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The Melting Himalayas

Examples of Water Harvesting Techniques

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The Melting Himalayas
Examples of Water Harvesting Techniques

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Preface

The glaciers of the Himalaya are a hot topic in many research areas, mainly because of its wide-ranging impacts on both natural and human systems. My interest for glaciers and water harvesting has been present since a long time back, and this thesis has made it possible for me to explore a rather unknown water harvesting technique in a glaciated environment. This is a Bachelor's thesis in Physical Geography and Ecosystem Analysis, written during fall 2011 and spring 2012.

Acknowledgements

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Abstract

Himalayan glaciers are both growing and shrinking as a response to global climate change. The major trend is a loss of ice sheets, especially among the smaller glaciers. As glaciers retreat there is a change in hydrology and seasonal water availability both upstream and downstream of the river basins. This is most apparent in high altitude and glacierfed areas where meltwater is the main (sometimes only) water supply for agricultural and domestic use. The change in hydrology is most noticeable during the first months of sowing since the amount of meltwater is increasingly unpredictable. This uncertainty increases the risk for crop failure, as the cropping season is limited from March/April to September/October.

To deal with water shortages and an unpredictable water supply, high altitude areas have developed water harvesting-methods by storing water as ice. This thesis seeks to explore and explain two techniques, first an indigenous technique called glacier grafting where glacial ice is relocated to shaded cavities where it is left to grow. Secondly, a more recent innovation is described where water is diverted to create icings (also called artificial glaciers) that melt just in time for the sowing season. Both techniques have been developed and incorporated into the agriculture of the western part of the Himalaya (The Karakoram).

In order to assess the effectiveness of this water-harvesting technique, a case study has been compiled from a village in Ladakh, north India, where one of the artificial icings is located. Cropped areas are estimated to calculate and establish the water need. In addition to this, the volume of water that the icings are likely to contain is estimated. Thereafter a comparison between water demand and the extra water supply is made possible, to conclude if the artificial icings is an adequate water storage.

Keywords: Climate Change • Himalaya • Glacier • Water Harvesting • Glacier Grafting • Artificial Icings

Sammanfattning

Himalayas glaciärer både växer och blir mindre som ett svar på klimatförändringarna. Den dominerande trenden är att ismassor minskar, speciellt för mindre glaciärer. Allt eftersom glaciärer drar sig tillbaka, ändras hydrologin och vattentillgängligheten, både uppströms och nedströms inom dräneringsområdet. Denna förändring är mest tydlig på hög altitud där jordbruk och hushåll till stor del (ibland endast) får sitt vatten från glacialt smältvatten. Mest märkbart är detta på våren, vid början av utsädesperioden, då volymen av smältvatten är mer och mer oberäknelig. Osäkerheten om vattentillgång ökar risken för en sen start av växtsäsongen, vilken är begränsad från mars/april till september/oktober. En sen sådd kan slå ut en hel skördesäsong.

För att hantera vattenbrist och en oberäknelig vattentillgång har människor i dessa områden utvecklat water harvesting-metoder där man lagrar vatten som is. Denna uppsats ämnar att utforska och förklara två av dessa metoder, först en inhemsk teknik som kallas glacier grafting, där glaciäris placeras i hålrum där den sedan lämnas för att växa. Vidare beskrivs en senare teknik där smältvatten leds till skuggområden där det fryser och skapar konstgjorda svallisar (också kallade konstgjorda glaciärer). Svallisen smälter sedan lagom till början av växtsäsongen. Båda metoderna har uppkommit, utvecklats och blivit en del av jordbruket i västra delen av Himalaya (Karakoram).

En fallstudie är utformad för en by i Ladakh, norra Indien, där en av de konstgjorda svallisarna finns. Detta är ett försök att uppskatta hur effektiv denna nya (mindre etablerade) water harvesting-metod är, jämfört med hur mycket vatten som krävs av jordbruket. För att göra denna uppskattning beräknas jordbruksarealen, grödornas vattenbehov, samt hur mycket vatten de konstgjorda svallisarna kan tänkas innehålla. Därefter jämförs det totala vattenbehovet med den extra vattentillgången.

Nyckelord: Klimatförändringar • Himalaya • Glaciär • Water Harvesting • Glacier Grafting • Konstgjord svallis

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Introduction

More than one sixth of the world's population lives in glacierfed and snowfed water basins (Stern 2007). As global temperatures are increasing, snow-cover is decreasing in most regions of the world. There is a melt-off and mass loss for the majority of the world's glaciers and ice caps that changes the hydrology of glacierfed water basins (Bates et al. 2008). As glaciers melt due to global warming, river discharges for glacierfed rivers will increase in the short term but decrease over the next few decades as ice storage gradually diminishes (Kundzewicz et al. 2007).

The climate of the Himalayas is highly variable because its wide range of geographical factors such as elevation and rain shadow effects that contribute to variations in temperature and precipitation (Young & Hewitt 1990). This thesis will focus on the western part of the Himalayas, which has very low annual precipitation, a short growing season and relies heavily on glacial meltwater for agricultural production to sustain livelihoods. For these reasons water-harvesting techniques have been developed in this area over many centuries, as a way to decrease vulnerability in periods of water scarcity. The quantity of the water harvested by different techniques varies depending on the water use purpose, particularly whether it is for domestic (e.g. drinking water) or agricultural use. Because climate change is increasing the water stress in regions that are already dry (Houghton 2009), there is an urgent need for improvement and implementation of water management techniques, as well as the spread of knowledge of existing solutions to regions under increased water stress.

The research questions of this thesis are what the glacial response is to climate change in the Himalayas and how villages are dealing with water scarcity. To answer these questions it will further examine and explain:

- The effects of climate change on the Himalayan glaciers.
- The effects of climate change on agricultural production in glacierfed water basins.
- How people are coping with unpredictable water supply through water harvesting techniques where water is stored as ice.
- If the volume of water stored in artificial icings is sufficient to the water need.
- How the water harvesting techniques can be improved and expanded to other areas
- What climatological and geographic characteristics that are important for mapping areas suitable for artificial icings.

The thesis is divided into five different parts. *Chapter I* gives a geographical and climatological description of the Himalayas, as well as a regional area description of the western range; the Karakoram and the Indus River basin. *Chapter II* gives examples of water harvesting techniques that have been developed in the western Himalayas to deal with water stress and scarcity. *Chapter III* describes a case study from a village in Ladakh to show how crop water demand compares to the water equivalent provided by the artificial ice storage. *Chapter IV* summarizes important factors for different water harvesting techniques and gives suggestions for improvements. It also shows what geographical and climatological parameters that are important for mapping areas where artificial icings have potential to be practiced. Finally *Chapter V* summarizes the work with a discussion and conclusion.

1. Water in the Himalayas

1.1. Area Description of "The Water-tower of Asia"

The Himalayan mountain range is the most extensive and tallest mountainous area on Earth and stretches across the border of the Indian and Eurasian tectonic plates with a length of 2,400 km and a width of 150-400 km (Figure 1, Table 1, Hasnain 2002). The Himalayan glaciers support all the rivers of Asia with perennial stream flow and are of large importance for high altitude regions as they affect the climate and hydrological cycle (Rieliy, 1996). The region is often called "The water-tower of Asia" as it is the source of the 10 major rivers of the Asian land mass: Indus, Ganges, Mekong, Yangtze, Yellow River, Amu Darya, Brahmaputra, Irrawaddy, Salween and Tarim (Xu et al. 2007; Bates et al. 2008). These rivers provide water for about 1.3 billion people; a population that is likely to increase given that the global population is projected to increase by approximately 3 billion by 2050 (Miller 2009).

Table 1. The Himalayas in numbers.

The Himalayas	
Length (E-W)	2 400 km
Width (N-S)	150-400 km
Population supported by Himalayan melt water	1.3 billion (and increasing)
Number of Glaciers	15 000 (approx.)
Glacier Mass	116 180 km^3
Freshwater Storage (Water Equivalent)	12 000 km^3
Glacial Area Cover	30 000 km^2 (17% of the mountain range)
Runoff contribution	Varies with season and distance from source

The mountain range holds approximately 15,000 glaciers that cover about 30 000 km^2 (Cruz et al. 2007; Owen et al. 2002; Li et al. 2008). The volume of freshwater that is stored in the glacial snowfields is equivalent to about 12,000 km^3. Assuming a steady state, the glaciers and snowfields get discharged and recharged annually, thus provide the rivers, soils and groundwater with water throughout the year. Meltwater is an important water source for Himalayan rivers, and is especially critical during the dry season as it provides rivers with water even when precipitation is low or nonexistent. This makes glacial meltwater essential for agricultural and domestic purposes at both higher and lower altitudes (Bocchiola et al. 2011).

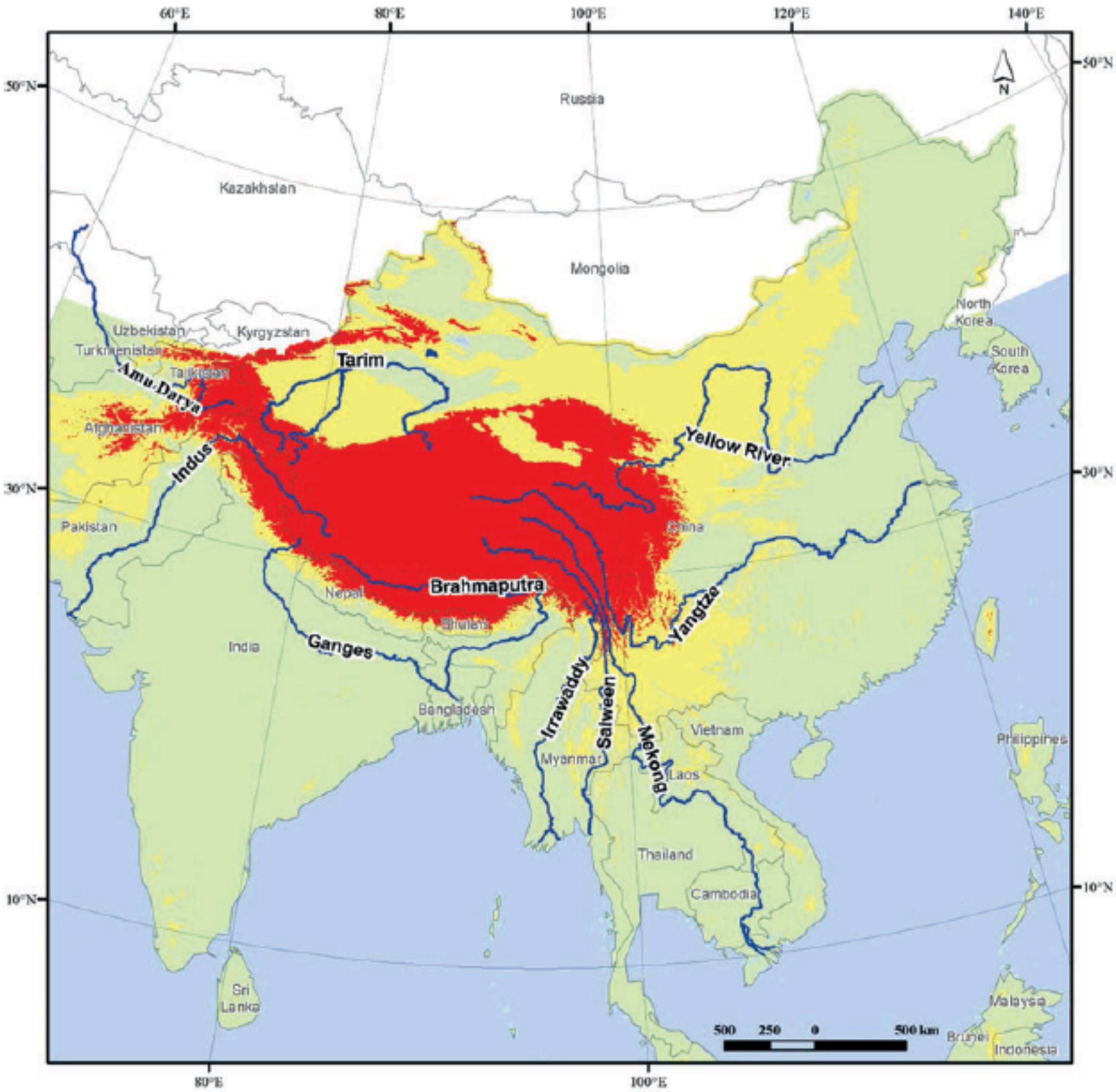

Figure 1. The map shows the ten major rivers that have headwaters originating from the Himalayan Mountains. The red (alpine) and yellow (montane) areas show the extent of the Himalayas, where red color shows areas that have an altitude above 3000 masl (meters above sea level). The green color shows the extent of low-land areas that are impacted by the ten rivers. Reprinted with permission (Xu et al. 2007).

1.2. Different Kinds of Watersheds

There are four kinds of watersheds in this extensive high altitude region; rainfed, snowfed, glacierfed and complex (Figure 2, Singh & Bengtsson 2005). In *rainfed* watersheds, runoff is generated only by precipitation, and these cases are found at lower altitudes from about 500 to 2000 masl (meters above sea level). In *snowfed* watersheds runoff comes from both precipitation and snowmelt and these watersheds occur at altitudes from 2000 to 4000 masl. *Glacierfed* watersheds occur at the highest altitudes, from 4000 to 7000 masl, and in these basins runoff is mainly generated from melt of permanent snowfields and glaciers, and runoff from rainfall is insignificant or non-existent. Ice surfaces that melt with more than 80% in summer and contribute significantly to water supply lie at altitudes between 3800 and 4800 masl (Hewitt 2007). The fourth kind of watershed receives its water from rainfall, snowmelt and glacier melt which all contribute to runoff (Singh & Bengtsson 2005). These are *complex type* watersheds, and include all of the large watersheds in the Himalayas. Climate change will have various effects on the different types of watersheds and its hydrological characteristics.

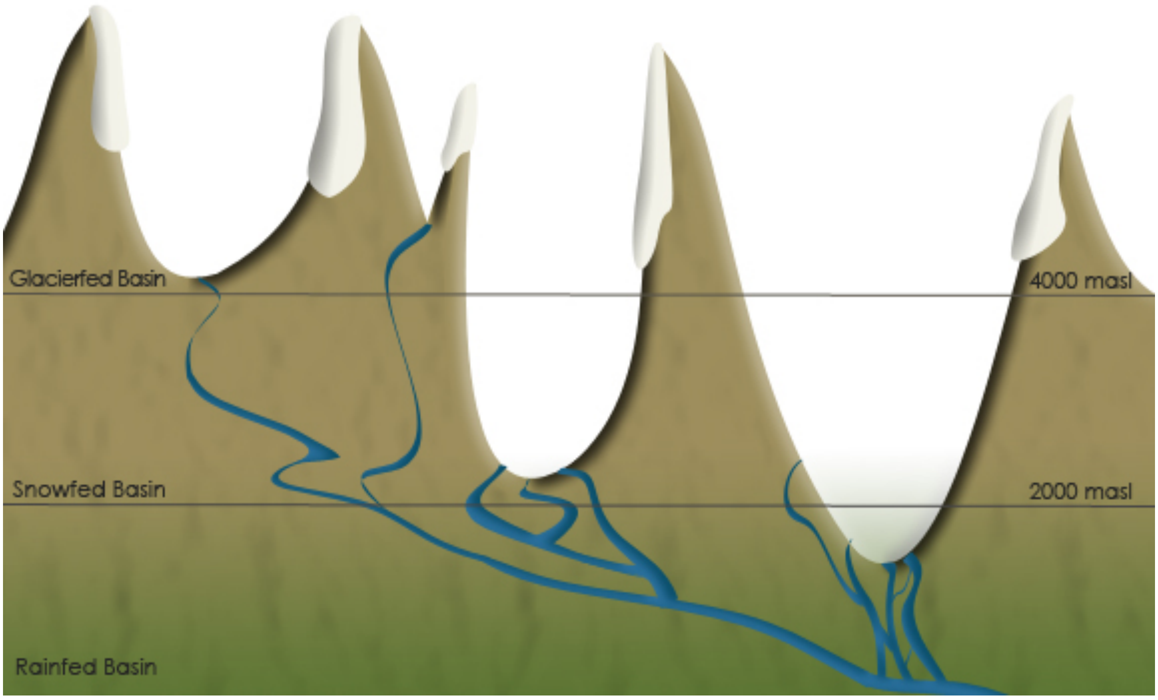

Figure 2. Schematic of three main watershed types in relation to altitude and type of precipitation. With basins <2000 masl being rain fed, basins between 2000-4000 masl being snow fed and basins > 4000 masl being glacier fed. Modified from Singh & Bengtsson (2005).

1.3. Glacial Meltwater and River Streamflow

Surface melt is the primary source of meltwater from temperate and cold glaciers (Hambrey 1994). This is supplemented by runoff from snowmelt along the valley sides and a small amount from basal melt. Solar radiation is the source of energy for the melting process, however rainfall also contributes significantly to this process. Meltwater is also produced by frictional heat, as the ice slides over its bed.

The percentage of water that originates from snowmelt and glacial melt increases with altitude (Singh & Bengtsson 2005). It also varies with season and geographical location (Xu et al. 2007; Rees & Collins 2006). It is therefore difficult to generalize how large the fraction of meltwater is within the river streamflow. However discharge from meltwater often dominates flow for considerable distances downstream, in particular where other sources of runoff are limited (Rees & Collins 2006). Case studies have provided several estimates for major rivers. As an example, snowmelt and glacial melt generates 50 percent of the total runoff of the Indus River that is used for irrigation in Pakistan (Winiger et al. 2005). Singh & Bengtsson (2004) and Barnett et al. (2005) estimate that the Himalayan glaciers supply up to 70% of the flow in Ganges and Indus during summer, before and after precipitation from the summer monsoon. The main stem of the Upper Indus receives as much as 80 % of its flow from snow and ice melt, as do the western tributaries to the Indus River (Young & Hewitt 1990). During spring and early summer meltwater is most important for stream flow, whereas in late summer the monsoonal rain adds to the meltwater. These numbers might indicate the importance of glacial meltwater to river systems, especially at high altitudes where water basins are glacier fed.

1.4. Glacial Change in Response to Climate

The state of a glacier depends on its mass balance, which is a result of how much snow is preserved in the *accumulation zone* relative to how much is lost in the *ablation zone* (Figure 3) (Hambrey 1994). If the loss exceeds gain the net mass balance is negative and the glacier will become thinner and/or shorter. But if gain exceeds loss the net mass balance is positive and the glacier will increase in total size, either from the build up of firn in the accumulation zone or from reduced melting in the ablation zone. Current knowledge of glacial mass balance is limited due to the fact that most reports are of changes in *terminus* (Figure 3), which is the ice-tongue position at the lowest elevation (Hewitt 2011). Although the position of terminus is indicative of glacier change, it does not adequately capture the total change of a glacier's ice volume. The ice might be thickening in the glaciated areas above termini at the same time it retreats.

During recent decades, there are reports of substantial worldwide loss of glacial volume, but if this is in response to climate change and rising global air temperatures is widely discussed (Barnett et al. 2005). There are year-to-year changes in glacial mass in response to climatically controlled variations. Glaciers respond individually to climatological changes, because they all have a unique microclimatological setting, some glaciers may advance while others recede.

Global temperatures are rising due to anthropogenic fossil fuel emissions and climate change, but the temperature rise over high elevations such as the Himalayas is occurring at three times the global average increase (Cruz et al. 2007). The Intergovernmental Panel on Climate Change (IPCC) Assessment Report tells that there will be an annual mean temperature increase of 3 °C by the 2050s over the Asian land mass and about 5 °C by the 2080s (Cruz et al. 2007). There are predictions that temperatures will rise even more over the Tibetan Plateau. It is the high altitude and the low humidity that are the main reasons for this more pronounced heating over the plateau (Central Groundwater Board 2009). In addition to increased temperatures, there are observations of decreased winter snowfall in parts of the Himalayas (Bagla, 2001).

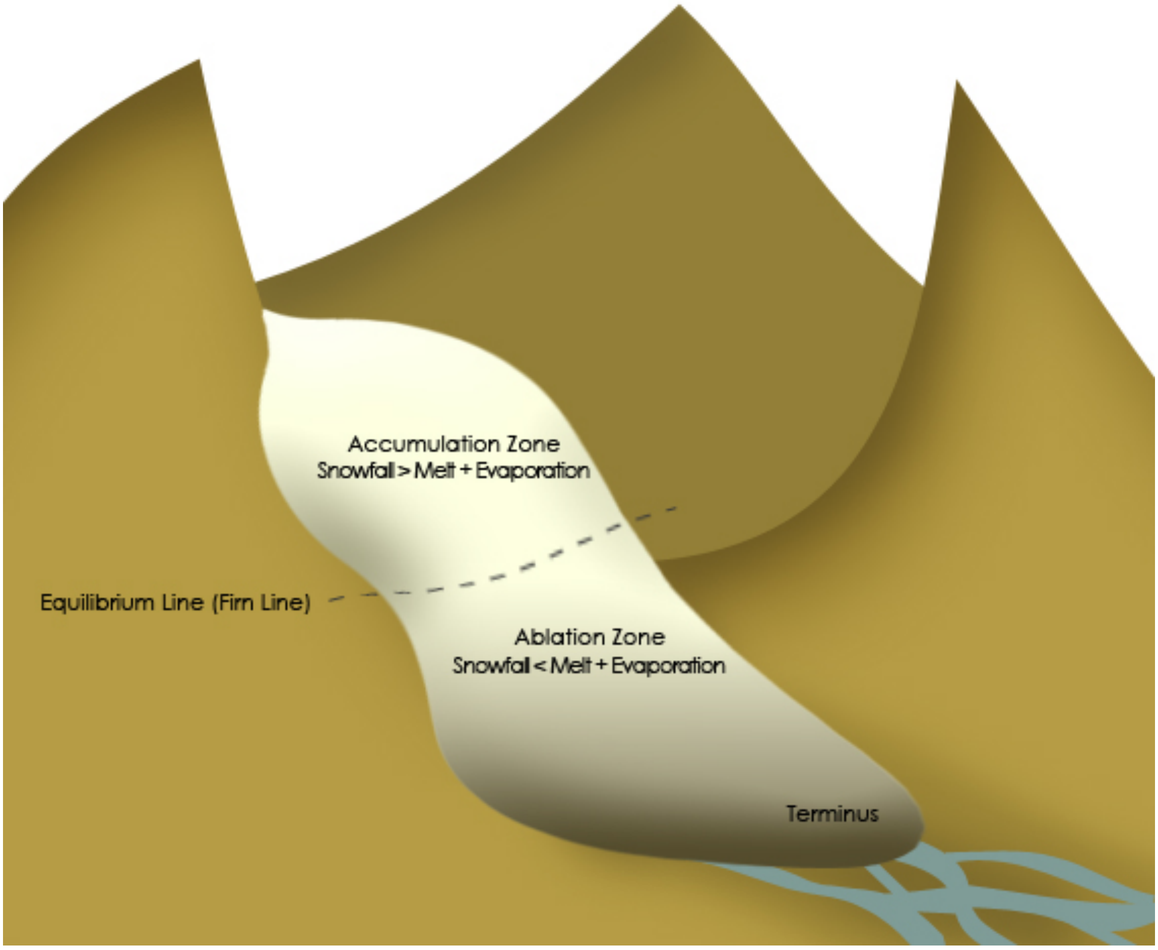

Figure 3. Scematic of the main parts of a glacier. The Accumulation zone where snowfall exceeds melt and evaporation. The ablation zone where snowfall is lower then melt and evaporation. The firn line where the glacier is in equilibrium, and the terminus that marks the end of the glacier at any given point in time.

Shen et al. (2002) states in the IPCC (2007) report that the Himalayan glaciers are retreating at a faster rate than in any other region of the world. They also say that if the current melt rate continues it is likely that the glaciated area of the Himalayas will decrease from 500,000 km^2 to 100,000 km^2 by the year 2035. Glaciers shorter than four km in length on the Tibetan Plateau are projected to disappear completely. However, some of these estimates have received criticism, and a more recent report refers to them as "poorly substantiated estimates" (IPCC 2010). There are also studies that suggest that the changing climate conditions have lead to an intensification of glacier nourishment in some parts, especially in the Karakoram, Indus Basin (Hewitt 2007). As mentioned earlier, glaciers respond individually to climate. It is therefore hard to identify a trend of recession or build-up that is true for all areas. However, the overall agreement seems to be that glaciers are retreating, and will continue to do so as a consequence of global climate change.

EFFECTS ON RUNOFF

Most of the glaciers in the Himalayas are summer fed, this means that there is snow accumulation and glacier growth primarily during summer months, when the monsoon is present over the South Asian continent (Hasnain 2002). Although temperatures are colder in the winter, there is little moisture supply for snow accumulation. Warmer temperatures have three major negative impacts on glacial mass balance as it affects both accumulation and ablation (Hasnain 2002):

1. There is an increased proportion of the precipitation falling as rain instead of snow, inhibiting the accumulation and growth of ice on summer fed glaciers.
2. More sensible heat increases the ablation.
3. A decrease in snowfall decreases the albedo of the glacier surface, which means that more solar radiation is absorbed, increasing ablation.

This will cause more discharge at first, but as glaciers retreat and the total ice mass decreases so will also the discharge (Xu et al. 2009). The long-term effect on glacial runoff will most likely be increased water shortages and limited water supplies for downstream communities. Thereby affecting livelihoods and ecosystems, particularly during dry seasons.

Akhtar et al. (2008) simulates the effects on runoff for three stages of glacial coverage: 100%, 50% and 0 %. In a changed climate following the future projections of IPCC's Special Report Emission Scenarios (SRES) A2 scenario (Nakicenovic et al. 2000), the conclusion is that streamflow increases as long as there is a glacier cover, but for the 0% glacier scenario a drastic decline in water resources occurs (two models are run showing a 94% and 15 % decline in water resources/discharge). Essentially, while there are glaciers present, warming increases the total water flow and supply by "mining" the water stored in glaciers. Once the glaciers disappear, water availability is limited by precipitation. The effects on temperature and precipitation from climate change is likely to change stream flow volume as well as the temporal distribution of flow throughout the year, imposing significant water stress in parts of the Himalayan region (IPCC 2001).

WATER STRESS AND EFFECTS ON CROPS (CO_2 FERTILIZATION)

The extent to which an area is water stressed is related to the proportion of freshwater supply and demand (Houghton 2009). As global and regional temperatures increase with climate change, so does evaporation. Therefore areas with no change or a decrease in precipitation might experience more water stress, as a higher proportion of water falling on the surface will evaporate. This combined effect results in less soil moisture and runoff for crop growth and domestic use, an effect that is critical in areas where rainfall already is marginal, such as the cold deserts of the Himalayas. However, there can also be positive effects for the water use efficiency of crops, as plant transpiration is reduced with a higher concentration of CO_2 (Houghton 2009). This process is called CO_2 fertilization, where the higher CO_2 concentration stimulates photosynthesis through enabling plants to fix carbon at a higher rate. The CO_2 fertilization effect is highest for plants such as wheat, rice and soya bean, but also affects crops including maize, sorghum, sugar cane, millet and pasture grasses (Houghton 2009). For the first group of plants, a doubling of CO_2 can produce as much as a 30% increase in yields, even though grain quality tends to decrease with CO_2 enrichment and higher temperatures (Houghton 2009). The positive effects of CO_2 fertilization are most likely to be outweighed by negative effects of water stress, hence water availability for irrigation is still important to deal with as regions get drier from the effects of warmer temperatures (Houghton 2009). The scope of this thesis is to small to investigate this aspect further, but one should keep in mind that there are effects of an increased atmospheric CO_2 level that might enhance the water use efficiency of plants.

1.5. The Karakoram and the Indus Basin

The western part of the Himalayas constitutes the source of water for the entire Indus River basin (Young & Hewitt 1990). This particular area is called the Greater Karakoram Range and has extensive glaciers (about 7000 glaciers) that are among the largest of the Himalayas (Hewitt 2011). The headwaters lie mainly in Pakistan but also in China and India (Figure 4). The glaciers of the Karakoram have declined steadily from the 1920s to the 1990s and lost perhaps one third of its ice mass. During the 1970's the retreat slowed down and from the late 1990's there are reports of glaciers stabilizing and even advancing in the high Karakoram (Hewitt 2005; Immerzeel et al. 2009). Some of the largest glaciers in this area have undergone rapid thickening since the mid-1990's where twelve intermediate glaciers and fifteen high altitude tributaries were observed advancing (Hewitt 2007). The recent expansion is observed only in the highest and central parts of the Karakoram, whereas in surrounding areas glacier recession of smaller glaciers is continuing. Local sources confirm the trend of retreating (Than 2012), but how this pattern is related to climate change and how it is likely to continue is uncertain.

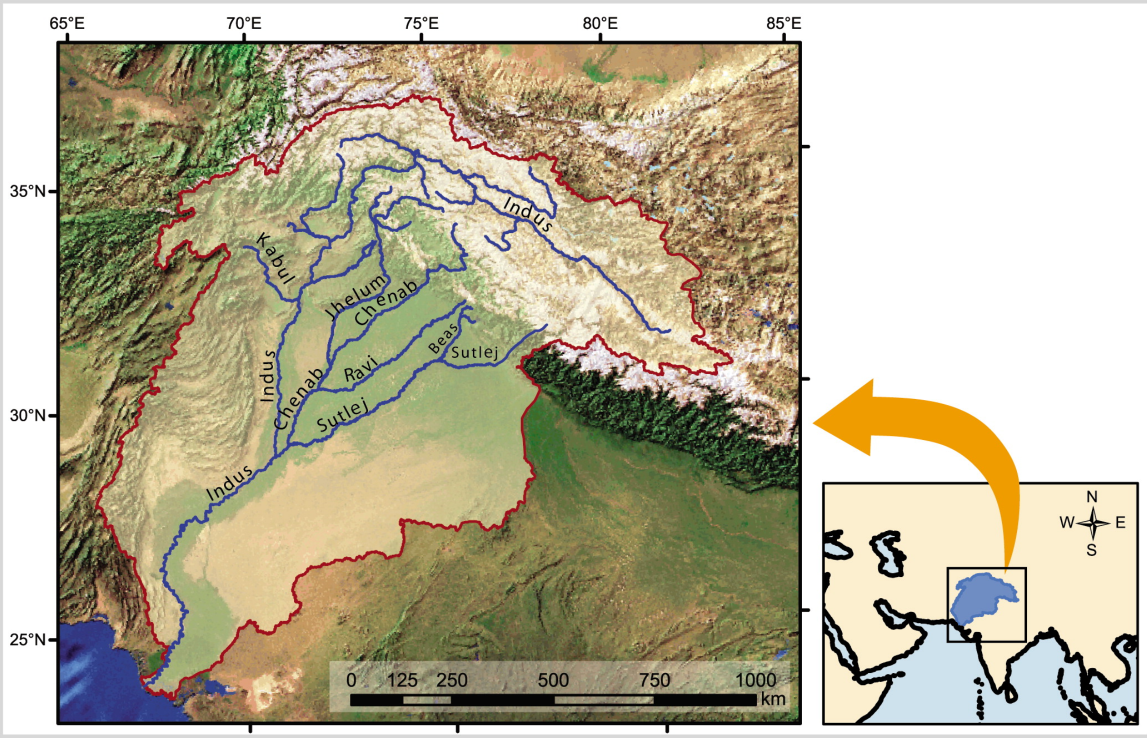

Figure 4. Map of the Indus River Basin. (Map by ICIMOD) Reprinted with permission.

CLIMATE OF THE KARAKORAM

There are a few cold deserts in the world with the biggest extent in Asia (Figure 5). The cold deserts are connected to the Himalayas as a result of rain-shadow effects of the range itself and its high altitudes (Peel et al. 2007). The Karakoram has this dry and cold climate (Table 2). Cold desert areas experience high fluctuation in seasonal and diurnal temperatures and are limited in water supply (Central Groundwater Board 2009). Therefore it is uncertain for the farmer if there will be sufficient stream flow during the limited cropping season (Bagla 2001).

Table 2. Definition of cold desert climate, BWk, according to Köppen's climate classification (Strahler & Strahler 2006).

Cold Desert Climate, BWk		
Letter Code	Basic Description	Classification Criteria
B	Dry	PET> Precipitation
W	Arid (desert)	Annual Precipitation < 400 mm
k	Cold and dry	MAT** < 18 °C

*PET = Potential Evapotranspiration
**MAT = Mean Annual Temperature

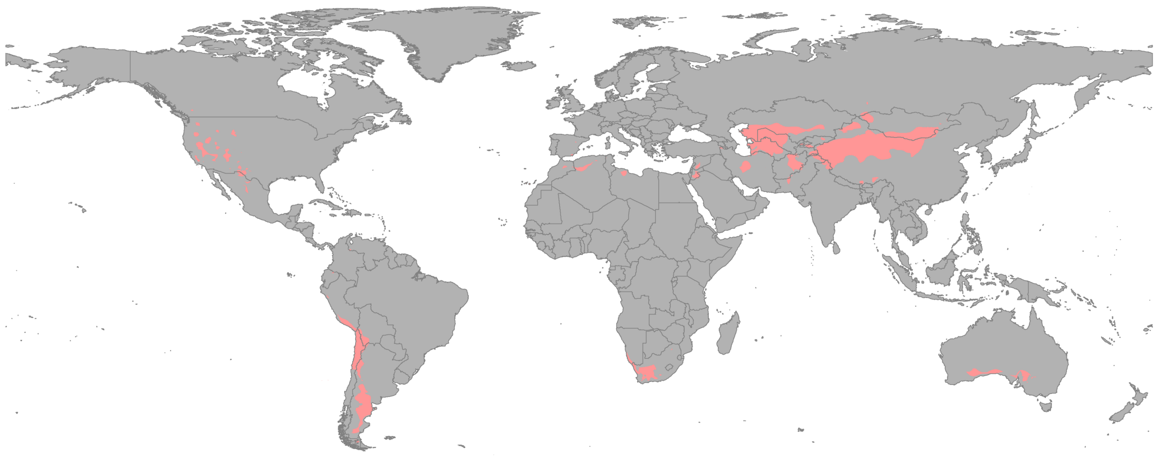

Figure 5. Köppen's climate classification. Pink color shows the areas with a cold desert climate classification (Peel et al. 2007).

PRECIPITATION AND TEMPERATURES

The Karakoram glaciers are under the influence of three seasonal weather systems (Hewitt 2007). The Sub-Mediterranean circulation is a low-pressure system from the west that is the major moisture source during winter months. It is the dominant source of precipitation for glacier systems of the Karakoram and accounts for about two-thirds of glacier nourishment in this area (Young & Hewitt 1990; Hewitt 2007). In summer (July to September) the dominant source of precipitation comes from the Asian summer monsoon that brings in storm systems and Indian Ocean air to the main Himalayas. During years of a strong monsoon, they may break through the front ranges and deliver substantial precipitation over the Karakoram Region. The Indian Ocean air accounts for about one third of glacier nourishment. Inner Asian anticyclones affect the behavior of these two systems as it influence storm paths and thereby the occasions of clear weather. This is important since direct solar radiation accounts for 80-85% of ice melt (Hewitt 2007). The explanation for the sudden advance of the largest high altitude glaciers is most likely due to increased summer storms and cloudiness, counteracting the melt effect of increased temperatures. As well as there are annual and interannual variations in precipitation, there is a large spatial variability where altitude and rain shadow processes plays a big role (Young & Hewitt 1990). Front ranges towards the south and east receive heavy precipitation whereas regions further north and west receive less of this precipitation. The bulk of the precipitation falls within the altitudinal zone between 2500 and 6000 masl and the altitude of maximum precipitation in the western Karakoram is at ~5000 masl and in the eastern Karakoram ~6000 masl (Young & Hewitt 1990).

Surface air temperature is extremely variable (Figure 6), primarily because of elevation but also because of seasonal and diurnal variations (Young & Hewitt 1990). Solar radiation is the main cause of snow and ice melt (Young & Hewitt

1990). Radiation, thus melting capacity, varies as a function of elevation, surface slope, aspect, and weather conditions. Hence, north and south sloping mountain faces have quite different radiation regimes and a distinct difference in local hydrology. The Upper Indus Basin has high summer temperatures and, in combination with a very dry atmosphere, this means that evaporation rates are high (Young & Hewitt 1990). In many low-lying areas of the western Himalayas evaporation rates are so high that surface runoff only occurs during very rare thunderstorm events. Most of these areas have a negative annual water balance.

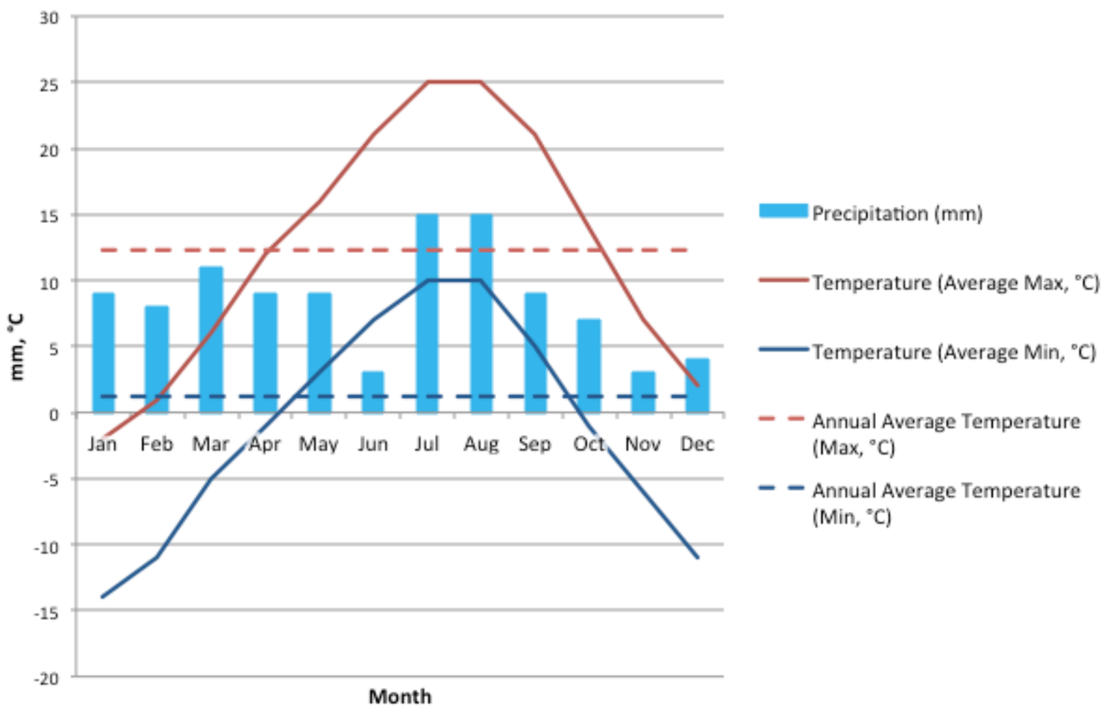

Figure 6. Diagram of precipitation (mm), monthly average maximum and minimum temperatures (°C), and annual average maximum and minimum temperature (°C). Station for meteorological information: Leh. Period: 1951-1980. Data retrieved from India Meteorological Department, Nov 16 2011.

IMPORTANCE OF GLACIAL MELT WATER FOR AGRICULTURE

Even though cold deserts are not ideal for agriculture, the economy of the upper Indus basin is based on agriculture and depends heavily on water availability (Akhtar et al. 2008). Seasonal fluctuations in river runoff are a challenge for the farmer since there are months that are more water stressed than others. The annual runoff cycle includes periods of low discharge from September to April and high discharge from May-August (Young & Hewitt 1990). Peak flow is expected throughout July and August. Periods of low flow can cause problems for agricultural productivity, since the growth period is strictly limited to the period from March to October and might inhibit the early growth as well as the late maturation of crops (Nørstegård Tveiten 2007).

Glaciers act as stabilizers of annual runoff, and villages that are located in a glacierfed water basin have less variation in annual runoff than a village located in a water basin without glaciers (Nørstegård Tveiten 2007). This gives a more beneficial hydrologic pattern for agricultural activities since it is more stable (Singh & Singh 2001). In non-glacierized watersheds the stream flow is low for the months of September and October, and water shortages influence the maturation of crops. Therefore farmers in watersheds without glaciers struggle to get enough water after the snowmelt has finished. River discharge in snowfed watersheds is particularly sensitive to long-term changes in both precipitation and temperature, where changes in precipitation can affect the volume of runoff coming from melt of accumulated snow storages (Barnett et al. 2005). However, in regions where agriculture is heavily dependent on the *timing* of runoff, from winter accumulation and spring-melt, changes in temperature pose a greater difficulty for water management. During dry season the crops experience water stress because of the absence of precipitation, but can be supported by surface and groundwater irrigation from glacial meltwater (Rasul 2011). Consequently, glaciers are vital for agricultural production and ecosystems in high altitude regions, but are also important downstream.

Some regions make use of water harvesting techniques to secure water availability and meet domestic and agricultural water demand throughout the year (Gould & Nissen-Petersen 1999). By collecting snow and ice in reservoirs of different sizes, the water is stored and can be utilized when needed, either at a small-scale for immediate domestic use or at a larger scale for agricultural use. There are several water harvesting techniques that have been applied in the Himalayan region to deal with the increased water stress and the need of water for domestic use and irrigation. The techniques include *artificial icing* (or *artificial glaciers* as they are more commonly named) and *glacier grafting.* These two techniques will be further described and discussed in Chapter II.

2. Water Harvesting

Water harvesting is a name for a variety of techniques used to capture and store water, not only in arid areas but anywhere. However, the importance of water harvesting is greater in arid areas where the water supply is scarce. Techniques vary from roof catchments, ground catchments to rock catchments, depending on the type of surface used (Gould & Nissen-Petersen 1999). In the cold deserts of the world, techniques for storing freshwater as ice have been developed over centuries, as a response to the uncertainty of water availability throughout the year.

The following sections will describe three techniques that have been developed in different parts of the Himalayan cold deserts, and that are gaining increased attention now that glaciers have started to retreat at a more pronounced speed. The water harvesting techniques show different ways of retaining and storing water as ice. First a storage method used mainly for domestic use is described, referred to as snow water harvesting, where snow is packed in watertight pits. Secondly, a technique of glacier growing or *glacier grafting,* used in Pakistan for centuries, is described. The melt water from this storage is primarily used for irrigation of crops. Thirdly, a more large-scale storage where glacial meltwater is diverted and refrozen to form *artificial icings* is described. This method is fairly "young" and developed in Ladakh, located in the western part of the Himalayas, as a response to retreating glaciers and increased need of irrigation water.

2.1. Snow-Water Harvesting

In the mountainous areas of Afghanistan and Iran some communities pack snow in watertight pits, so that spring and summer melt can provide the households with drinking water (Figure 7, Gould & Nissen-Petersen 1999). The snow is commonly carried in bags by donkeys, emptied in the pits where it is compacted and then covered with soil. The soil acts as an insulator and when full, a snow storage system of 300 m^3 can provide a community of 10 families with drinking water for up to 2 years. Presumably storing ice instead of water is a hygienic issue as it can maintain good water quality for a longer time than water. This particular water harvesting technique is good for domestic use, but for securing water availability for agricultural production a larger reservoir is needed.

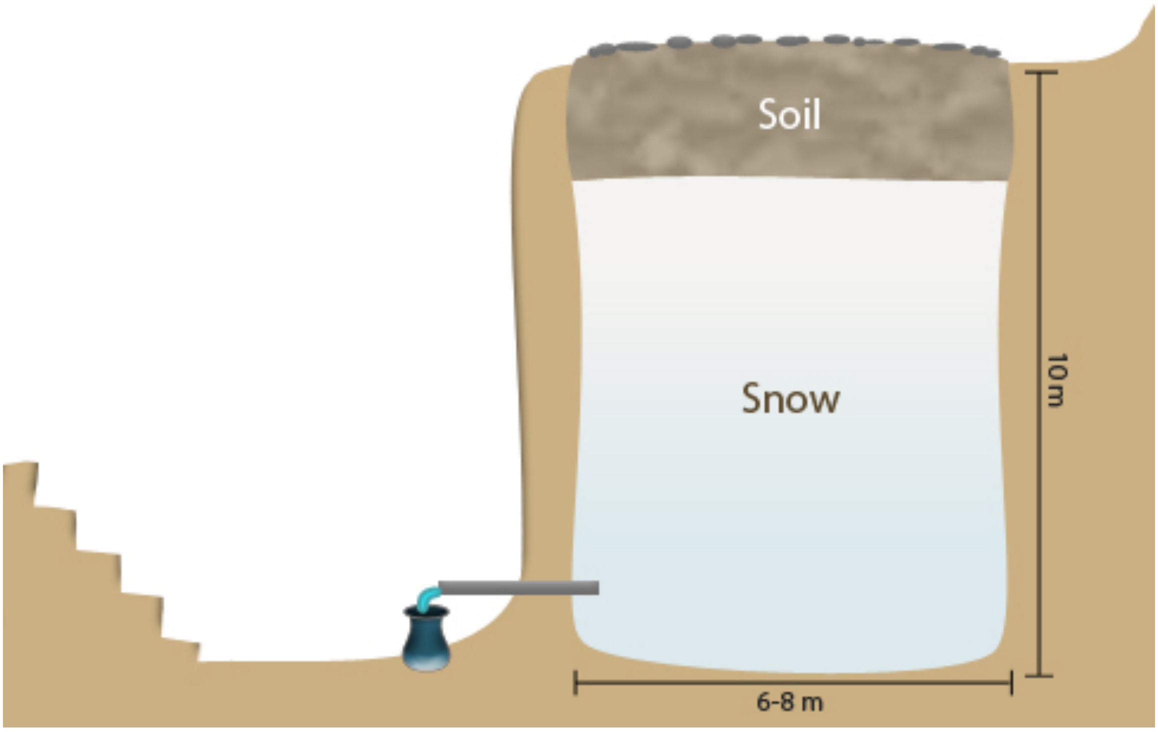

Figure 7. Illustration of a watertight pit holding packed snow. The pit is covered by soil, which acts as an insulating layer to prevent immediate thawing. The melt water is accessed from an iron pipe jammed through the bottom of the pit.

2.2. Glacier grafting

This section will describe an ancient water harvesting technique commonly used in the high mountain areas of Pakistan; the Karakoram Mountains (Mingle 2010). It is a technique where two types of glacier ice are put in cavities where they grow in volume and act as a frozen water reservoir. The following paragraphs will describe the construction and its site-specific conditions, followed by an example from Kwardo village, Pakistan.

THE CONSTRUCTION AND SITE SPECIFIC CONDITIONS

G*lacier grafting* has been applied in water scarce areas of Karakoram mountains, northern Pakistan, for centuries (Mingle 2010). For glacier grafting, villagers transport glacial ice to shaded, high altitude valleys where it is packed between rocks or in caves (Mingle 2010). The packed ice serves as a seed that spurs the growth of new ice masses that can grow up to 250 meters in length and contain around 200-400 kg of ice (approx. 200-400 L of water) (Mingle 2010; Nørstegård Tveiten 2007).

Some site-specific conditions need to be considered to successfully grow ice, concerning aspect, relief, shadowing, altitude and presence of permafrost or interstitial ice.

Most glacier growing sites are situated at an *altitude* above 4000 m, but there are exceptions (Nørstegård Tveiten 2007). *Aspect* has a great influence on the survival of snow during summer months, and thus on ice formation. The best locations have the least solar exposure; hence north-facing slopes are optimal in the Northern Hemisphere as they receive less solar radiation throughout the year. The optimal location for glacier grafting is in north facing cirques where the *shadowing* effect is pronounced by the horseshoe shape of the surrounding cliffs and provides an effective protection from solar radiation. *Relief* is important, as steep mountainsides prone to snow and rock avalanches increases the chances for a large addition of snow and frozen rocks. Many grafting sites are located on talus slopes where the grain size is equivalent to boulders (0.5-7 m). This is because the ice needs to be put in a "dug-out" cave among boulders with interstitial ice. The larger the surrounding rock masses are, the bigger are the chances that they have interstitial ice that survived the summer. This surrounding might both spur the growth of more ice at the same time as it conserves it and prevents it from melting. A mix of finer grained sediments is necessary for water to migrate to the growing ice mass. *In situ ice* is important in the process of glacier grafting, but not always necessary. Most of the grafting that is started where there is no *permafrost* tends to fail. In situ ice is found in permafrost underground, or between big boulders that have interstitial layers of ice, mainly due to the insulation and preservation of ice by the boulders themselves.

For practitioners of glacier grafting the concept of "female" and "male" ice has evolved, along with the requirement to have both parts to make new ice grow (Nørstegård Tveiten 2007). A female glacier is white or bluish in color, fast growing and gives off a lot of water. The male glacier, on the other hand, is dark in color, moves slowly and gives off little water. The glacier is dark because it contains and is covered by soil and rocks. A combination of the two kinds of ice is necessary to have a successful ice growth. The materials are crushed and mixed together and the mix is placed in layers with compressed snow, fresh snow is added to the stock at times of snowfall (Faizi 2007). Sites with only male or female ice have shown little or no growth, but the explanation why is not clear. A more scientific classification of these two kinds of ice would include terms such as "debris" and "non-debris" covered glaciers.

Another feature that is important for glacier grafting is the concept of "barren" or "infertile" glaciers (Nørstegård Tveiten 2007). This refers to ice that is present in the ground but does not produce water, move or increase and can be found in between boulders or below the soil surface. This can be translated into many periglacial landscape features that occur in terrains with permafrost or in areas with high relief where rock fall and avalanches are frequent. Examples of landscape features are given by Nørstegård Tveiten (2007), such as; small patches of ice in the ground, chunks of ice in cavities between boulders, remnants of an older glacier covered in talus, alternating layers of ice and rocks from avalanching. The infertile ice is important as it ties back to the importance of having in situ ice where you want your ice to grow.

GROWING STAGE AND PRESERVATION

The glacier starts to grow within a year, and the people that maintain it look after the process for three to four years. After this, the glacial activity continues automatically and more and more ice accumulates every year (Faizi 2007). After achieving ice growth, it is important to preserve it to be able to use the meltwater when extra water is needed. Different methods are used to prevent the ice from melting, primarily by covering it with insulating material (Nørstegård Tveiten 2007). This could be any local material with good insulating properties, such as; charcoal, sawdust, wheat husk, nutshells, branches and even pieces of cloth. A debris cover of more than 5-10 mm also insulates the ice and prevents it from melting (Nakawo et al. 2000).

SIMILAR PERIGLACIAL FEATURES

This way of spurring ice growth leads the thought to periglacial features like pingos and rock glaciers. A pingo is an ice-cored mound that is formed in permafrost zones (Holden 2008). The mounds can be up to 55 m high and 500 m in length (conical or elongated) and contain segregated ice. Pingos form over drained lakes or old river channels where there is a remnant ice core, as glacier grafting builds on placing a "seed" in a periglacial environment it can be compared to artificially creating a pingo-like feature. Similarities can also be seen in rock glaciers, which are tongue-like features of debris resembling a small glacier but with no ice evident on the surface (Holden 2008). In rock glaciers ice crystals instead occupy the pore spaces of the debris and rocks (*interstitial ice)*. Some rock glaciers form from relict glaciers that have been covered by debris, while others form where avalanches of snow and ice-cemented rocks are frequent.

EXAMPLE FROM KWARDO VILLAGE

To construct a glacier close to the village of Kwardo, groups of people are sent out to collect the ice and bring it back to the glacier-growing site (Figure 8, Nørstegård Tveiten 2007). The groups walk distances that involve 1-2 days of travel with a load of 30-35 kg carried between pairs of men. This is done during the early winter months when temperatures are cold, so the minimum volume of ice loss is expected, and when the chance of "survival" and growing of the ice is the highest. A story from Kwardo village tells how 12 people were sent to collect ice from a female glacier and 12 people from a male glacier. The teams walked without break for about 12 hours carrying approximately 30 kg of ice in pairs. None of the ice melted since it was done in November when the temperatures were cold. After collecting and bringing the ice to the village, there was another group of men waiting to carry the load up to an appropriate side valley carrying a stream. The two types of ice were then put into a dug out cave where it was left to grow.

Figure 8. Image from Nørstegård Tveiten (2007) of people collecting ice from a glacier, for glacier grafting.

2.3. Artificial Icings (Artificial Glaciers)

Another technique to store water as ice is by creating artificial icings. This method was developed in Ladakh, Northern India, and is being constructed in more and more villages.

THE CONSTRUCTION

Icings are common features in cold climates and are created in a process where flowing water freezes on top of a previously frozen surface. The idea behind *artificial* icings (more commonly know as artificial glaciers) comes from the retired civil engineer Chewang Norphel (Mingle 2010). Mr. Norphel saw the change of snow pattern in his Ladakhi native village and increased local need for extra water storage during the first months of irrigation.

"Now due to change in climate and global warming, all our natural glaciers are receding year by year. Without water we can't cultivate anything. My main intention is first, I have to find a good design which can be replicated in each and every village. Then I'm going to educate the people so they can do by themselves."

- ***Chewang Norphel*** *(CSMonitor, 2009)*

The method involves using a simple system of pipes and stone dams to divert some winter meltwater into heavily shaded areas where the winter sun is blocked by a ridge or a mountain slope (Bagla 2001, Mingle 2011). Along the mountain slope, stone embankments are set up at regular intervals to impede the flow of water. These stone embankments form shallow pools where the melt water refreezes. During winter (starting in November) the pools form thick ice masses as the temperatures fall steadily. The walls of the pool are gradually raised, trapping and freezing the water above (Daultrey & Gergan 2011). As this procedure is repeated over many weeks, a thick ice sheet is formed, resembling a long thick icing. In spring (April-May) the frozen water melts in good time for the sowing period and secures the village from water shortage.

Since 1987 Mr. Norphel has built more than ten artificial icings close to villages, as a way to adapt to new water flow regimes. The frozen water helps the farmers to avoid spring and summer shortage that is becoming an increasing problem in this part of the Himalayas (Parvaiz 2010). At present there are experiments conducted on different designs for artificial glaciers, using shadier slopes and varying the pool depth between 1.5-2 m (Arnoldy 2009). By changing the dimensions the ice storage capacity can be improved.

DIMENSIONS, MATERIALS AND COSTS

The first artificial icing, constructed in 1987, is now two km long and is estimated to be able to hold up to 1 million $feet^3$ of water, corresponding to about 28 000 m^3, after only four months of diversion and refreezing of melt water (Mingle 2010). This particular icing supports four different villages with supplementary water. Another icing is located near the village of Phuktsey, Ladakh (Bagla 2001) and is 300 m in length, 45 m in width and 1 m in depth. The storage of 13 500 m^3 ice mass supplies irrigation water to the entire village of 700 people. The total costs for constructing this particular artificial glacier was about $2,000. The construction requires a fairly small monetary investment, which is supported by the local NGO *Leh Nutrition Project* (Mingle 2011).

The material needed for constructing artificial glaciers are basically pipes, rocks, working power and runoff (Arnoldy 2009). Rocks are plentiful in this high altitude terrain, and it takes about 20 people to build the 300 m of rock walls needed for a good construction. The cost for a good construction is estimated to $50,000, but the projects are normally financed with around $20,000 (Arnoldy 2009). With low funding, the projects are sometimes scaled back in scope or upkeep. One problem with the technique is that there needs to be a water source for the growth of artificial glaciers, and when the natural glaciers are all gone it will be hard to solve the water scarcity problem.

Another example of an artificial icing is in the village Igoo, Ladakh. At an altitude of 4,206 masl, there is a construction with a cross section of 60 m (Daultrey & Gergan 2011). In *Chapter III*, an assessment is made to estimate the cropped area of Igoo, the crops' water demand during the first two months of sowing and the irrigation water contribution from the artificial glacier. These rough estimations are calculated to give an impression of storage capacity relative to water demand.

3. Case Study: Igoo, Ladakh

The following paragraph will give an area description of Ladakh. This is the area where artificial icings have been developed, applied and integrated into agriculture and livelihoods since the late 1980's.

3.1. Area Description, Ladakh

Ladakh is a high-altitude area (68% of total land area > 5,000 masl) in the Indian state of Jammu & Kashmir, situated in the Greater Himalayas, the Karakoram (Table 3, Daultrey & Gergan 2011). The region of approximately 97,000 km^2 is home to about 300,000 people (Pudasani 2010). Seasonal migration, temporary communities and nomadic subsistence farming characterize the society, and every summer several hundred thousand visitors come to the region to explore its cultural heritage (Daultrey & Gergan 2011). The increasing tourism to the area has an impact on the local water sources, as it requires more water for domestic use with higher convenience demand from the visitors such as flushing toilets (CSMonitor 2009). Ladakh is located within the upper reaches of the Indus watershed, which in total supports around 120 million people in India and 93 million in Pakistan downstream (Daultrey & Gergan 2011). Hence, careful management of water resources are vital, not only for the Ladakhis but for the health of the whole river system.

Table 3. Area description of Ladakh, India. The high altitude region where artificial icings have been implemented into agriculture since early 1980's.

Area Description, Ladakh	
Altitude	68% > 5 000 m
Indian State	Jammu & Kashmir
Mountain Range	Karakoram (the Western Himalayas)
Area	97 000 km^2
Population	~300,000
Watershed	Indus

Climate and Agriculture

Ladakh is a cold desert as it lies in the rain shadow of the Himalayas, meaning that the monsoon winds lose most of their moisture before reaching the area (Central Groundwater Board 2009). The climate of this particular area has following main features:

- Broad diurnal and seasonal temperature variations, with a range of -40 °C in winter to +35 °C in summer.
- Annual precipitation ~100 mm (mainly as snow).
- Relative humidity ranges from 6-24%.
- Altitude varies between 3000-5000 m asl.

The total cropped area of Ladakh equals to about 8,447 ha, with the most dominant crops being millet and wheat. Other types of crops are barley, pulses and fruits (Table 4). The sowing season is short, and sometimes begins before the bulk of glacier meltwater begins to flow to the region (Bagla 2001). Water shortages are especially damaging in March and April during sowing season and this is when there is need for extra water for securing the yearly agricultural production.

Table 4. Crops grown in Ladakh and estimated area distribution.

Crop	Area (ha)	%
Wheat	2,482	29%
Barley	127	2%
Millet	5,216	62%
Legumes	276	3%
Fruits	346	4%
Total	**8,447**	**100%**

IRRIGATION AND HYDROLOGY

Altitudes in the area vary between 3000-5000 masl which this imply that the water basings are glacierfed (> 4000 masl) and snowfed (2000-4000 masl) (Figure 2). The irrigation water for crops originates mainly from surface water runoff, which is carefully managed by handmade canals (Daultrey & Gergan 2011). Approximately 10,190 hectares of land is brought under irrigation by canals in Ladakh, and the use of groundwater for agriculture is negligible (Central Groundwater Board 2009).

Climate change has altered the hydrology of Ladakh and the area now experiences water shortages as some springs are drying up and free running water have disappeared (Central Groundwater Board 2009, GRWH 2011). 80% of the farmers are entirely dependent on glacier- and snowmelt for their livelihoods (Parvaiz 2010). Around the town of Leh, Ladakh, most of the glaciers have disappeared during the past 15 years. The snowline has risen approximately 150 m and the remaining glaciers have retreated as much as ten kilometers (Vince 2010). As many glaciers are retreating, there are increased distances between villages and their water sources. The increased distance has a negative effect on water security, as the agricultural need for irrigation is fundamental during the limited cropping season. With glaciers located further away and at higher altitudes they do not produce significant meltwater until May or June, which pose a problem during sowing season.

The cropping window is the period in which cultivation can be practiced. In Ladakh this period lasts for about five to seven months (Bagla 2001, Pudasaini 2010). The first two months are particularly important, as a delay in sowing can wipe out an entire harvest if the crops do not mature in time before the severely cold winter weather. Low water availability during the sowing season thereby increases the risk for late crop maturation (Bagla 2001). To decrease the risk of crop failure artificial icings are used as an extra storage of freshwater. To get a general idea of the artificial icings' contribution of water compared to the agricultural water demand during the two first months of sowing and growth, following sections will show an estimate of cropped area and its water demand relative to the crop distribution described in the previous section. This demand is then compared to the water supplied by the artificial icing to determine if the extra meltwater is noteworthy or negligible.

3.2. Mapping of Igoo

CALCULATING THE CROPPED AREA

The village Igoo is cropped from the main river up to ten kilometers into the glacierfed valley. To calculate the cropped area, Google Earth Pro is used as a tool for satellite image interpretation, mapping and areal calculations. The program is used because of its easy access to high-resolution satellite images over this particular area. The cropped area is interpreted from satellite images and identified by agricultural landscape features such as terraces (Figure 9, Figure 10). The fields are encircled by 28 polygons in total, which covers an area of 1 689 494 m^2 (polygon area calculated in Google Earth Pro). This number is rounded off since it sometimes is hard to differentiate houses from open fields as everything has the same beige color. There are also uncertainties in whether the artificial icing is supposed to provide water for the whole valley or only a part of it, and the exact extent of the village of Igoo is unclear. Hence the cropped area can be approximated to $1{,}7 \times 10^6$ m^2.

Figure 9. The watershed of Igoo, from the glacial meltwater source furthest to the east (outside of the picture) to the connecting river of the larger watershed. Satellite image interpretation of agricultural landscape features. The fields are encircled by 28 polygons in total, covering an area of 1,689,494 m^2

Figure 10. The agricultural landscape features are encircled by polygons in *Google Earth Pro* to estimate the cropped area of Igoo.

The crop distribution in Ladakh is approximately as follows (Table 5): Millet 62%, Wheat 29%, Barley 2%, Leguminous plants 3%, Fruits 4% (The last three grouped together as "Other"). As there is little information about Igoo specifically this data is used to estimate the water demand from crops in relation to the contribution of water from the icings, keeping in mind local variability. With a cropped area of 1,700,000 m^2 each crop is estimated to cover:

Table 5. Approximate crop distribution of Ladakh, and its calculated areal extent in Igoo.

Crop	%	Area (m^2)
Millet	62%	1 000 000
Wheat	29%	500 000
Other (Barley, Legumes & Fruits)	9% (2, 3, 4% resp.)	200 000
Total	**100%**	**1 700 000**

3.3. Calculating the Water Demand

The primary purpose of the icing is to provide with extra water during the first two months of sowing, it is thereby helpful to calculate the water use of the area's typical crops in relation to the regional climate. These calculations and assumptions are based on a manual developed by Critchley & Siegert 1991, FAO. The water demand from crops mainly varies with climate, plant type and growth stage (i.e. initial sowing, crop development and maturation) (Figure 11, Kassam and Smith 2001).

Climate factors that influence evapotranspiration and thereby crop water needs are primarily; radiation, temperature, humidity and wind speed (Table 6, Critchley & Siegert 1991).

Table 6. Climatic factors that influence crop water need. Ladakh's cool temperatures, low humidity, windy and sunny climate is contributing to high crop water need.

Climatic Factor	Crop Water Need **High**	 **Low**
Temperature	Hot	Cool
Humidity	Low (Dry)	High (Humid)
Windspeed	Windy	Little Wind
Sunshine	Sunny	Cloudy

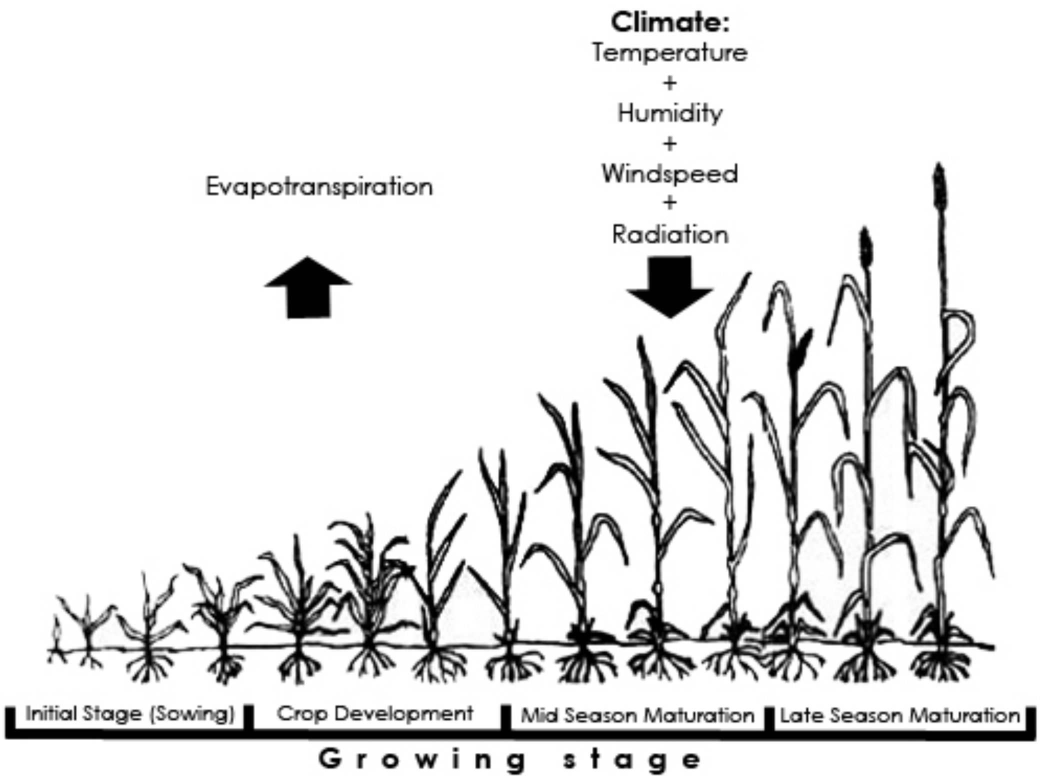

Figure 11. Schematic of different factors influencing evapotranspiration and thereby crop water need; climatic factors, plant type and growing stage. Modified from Brouwer & Heibloem (1986).

To determine the water demand for different crops in various climatic regions, it is useful to compare specific crops with a reference crop (Critchley & Siegert 1991). The water demand can then be calculated relative to the reference value. As a reference crop standard grass is used (

Table 7). The table below shows the average daily water need of standard grass throughout the irrigation season.

Table 7. Average daily water need for standard grass (mm). Ladakh's mean daily temperature and desert climate gives the reference value of 4-6 mm.

Average Daily Water Need of Standard Grass (mm)			
Mean Daily Temperature	Low (< 15 °C)	Medium (15-25 °C)	High (> 25 °C)
Desert/Arid	4-6	7-8	9-10
Semi-arid	4-5	6-7	8-9

Some crops demand more water than standard grass, and some less (Critchley & Siegert 1991). For the crops in Ladakh this corresponds to a 10% higher water need for wheat and millet (4,4-6,6 mm compared to 4-6 mm) and the same for "other" (4-6 mm) (Table 8). The relative water need is thereafter calculated to volume based on the crop distribution area calculations (Table 9). The daily water demand results in a total volume of approximately 9 x 10^3 m^3 (9 x 10^6 L).

Table 8. Estimation of crop water need (mm) for the crops of Ladakh in relation to standard grass.

Crop	Average Daily Water Need for Standard Grass (mm)	Water Demand Relative to Standard Grass (%)	Relative Daily Water Need (mm)
Millet	4-6 mm	+10	4.4-6.6
Wheat	4-6 mm	+10	4.4-6.6
Other	4-6 mm	0	4-6

Table 9. Estimation of the volume of crop water need based on area calculations of Igoo.

Crop	Average Relative Daily Water Need (m)	Area (m^2)	Water Demand (m^3)	Water Demand (L)
Millet	0.0055	1 000 000	5 500	5 500 000
Wheat	0.0055	500 000	2 750	2 750 000
Other	0.0055	200 000	1 100	1 100 000
Total			**9 350**	**9 350 000**

The water need for crops in the initial stage of growing is less than when the plants are fully developed (Critchley & Siegert 1991). The total growing period is heavily dependent on local circumstances and for millet, wheat and others it varies between 105-150 days. For a cold climate it is generally assumed that the growing period is longer than when in warm climates.

During the initial growing stage the crops cover approximately 10% of the ground (Critchley & Siegert 1991). The duration of this period is approximately 20 days. The crop development stage lasts until the ground is covered to 70% and is about 30 days for all crops in the area (Figure 12). Calculations are preformed assuming a linear increase in ground cover during the development growing stage, and the water demand is recalculated relative the ground cover (Figure 13, Figure 14). The total water demand for the first part of the growing stage (first 50 days) of the crops is estimated to $1{,}3x10^5$ m3 ($1{,}3x10^8$ L) for the whole cropped area.

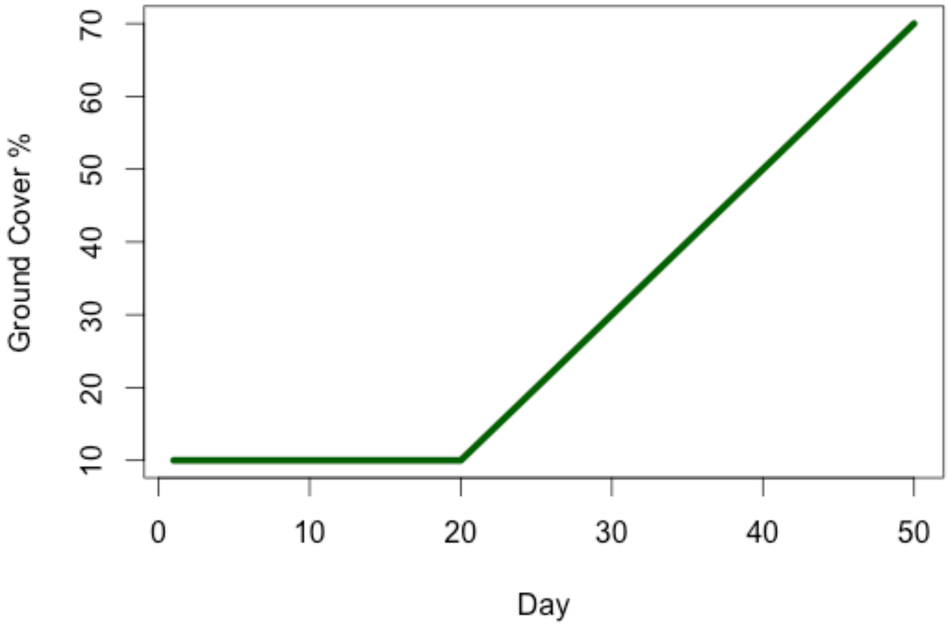

Figure 12. The ground cover is approximately 10% during the initial growing stage, which lasts 20 days. Thereafter the ground cover increases during the development growing stage until the ground is covered about 70%. This stage lasts about 30 days.

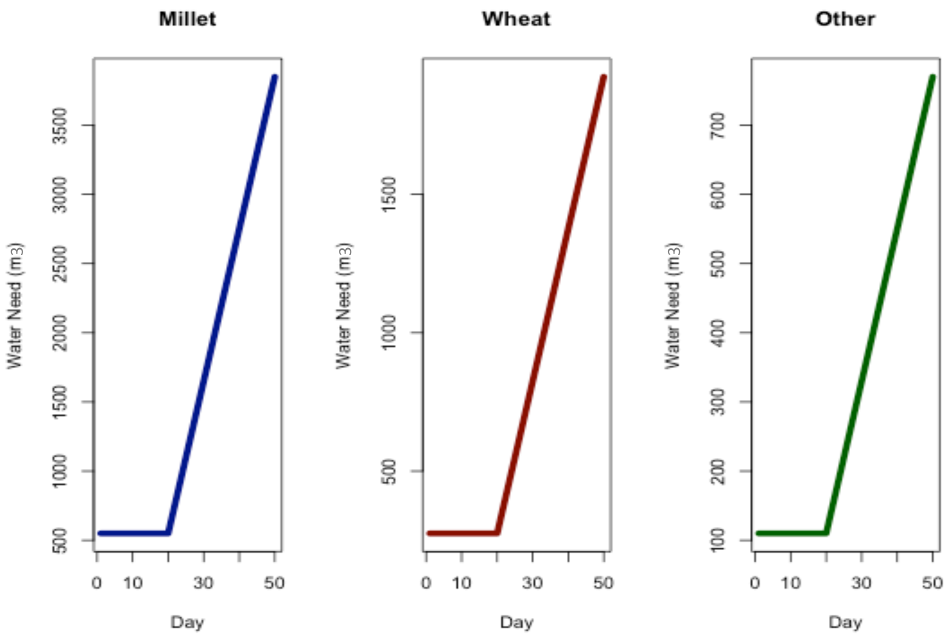

Figure 13. The daily water need for the three different crop categories. The calculations are considering the area each crop type holds as they are based on the water demand (m^3) in **Table 9**. The water need of millet is largest as it covers a larger area.

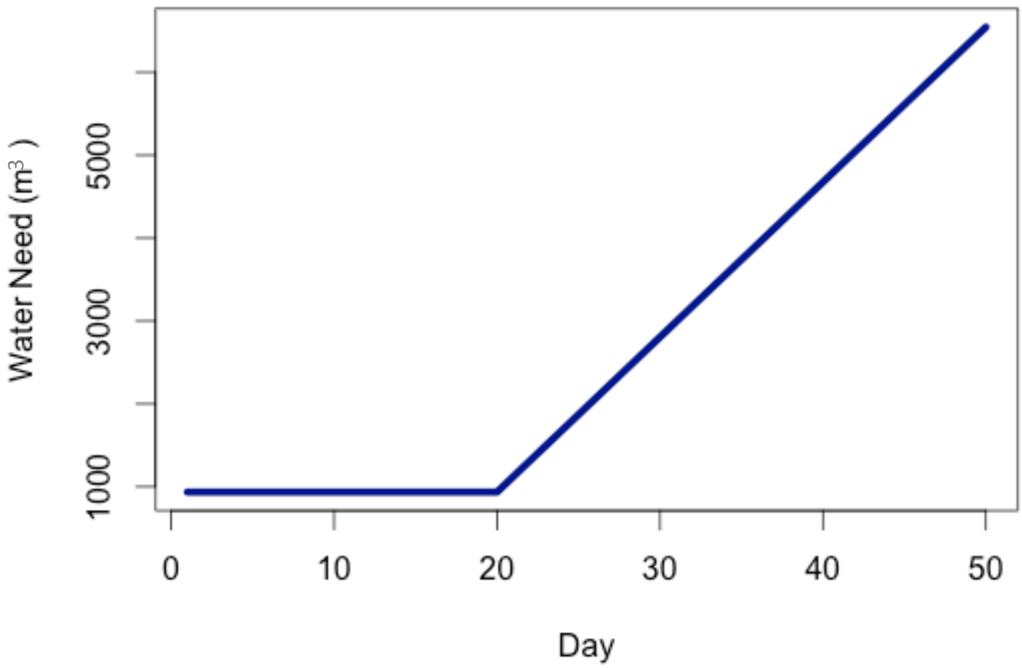

Figure 14. The change in daily water demand (m^3) for all crops of Igoo during the first 50 days of the cropping season. Based on area estimations, crop distribution and growing stage. The total water need for this period is approximately $1{,}3 \times 10^5$ m^3, $1{,}3 \times 10^8$ L.

3.4. Calculating the Water Supply (Water Equivalent)

The icing of Igoo is described as having a diameter of 60 m, but with unknown depth and length (Daultrey & Gergan 2011). Other icing are described with a depth of 1 m varying between 300 - 2000 m in length and estimated to contain 13,500 – 28,000 m^3 of ice respectively (Bagla 2001). To not overestimate the storing capacity of the icing in Igoo a length of 300 m is assumed. With this length the icing would store 18,000 m^3 of ice.

Figure 15. The artificial icing of Igoo from Daultrey & Gergan (2011).

VOLUME

The mass of the icing in Igoo can be simplified to the shape of a rectangle, and thereby the ice volume, v, can be approximated according to

$$v_i = w \times l \times h$$

where w is width, l is length and h is the height of the icing. If a depth, h, of 1 m is assumed, the volume would correspond to

$$v_i = 60 \times 300 \times 1$$

$$v_i = 18\,000\ m^3$$

ICE WATER EQUIVALENT

With a known volume of ice, the water equivalent can be calculated with the formula

$$h_w = \frac{\rho_i}{\rho_w} \times h_i$$

Where h_w is height of the melt water column, p_i is the density of ice, p_w is the density of water and h_i is the height of the icepack (Dingman, 2002).

$$h_w = \frac{917\ kg/m^3}{999.87\ kg/m^3} \times 1m$$

$$h_w = 0.917\ m$$

The height of the water column from 1 m of ice is thereby 0.917 m.

The equivalent volume of water is obtained by multiplying the height of the water column by the areal extent of the icing:

$$v_w = h_w \times h_i \times A$$

$$16\,506\ m^3 = 0.917 \times 1\ m \times 18\,000\ m^2$$

During the first two months of sowing, the icing in Igoo contributes up to 1,7 $x10^4$ m^3 of water:

$1m^3 = 1\,000\ dm^3 = 1\,000$ L

16,506 m^3 ≈16,500,000 L of water

Assuming a length of 300 m for the artificially made icing in Igoo results in a supply of approximately $1.7x10^7$ L for the first two months of the cropping season.

Another way to assess how much storage capacity an artificial icing has is by looking at the order of magnitude. The thickness of the icing is likely to be from over to a few meters thick, an order of $1x10^0$ m. The length can be up to thousands of meters, an order of $1x10^3$ m and the width is likely to be in tens of meters, $1x10^1$ m. Thus the volume will be on the order of 10^0 x 10^3 x 10^1 m, which is an order of 10^4 m^3.

3.5. Demand compared to Supply

The water demand results in a total volume of approximately $1{,}3x10^8$ L. The artificial icing in turn contributes with a volume of $1{,}7x10^6$ L. This corresponds to approximately 13% of the total water demand for this period.

$$\frac{1.7\times10^7\ L}{1.3\times10^8\ L} = 0.131\ \approx 13\%$$

As the size of the artificial icing and therefore the volume of the ice storage is based on many assumptions and is highly approximated, the demand and supply can be compared in order of magnitude. An ice volume of order 10^4 m^3 can be expected, this value can be compared to the order of the water demand previously calculated to be 10^5 m^3.

$$\frac{10^4 m^3}{10^5 m^3} = 0.1 \approx 10\%$$

This approximation shows that the artificial icing contributes with 10% of the total water demand, similar to the approximated values for the icing in Igoo.

4. Improvements

There are many possible ways to improve water harvesting in the water scarce areas of the Himalayas, and thereby find ways of adapting to climate change and its effects on water availability. In this chapter I will mention two main improvements, first how the water harvesting technique itself might be improved and thereafter how the spread of the knowledge might be improved by mapping areas suitable for artificial icings.

"The technology is very simple, very cheap with high benefit for the farmers. It can be replicated anywhere with similar topography, temperature. If we can create it here, why not create it in other parts?"

– ***Chewang Norphel (Mingle 2011)***

4.1. Improvements of Artificial Icings

To discuss how artificial icings might be improved there are some questions that need to be considered.

- How can the artificial glaciers be improved without increasing the cost and making it more complicated for the local farmers?
- How much more thickness is needed to change the water storage capacity of the artificial icing?
- What would be the limit of thickness?
- Is it possible to combine different water harvesting techniques to make them better? Glacier grafting and artificial icings? Mixing grains?

One way of improving the water storage capacity of artificial icings is by increasing its ice volume. This is done either by making it thicker or more extensive. To keep as much land as possible for agricultural production, it is better to increase the volume by thickness rather than extension. As many artificial icings seem to be around one meter in thickness, a doubling of height would double its volume. The thickness of the icing is mainly determined but also limited by the height of the retaining wall. The slope also determines the speed of water flow and its likelihood of refreezing. This being said, there is a trade-off between increasing the extent and loosing agricultural land. There are also two factors limiting the adjustment of thickness, both by how high humans can build without complicating the construction as well as how high the embankments can be and still retain a slow speed of water.

Dirt is a factor that controls ice melt by either reducing it or enhancing it (Hewitt, 2007). A debris layer thicker than 4-5 cm acts as an insulator and reduces meltoff to the degree that it is considered to be minimal. A dirt layer of a few millimeters in thickness can on the other hand enhance melting by 40% or more. By using either a thick or thin debris layer, the control of the artificial icings can be enhanced. If for instance the natural water flow is enough during the start of the cropping season, the ice reservoir could be covered with a debris layer and saved to melt at a later time during the season when water demand from crops is higher.

4.2. Climate Parameters needed for mapping areas appropriate for artificial glaciers

A good location can be selected by implementing the knowledge that solar radiation is the primary source of energy and thereby also the main cause of snow and ice melt (Young & Hewitt 1990; Hewitt 2007). The radiation, thereby melting capacity, is varying as a function of elevation, surface slope, aspect and changeable weather conditions controlling cloud cover. Hence, north and south sloping mountain faces have very different radiation regimes and a distinct difference in local hydrology. This knowledge is already implemented in the choice of location, but is good to have in mind for future mapping of appropriate locations for artificial icings.

To be able to map areas suitable for artificial icings following map layers are needed:

- Elevation
- Temperature
- Remotely sensed images (with high resolution)

Information about elevation is important since both slope and aspect can be derived from this layer. The aspect would tell us something about the insolation and hillshading effect, as stated in chapter 2.2 and 2.3 the shading is a major concern for storing water as ice. The slope is relevant to know since the artificial icing builds up by a certain flow speed of water. Constructed embankments can control the speed, but too steep slopes might have too fast water flow to be reduced to a decent speed for efficient freezing and replenishing.

Annual temperature as point data could give an interpolated surface and estimate the time of year when meltoff is generated by heat. It might be relevant to see areas where temperature and exposed hillsides (seasonal differences of insolation) overlap, as they would have a fast meltoff that generates much water in a short time. It might also be good to see where these two variables are not overlapping and on the contrary has a slow meltoff that generates a small amount of water during a longer time period.

Remotely sensed images, or any map layer that can identify cities and villages, might be useful to make a distance/accessibility analysis. There is no use of constructing an artificial icing that is located too far from villages. Both in the sense that people need walking distance to work on the construction and that a shorter distance minimizes the water loss.

Wind velocity, wind direction and relative humidity are thought to be important as it has an effect on evaporation and sublimation, thereby the loss of water from the ground surface and snow surface (Central Groundwater Board 2009).

Retaining information about these three factors might be harder that the ones mentioned above as weather stations are sparse in this vast and remote area. The impacts of these factors are on the other hand less important than the previous.

5. Discussion and Conclusions

The aim of this thesis was to answer what the glacial response is to climate change in the Himalayas and how villages are dealing with water scarcity. This was achieved by examining following questions:

- The effects of climate change on the Himalayan glaciers.
- The effects of climate change on agricultural production in glacierfed water basins.
- How people are coping with unpredictable water supply through water harvesting techniques where water is stored as ice.
- If the volume of water stored in artificial icings is sufficient to the water need.
- How the water harvesting techniques can be improved and expanded to other areas
- What climatological and geographic characteristics that are important for mapping areas suitable for artificial icings.

It is hard to explain how the Himalayan glaciers are responding to climate change. There are contradictory answers as some areas show an increase in ice mass while other show a decrease. Scientific papers may describe growth of glaciers in certain areas while other research propose a decrease. The scientific sources may also describe a different state of the glaciers than local sources such as farmers from non-scientific papers (Than 2012). One reason for these contradictory answers might be the fact that there *is* a great variability in glacial response to climate change, where each individual glacier is highly dependent on its local climate and geographical properties. Another reason might be that the hydrology of these high altitude water basins are little studied and poorly understood, mainly because the areas are badly gauged (Bocchiola et al. 2011). The weather and gauging stations are at elevations well below the glacier basins, and the ones that exist are located in valley floors strongly modified by surrounding mountains and valley wind systems (Hewitt, 2007) For this reason it is hard to predict the future of high altitude river flows and more detailed studies of water use for irrigated agriculture is needed.

The conclusion that can be drawn is that glaciers are not in steady state as many of them are melting and thus there is temporarily extra water available, but in the future there will be less water. This will most likely have an effect on agriculture in glacierfed water basins and adaptation techniques needs to be developed for these regions to handle the water stress.

The water harvesting methods used for irrigation are mainly glacier grafting and artificial icings. The technique of snow-water harvesting is more small scale and used for domestic purposes. Since glacier grafting is an indigenous method that has been used for centuries I felt an urge to put more emphasis on exploring the newer method of artificial icings. Are icings economically sustainable and is it a good long-term investment? The monetary cost of constructing icings is low. But if it is needed for every village in a region, and if they need larger and larger artificial icings in the future, the cost could be significant. If the technique should function it is important that the total volume of water available during the year is sufficient, if the glaciers are retreating according to IPCC's future predictions there is a big risk that the smaller glaciated areas will be gone by the year 2035 and the constructed areas will not be fed by glacial melt water. Therefore, artificial icings will not solve the problem of water scarcity in water basins that are not glacier fed.

Exploring these techniques opened up my eyes for the difficulties of finding good data. The area wished to examine is very remote and has little available data, therefore the sources for the calculations in this thesis are "weak" and very much estimated. The water equivalent, the mapping of the cropped area and the crop water need are all rough estimates. On the other hand rough estimates can give a general picture of the water need in comparison to the amount of water the artificial icing can provide. As it is hard to get information and good maps of this remote area, Google Earth was considered as a good enough tool for mapping the cropped area.

The water need is bigger than the water supplied by the artificial icing. According to the calculations the icing would provide about 10% of the total crop water need during the first two months of the cropping season. On the other hand, the icing is only meant to be a supplementary source of water to serve as a security buffer in cases of low natural water supply because of seasonal variability. No consideration is taken to if there is water available in the soil already, but assuming no available soil moisture. There are also many sources of error considering the dimensions, both in the extension of the cropped area that is given water from the artificial icing and if the icing itself is accurately sized. There is no estimate of how fast the ice reservoir melts, or for how long the meltwater can be kept, hence no conclusion is made on how long the extra water is available. Even though the supply in comparison to the demand is small, it is not negligible. We should not conclude that this water harvesting technique is useless, but keep in mind that it needs a water source to grow during the winter season. Reading and listening to interviews from local people of Ladakh have confirmed the usefulness of these water reservoirs, and there is no information about how much *extra* water that is actually needed for the first two months. Assuming vast glacial retreat for many of the Himalayan watersheds, the water harvesting technique would need to be improved to be able to outweigh the diminishing and delay of natural runoff.

For future it could be useful to map areas that would be suitable for artificial icings. But as climate and circumstances vary in every local drainage basin it might be hard to make such mapping. Although, the climatological and geographical characteristics that needs to be fulfilled are all parameters that are easy to map. What is a more challenging quest is to find the data. Mapping can also be performed for other areas than the Himalayas, to see where in other parts of the world this water harvesting technique could be implemented.

References

Akhtar, M., Ahmed N., Booij M. J., 2008. *The Impact of Climate Change on the Water Resources of Hindukush-Karakorum-Himalaya Region under different Glacier Coverage Scenarion.* Journal of Hydrology, 355 (1-4), pp 148-163.

Arnoldy, B., 2009. *Global Warming: Indians Decide to Make Their own Glaciers.* The Christian Science Monitor. Oct 21. Retrieved from http://www.csmonitor.com/World/2009/1021/p11s01-wogn.html. 11/7/11 3:56 PM.

Bates, B. C., Kundezewicz, Z. W., Wu, S., and Palutikof, J. P., 2008. *Climate Change and Water, Techical Paper.* IPCC, Geneva.

Bagla, P. 2001. *"Artificial Glaciers" Aid Farmers in Himalayas.* National Geographic News, Oct 28, 2010. Retrieved from http://news.nationalgeographic.com/news/2001/08/0830_artglacier.html 10/18/11 1:36 PM

Barnett, T. P., Adam J. C. and D. P. Lettenmaier, 2005. *Potential impacts of a warming climate on water availability in a snow-dominated region.* Nature, No. 438 pp.303–309.

Bocchiola, D., Diolaiuti, G., Soncini, A., and Mihalcea, C., 2011. *Prediction of Future Hydrological Regimes in Poorly Gauged High Altitude Basins: The Case Study of the Upper Indus, Pakistan.* Hydrology and Earth System Sciences. Vol. 15 No. 7 pp. 2059-2075.

Brouwer, C. & Heibloem, M., 1986. Irrigation Water Management: Irrigation Water Needs, *Chapter 3: Crop water needs.* Retrieved from http://www.fao.org/docrep/S2022E/s2022e07.htm, 11/2/11 10:26 AM.

Central Groundwater Board, 2009. *Groundwater Information Booklet of Leh District Jammu and Kashmir State.* North Western Himalayan Region Central Groundwater Board. May 2009, Jammu, Leh.

Critchley, W. and Siegert, K., 1991. *A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production.* Food and Agriculture Organization of the United States, Rome.

Cruz, R., et al. 2007. *Asia.* Pages 469–506 in M. Parry, et al. editors. Climate change 2007: impacts, adaptation and vulnerability. Contributionof Working Group II to the Fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

CSMonitor, 2009. Video in English. Rerieved from http://www.csmonitor.com/multimedia/2009/Dec/Squeezing-water-from-the-Himalayas. 20 January 2012.

Daultrey, S., Gergan, R., 2011. *Living with change: Adaptation and innovation in Ladakh*. Our Planet, Climate Adaptation, pp. 11.

Dingman, L. S., 2002. *Physical Hydrology*. Waveland Press Inc, Long Grove, IL, the U.S.

Faizi, I., 2007. *Artificial Glacier Grafting: Indigenous knowledge of the Mountain People of Chitral.* Asia Pacific Mountain Network (APMN) Bulletin. Vol. 8 No. 1. Summer 2007.

GRWH, 2011. *http://www.globalrainwaterharvesting.org/handpump.asp#* Retrieved 10/16/11 11:37 PM

Hambrey, M. J., 1994. *Glacial Environments*. UCL Press. Liverpool John Moores University, London.

Hasnain, S.I., 2002. *Himalayan glaciers meltdown: impacts on South Asian Rivers*. FRIEND 2002-Regional Hydrology: Bridging the Gap between Research and Practice. International Conference on FRIEND N°4, March 18-22, Cape Town, South Africa. IAHS Publications, Wallingford, No. 274, 417-423.

Hewitt, K., 2005. *The Karakoram Anomaly? Glacier Expansion and the "Elevation Effect," Karakoram Himalays.* Mountain Research and Development. 25(4):332-340.

Hewitt, K., 2007. *Glaciers of the Karakoram Himalaya, Climate Change and Water Supply Concerns.* Asia Pacific Mountain Network (APMN) Bulletin. Vol. 8 No. 1. Summer 2007.

Hewitt, K., 2011. *Glacier Change, Concentration, and Elevation Effects in the Karakoram Himalaya, Upper Indus Basin.* Mountain Research and Development. 31(3):188-200. International Mountain Society.

Holden, J., 2008. *An Introduction to Physical Geography and the Environment*. Pearson Education Limited, Essex, England.

Houghton, J. T., 2009. *Global Warming, the Complete Briefing*. Cambridge University Press, Cambridge.

Immerzeel, W. W., Droogers, P., de Jong, S. M. & Blerkens, M. F. P., 2009. *Large-scale Monitoring of Snow Cover and Runoff Simulation in Himalayan River Basin Using Remote Sensing*. Remote Sensing of Environment. 113:40-49.

IPCC, 2001. *Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken and K.S. White, Eds., Cambridge University Press., Cambridge, 1032 pp..

IPCC, 2010. *IPCC statement on the Melting of Himalayan Glaciers. Jan 20.* Retrieved from http://www.ipcc.ch/pdf/presentations/himalaya-statement-20january2010.pdf 10/19/11 4:15 PM

Kassam A. and Smith K., 2001. *FAO Meothodologies on Crop Water Use and Crop Water Productivity.* Expert Meeting on Crop Water Productivity, Rome, 3rd to 5th December 2001.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, P. Kabat, B. Jiménez, K.A. Miller, T. Oki, Z. Sen and I.A. Shiklomanov, 2007. *Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 173-210.

Li, X., Cheng, G., Jin, H., Kang S., Che T., Jin R., Wu L., and Z. Nan, 2008. *Cryospheric change in China.* Global and Planetary Change, Vol. 62 pp. 210–218.

Miller G., 2009. *Living in the Environment: Principles, Connections and Solutions.* Brooks/Cole, Kentucky, USA, pp. 250.

Nakicenovic, N. et al. 2000. IPCC Special Report on Emission Scenarios. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nakawo, M., Fountain, A. & Raymond, C. F., 2000. *Debris-covered glaciers.* International Association of Hydrological Sciences. no. 264, pp 288. IAHS Press, Wallington.

Nørstegård Tveiten, I., 2007. *Glacier Growing – A Local Response to Water Scarcity in Baltistan and Gilgit, Pakistan.* Department of International Environment and Development Studies, Norwegian University of Life Science (UMB), Ås, Norway.

Owen, L. A., R. C. Finkel, and M. W. Caffee. 2002. *A note on the extent of glaciation throughout the Himalaya during the global last glacial maximum.* Quaternary Science Reviews. Vol. 21 No.1-3 pp. 147–157.

Parvaiz, A., 2010. *Artificial Glaciers for Summer Irrigation.* New Agriculturist. March 2010. Retrieved from http://www.new-ag.info/en/developments/devItem.php?a=1367.

Peel, M. C., Finlayson, B. L., McMahon, T. A., 2007. *Updated world map of the Köppen-Geiger climate classification*. Hydrology and Earth System Sciences, Vol. 11 pp. 1633-1644.

Pudasaini, S., 2010. *Farming High in a Himalayan Desert. Science and Development Network*. SciDevNet, Feb 22, 2010. Retrieved from http://www.scidev.net/en/features/farming-high-in-a-himalayan-desert-2.html 10/18/11 2:26 PM

Reiliy, J., 1996. *Agriculture in a changing climate*. In: *Climate change 1995—Impacts, Adaptation and Mitigation of Climate Change: Scientific-Technical Analysis* (cd. by R. T. Watson), Cambridge University Press. Cambridge, pp. 427-467.

Rees, H. G. and Collins, D. N., 2006. *Regional Differences in Response of Flow in Glacier-fed Himalayan Rivers to Climatic Warming*. Hydrological Process, Vol. 20 pp. 2157-2169.

Strahler A. and Strahler A., 2006. *Introducing Physical Geography*. John Wiley & Sons, inc., Hoboken, USA.

Shen, Y.P., Wang, G.X, Wu Q.B. and Liu, S.Y., 2002. *The impact of future climate change on ecology and environments in the Changjiang - Yellow Rivers source region*. Journal of Glaciology and Geocryology, No. 24, pp. 308-313.

Singh, P., and L. Bengtsson. 2004. *Hydrological sensitivity of a large Himalayan basin to climate change*. Hydrological Processes, Vol. 18 No. 13 pp. 2363–2385.

Singh, P. and L. Bengtsson, 2005. *Impact of Warmer Climate on Melt and Evaporation for the Rainfed, Snowfed and Glacierfed Basins in the Himalayan Region*. Journal of Hydrology , Vol. 300 No. 1-4 pp. 140-154.

Singh, P. & Singh, V. P., 2001. *Snow and Glacier Hydrology (Water Science and Technology Library)*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 742.

Than, K., 2012. *Artificial Glaciers Water Crops in Indian Highlands.* National Geographic News, February 14, 2012. Retrieved from http://news.nationalgeographic.com/news/2012/02/120214-artificial-glaciers-water-crops-in-indian-highlands 3/8/12 9:09 AM

Vince, G., 2010. *A Himalayan Village Builds Artificial Glaciers to Survive Global Warming*. Scientific American, May 24 2010. Retrieved from http://www.scientificamerican.com/article.cfm?id=artificial-glaciers-to-survive-global-warming 10/18/11 1:57 PM

Winiger, M., Gumpert M., and H. Yamout, 2005. *Karakoram-Hindu Kush-Western Himalaya: assessing high-altitude water resources*. Hydrological Processes, Vol. 19 No. 12 pp. 2329–2338.

Xu, J., Grumbine, R. E., Shrestha, A., Eriksson, M., Yang, X., Wang, Y. and Wilkes, A., 2009. *The Melting Himalayas: Cascading Effects of Climate Change on Water, Biodiversity, and Livelihoods*. Conservation Biology, Vol. 23, No. 3, pp. 520–530.

Xu, J., Shrestha, A., Vaidya, R., Eriksson, M. and Hewitt, K., 2007. *The melting Himalayas: regional challenges and local impacts of climate change on mountain ecosystems and livelihoods. Technical paper*. International Centre for Integrated Mountain Development. Kathmandu, Nepal.

Young, G. J. and Hewitt, K., 1990. *Hydrology Research in the Upper Indus Basin, Karakoram Himalaya, Pakistan*. International Association Hydrological Sciences. IAHS Publication No. 190, pp. 139-152.

Institutionen av naturgeografi och ekosystemvetenskap, Lunds Universitet.

Student examensarbete (Seminarieuppsatser). Uppsatserna finns tillgängliga på institutionens geobibliotek, Sölvegatan 12, 223 62 LUND. Serien startade 1985. Hela listan och själva uppsatserna är även tillgängliga på LUP student papers (www.nateko.lu.se/masterthesis) och via Geobiblioteket (www.geobib.lu.se)

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