glaciers” as an appropriate tool to cope with water scarcity. While the first ice reservoirs were implemented through government agencies, the majority of constructions were realized after 1995 under the umbrella of the national Watershed Development Programme (WDP) and implemented by local NGOs. More recent initiatives include the Indian Army goodwill programme *Sadbhavana*, e.g., in Igoo 2008/2009, and corporate donations. The estimated costs of an ice reservoir vary between 300,000 and 1,000,000 Indian Rupees (INR, approx. 4600 to 15,330 USD in 2018; Interviews in 2014 and 2015), although lower costs of 70,000 INR are reported for the case of Nang by NGO officers. The ice reservoir at Igoo, constructed under the *Sadbhavana* scheme, is the second most expensive project so far. The higher costs were due to the need of road extension to reach construction sites above 4200 m. The most recent reservoirs in the form of “ice stupas,” designed by the Ladakhi engineer and politician Sonam Wangchuk and implemented by the NGO SECMOL (Students’ Educational and Cultural Movement of Ladakh) co-founded by him, on lands belonging to Phyang monastery, were even costlier. International crowdfunding efforts for their construction were successful in obtaining 125,000 USD by promoting these structures in the context of global climate change. This



amount is several times as much as the total amount of donations received for the construction of earlier ice reservoirs. Similar to Chewang Norphel, Sonam Wangchuk has received a high level of attention by international media.

The building of ice reservoirs by NGOs relies on the participation of village communities in construction and maintenance. Ideally, the villagers as beneficiaries are also involved in project planning, when their site-specific knowledge is needed. However, the degree of participation in decision-making varies between villages and also depends on the project and funding schemes. According to interviews with villagers in 2015, the *Sadbhavana*-funded projects showed a significantly lower level of community participation, whereas the vast majority of households were actively involved in decision-making in projects funded under the WDP. Insufficient integration in decision-making during project planning and implementation may result in lack of ownership and limited responsibility of villagers for maintenance and reconstruction after floods. According to an NGO representative, another reason for the limited spread of ice reservoirs is that people look for government support. Even where, as in Nang, structures have been built professionally using hired labor, the villagers are responsible for regular inspection and maintenance. These tasks include regular removal of debris and ice to ensure free flow in diversion channels in addition to repair of damage arising from floods or grazing yaks. In Igoo, reconstruction following the 2010-floods was only made possible by 275 residents donating their labor for 1 week in October 2013. While daily allowances are provided during the construction phase, funds for maintenance work are not available making local villagers reluctant to contribute their labor.

Construction and maintenance are also hampered by competing seasonal labor requirements for agriculture and better paying off-farm jobs in the tourism sector and administrative services. Further, as a consequence of the reduced importance of agriculture for local livelihoods, there is less interest in maintaining traditional water management institutions and many fields have been abandoned (Nüsser et al. 2012). Those villagers who continue agricultural production are mainly elderly and women with little capacity to repair and maintain the ice reservoir infrastructure. Donation of labor by the army through its goodwill initiative, as in the case of the “ice stupa,” redresses labor shortage to some extent. Problems for this ice reservoir also occur from insufficient attention of existing water sharing arrangements between the villages Phyang and Phey, where public opinion towards the “ice stupa” is ambivalent or even hostile. There have been protests against the project as it abstracts water from the main stream, thereby reducing water availability for downstream communities and households (Sharma 2017).

In interviews, smallholders reported benefits from improved water availability in spring as higher crop yields,

increased frequency of irrigation, and fewer restrictions on water use by the *chudpon*. Households in Nang mentioned better results for growing potatoes as cash crops. In Igoo, the ability to grow vegetables and trees were perceived as key benefits. Sales of cash crops and timber provide valuable incentives for communities.

## Discussion

The combination of remote sensing analyses and field measurements allows to monitor ice reservoirs and to identify natural icing sites, which may inform decisions about potential ice reservoir locations. Depending on the frequency, depth and duration of fluctuations across the freezing point of water (freeze-thaw cycles, Hewitt 2014), icing regularly occurs in upper tributaries with a broad valley floor and gentle slopes on frozen ground. This typical and important hydroclimatic feature of Ladakh has largely been neglected in previous research. Time series indicate that functioning of ice reservoirs does not solely depend on altitudinal position, but also on other topographic parameters such as slope angle and solar radiation. Additionally, the position of the zero degree line in winter and spring needs to be considered.

Whereas superimposed ice can be identified using satellite imagery, volume estimations require close range techniques such as SfM photogrammetry, which is costlier in terms of time and resources. Our results indicate that the ice reservoir volumes differ greatly, mainly depending on inter-annual variation in winter runoff. An improved understanding of ice reservoir efficacy requires more accurate estimations of climatic and hydrological conditions, including snow cover monitoring and investigations of the role of permafrost. However, these data are still not available for Ladakh and the wider Himalayan region (Gurung et al. 2017). Due to the complex set of variables, the environmental conditions for optimal functioning of ice reservoirs remain uncertain. Extended cloudy periods in spring may result in delayed melting, so that the anticipated increase in water availability is not guaranteed every year. The lack of such data impedes exact assessments of irrigation potential of ice reservoirs. Assuming optimal conditions and neglecting variations in water demands of cultivated plants, our approximation of potential irrigation cycles puts the exaggerated claims and anecdotal accounts over ice reservoirs into perspective. In five catchments, ice reservoirs allow at least one irrigation cycle of cropped area under optimal conditions, based on a water column of 2 cm (Table 1). However, under unfavorable conditions, a complete irrigation cycle can only be achieved in one catchment. In case of cash crop production, which requires higher amounts of water, the potential irrigation area is even further reduced. As agriculture in Ladakh is primarily for subsistence, the high upfront costs

for installing technological improvements to reduce evaporation loss, such as drip irrigation, hamper their implementation in this socioeconomic setting.

However, ice reservoirs can be regarded as appropriate local technology to reduce seasonal water scarcity at critical times. It is remarkable that the practice of building such structures can be traced back at least to the 1960s, possibly much earlier, contrary to contemporary reports. The benefits perceived by villagers include an increase of cash crop production (potatoes) and tree plantations, causing demands for the construction of more ice reservoirs. A comprehensive understanding of water management in Ladakh also needs to consider a number of diverse aspects such as established water sharing arrangements between communities and households, competing labor requirements for agriculture and better paying off-farm jobs and lack of funds for maintenance of irrigation infrastructure. As active participation of local smallholders and adequate solutions for potential resource conflicts are crucial for sustainable land use options, these aspects need to be integrated in research assessments and planning processes.

Although the first “artificial glacier” was constructed in 1987, these structures did not attract much global attention until the late 1990s, when they were presented as a strategy to improve irrigation and benefit farmers (Bagla 1998; Shaheen et al. 2013). However, following the controversy over the impending disappearance of Himalayan glaciers in 2007, “artificial glaciers” were promoted as appropriate climate change adaptation strategies (Vince 2009), though their function as water conservation structures to cope with recurrent water scarcity at the local scale had not changed. Based on our examination and counter to recent claims of the efficacy of “artificial glaciers” in addressing climate change, we believe these structures are unlikely to be effective adaptation strategies. The main reasons for this are they depend upon winter runoff and freeze-thaw cycles; they only serve to reduce water scarcity in spring; they are sensitive to climatic conditions. Therefore, it is important to see them as site-specific water conservation strategies rather than climate change adaptation, which is neither their original function, nor something they are likely to accomplish.

## Conclusion

The case of ice reservoirs in Ladakh is an illustrative example of the co-evolution of environmental processes and local livelihoods in a sensitive socio-hydrological system. We think that the term “artificial glacier” is not only inaccurate but also misleading in that it gives the false impression of them being potential replacement for disappearing natural glaciers. Therefore, we propose the term ice reservoir for scientific usage to ensure clarity and accuracy. Although climate change

is expected to have considerable impact on meltwater-dependent agriculture in this cold-arid region, the usefulness of ice reservoirs as reliable adaptation strategies to cope with the anticipated reduction of water storage in the cryosphere remains questionable. The main reasons for this assessment include climatic variability, natural hazards and an incomplete integration into the local socioeconomic setting. These different aspects significantly reduce the efficacy of ice reservoirs.

Despite limitations in data availability, our approach of combining research methods from natural and social science improves understanding of the interactions between glacio-hydrological processes and socioeconomic development. These methods are globally replicable for similar mountain regions and can help evaluate the potential transferability of this technology. The integration of local experiences and community-based mechanisms provides a more contextualized and holistic understanding of site-specific adaptation strategies and livelihood vulnerability (Barnes et al. 2013). In this sense, lessons from our Ladakh study are relevant for the Himalayan region and beyond.

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