Universiteit Utrecht

The effects of climate change and associated glacier melting in the Hindu-Kush Himalayas on the water supply and water use of the Indus, Pakistan

Bachelorthesis Milieu-natuurwetenschappen

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Abstract

Climate change leads to a temperature increase in the Hindu-Kush Himalayas. As a result of a warming climate, glacier coverage in the Hindu-Kush Himalayas will be decreased at the end of the 21st century. This thesis studied the effects of a decrease in glacier coverage due to climate change on water availability and food production in the Pakistani part of the Indus basin. A decrease in glacier coverage has impacts on the Indus, which is originated in the Hindu-Kush Himalayas. The Indus has the highest melt water contribution to the total river discharge of all rivers originated in the same mountain range. This means that the flow of the Indus will be highly affected by a change in glacier coverage. Pakistan is highly dependent on water supply of the Indus for irrigated agriculture. A decrease in glacier coverage in the coming decades in the Hindu-Kush Himalayas will lead to an increase in river discharge on the short term, in the first half of the 21st century, due to an increase in melt water. However, water availability will decrease on the long term, at the end of the 21st century. At the same moment, the population of Pakistan is expected to growth substantially, which will lead to an increased water demand. This increased water demand combined with a decreased water availability will cause water shortage for irrigation and thereby food insecurity.

Klimaatverandering leidt tot opwarming van de Hindu-Kush Himalayas. Als gevolg van een warmer wordend klimaat, zal de omvang van het oppervlak van gletsjers afnemen aan het einde van de 21e eeuw. Deze scriptie heeft de effecten van de afname van gletsjers, veroorzaakt door klimaat verandering, op de beschikbaarheid van water en voedselproductie in het Pakistaanse deel van het Indus stroomgebied onderzocht. Een afname van gletsjers heeft gevolgen voor de Indus, welke zijn oorsprong vindt in de Hindu-Kush Himalayas. De Indus heeft het grootste aandeel smeltwater van de totale stroom van de rivier van alle grote rivieren die ontstaan in de Hindu-Kush Himalayas. Dit wil zeggen dat een verandering in oppervlak van gletsjers in de regio grote gevolgen heeft voor de stroom van de Indus. Pakistan is afhankelijk van het water uit de Indus voor geïrrigeerde landbouw. Een afname in het totale oppervlak van gletsjers zal op de korte termijn, in de eerste helft van de 21e eeuw, leiden tot een toename van de afvoer van de Indus veroorzaakt door een toename van smeltwater. Echter, op de lange termijn, tegen het einde van de 21e eeuw, zal de watertoevoer door de Indus afnemen. Tegelijkertijd wordt een bevolkingsgroei verwacht, wat leidt tot een hogere totale waterbehoefte voor de landbouw. Deze toename in waterbehoefte gecombineerd met de afname in waterbeschikbaarheid zal leiden tot watertekort voor geïrrigeerde landbouw en daarmee tot voedselonzekerheid.

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1. Introduction

1.1 A large share of freshwater resources

Glaciers are important sources of fresh water; about 69% of earths freshwater is stored in glaciers (Kanwar, 2010). The Hindu-Kush Himalayas are referred to as the third Pole on earth (Boccholia et al., 2011), because they consist of the largest amount of ice outside the Poles (Sharif et al., 2012). According to the UN a glacier is a “mass of surface-ice on land which flows downhill under gravity and is constrained by internal stress and friction at the base and sides” (UNEP and WGMS, 2008). The Hindu-Kush Himalayas, shown green in figure 1, have a glacier coverage of about 22.000 km^2 (Sharif et al., 2012) which contribute to ten major river systems, shown in blue (Icimod, 2003), and are sometimes shortened to HKH in literature. This thesis focuses on the Pakistani part of the Indus basin, located in the western part of the Hindu-Kush Himalayas.

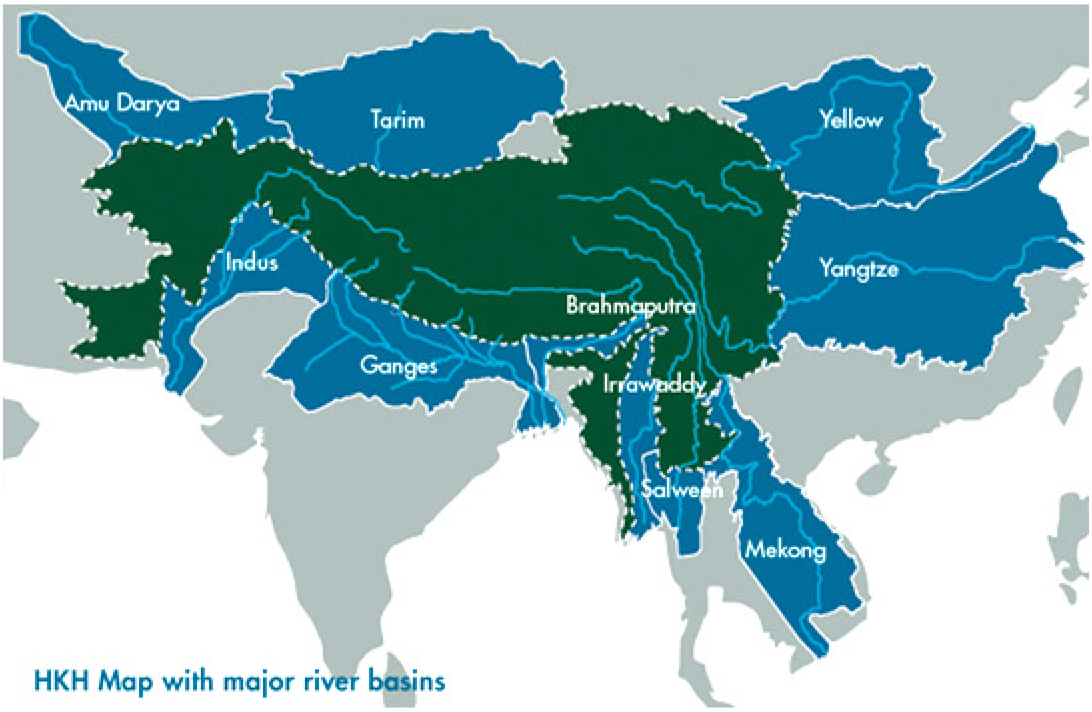

Figure 1 –The Hindu Kush Himalayas shown in green, with ten major river basins shown in blue (Icimod, 2003).

1.2 Water system of the Indus

Climate change has been observed through significant warming in the Hindu-Kush Himalayas (Panday et al., 2011). The IPCC Report of 2007 estimates a further warming of 3,7 °C at the end of the 21st century (Panday et al., 2011). An increasing air temperature influences the glacier mass balance (UNEP and WGMS, 2008), which is defined as the balance between accumulation and ablation of glaciers (Jansson et al., 2003). The accumulation zones of glaciers are colder than the ablation zones, and are the areas where glaciers grow (UNEP and WGMS, 2008). In the ablation zones, glaciers are melting because of the higher temperature (UNEP and WGMS, 2008). Changes in mass balance, cause changes in volume and thickness of glaciers which affect the flow of ice (UNEP and WGMS, 2008). This in turn determines the amount of melt water contributed to the river (Immerzeel et al., 2010).

Melt water is very important to the Indus flow (Immerzeel et al., 2010). However, precipitation also influences the Indus flow, especially downstream. The amount of precipitation upstream is 36% of the total flow, while downstream the influence of precipitation on the total flow is 64% (Immerzeel et al., 2010). Upstream areas are defined as all areas higher than 2000 meters above sea level (Immerzeel et al., 2010). Because a large fraction of the Indus flow is originated from melt water, both magnitude and timing of the flow are vulnerable to climate change (Sharif et al., 2012).

1.3 Description of the problem

The major river systems originated in the Hindu-Kush Himalayas, support the life of 1,5 billion people, 25% of world's population (Kanwar, 2010). Due to global warming, increased melting occurs, causing shrinkage of glaciers in the Hindu-Kush Himalayas (Miller et al., 2012). Therefore, effects of glacier melting on water supply of these rivers influence a large number of people. A change in glacier coverage in Pakistan due to global climate change could result in a decrease in water availability (Miller et al., 2012). This will have impacts for food security of the 145 million people living in the area. The income and food security of these people is dependent on the Indus flow (Kanwar, 2010), especially because food production is dependent on irrigation. Pakistan has the largest irrigation network in the world, with a net irrigation demand of 908 mm a year (Immerzeel et al., 2010).

1.4 Research questions

The aim of this thesis is to give an overview of the effects from glacier melting on food production in the Pakistani part of the Indus basin.

The research question of this thesis is: *What effects can be anticipated from the impact of global climate change and associated glacier melting in the Hindu-Kush Himalayas on food production at the Indus basin in Pakistan?*

The main question will be supported by the following sub-questions, each of them answered in Chapter 3, Results:

1. What are characteristics of water supply of the Indus basin from the perspectives of sediment load, water storage capacity, precipitation and river discharge?
2. How much of the total water flow of the Indus is used annually for food production?
3. What is the irrigation system of Pakistan like?
4. Which changes in characteristics of water supply of the Indus due to glacier melting are predicted for the future?
5. Which changes in water use of the Indus are predicted for the future?
6. What are the consequences from changes in water supply and use due to glacier melting for food production?

1.4 Hypothesis

A decrease of glacier coverage is expected as a result of global warming. I expect that this will lead to an increase in water availability on the short term. On the long term, I expect the water availability to decrease due to a decrease in melt water contribution. This decrease in water availability combined with an increased water demand, will cause water shortage for irrigation and thus food insecurity.

2. Methods

2.1 Geographical description of the region

The Hindu-Kush Himalayas are located in Central Asia, with many peaks exceeding 7000 m above sea level, see figure 2 (Lu et al., 2010), and is constituted by the Hindu-Kush, Karakoram and the Himalayan mountain ranges (Ashraf et al., 2012). The region extends from Afghanistan in the west to Myanmar 3500 km to the east (Panday et al., 2011).

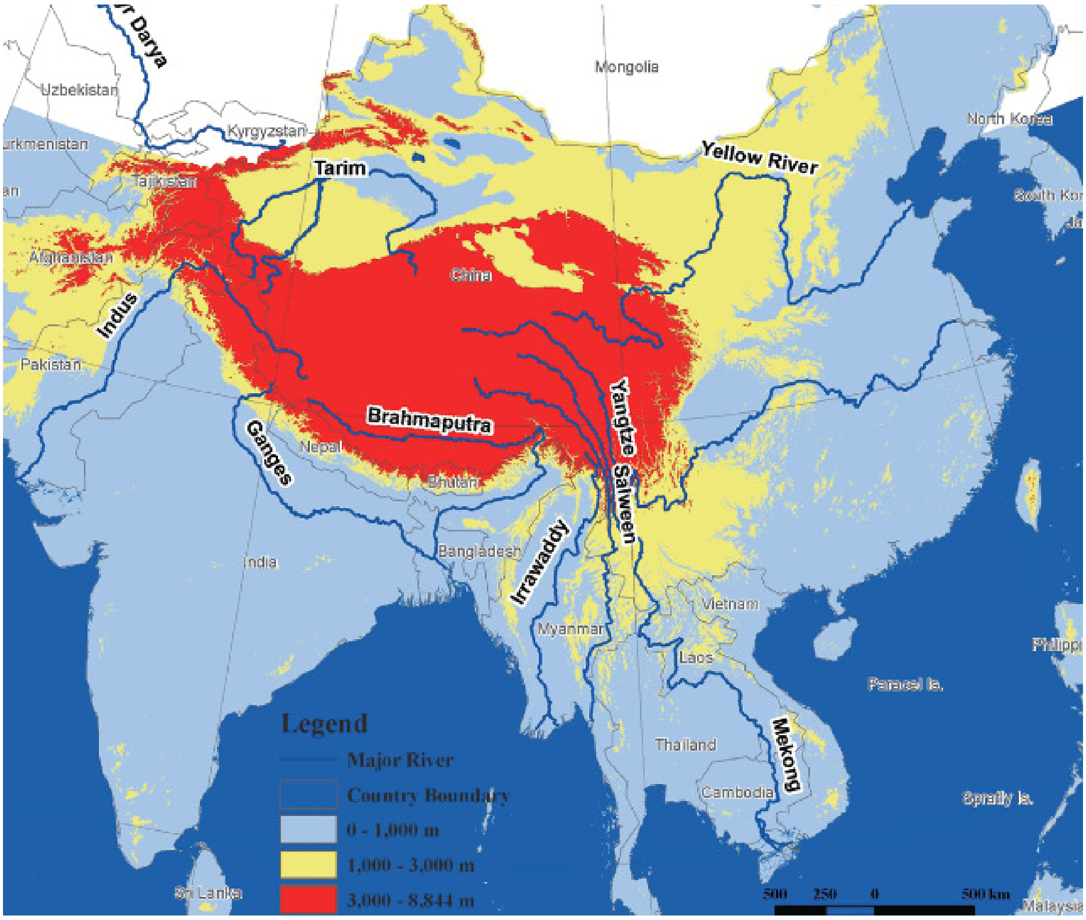

Figure 1 - The Hindu-Kush-Himalayas and its major river systems (Lu et al., 2010)

The Indus originates in the Himalayan range in China (Lu et al., 2010). It then flows through Northern India and Northern Pakistan in South-western direction to the Arabic Sea at the Pakistani coast, see figure 3. Four major tributaries join the Indus downstream: the Sutlej, Ravi, Chenab and Jhelum River, see figure 3 (Archer et al., 2010). The total hydrographic basin of the Pakistani part of the Indus basin has an area of 1.137.819 km^2, as defined by the International Water Management Institute (Laghari et al., 2012). The Indus and its tributaries are mostly fed by melt water of glaciers in the Karakoram region (Sharif et al., 2012). The largest part of the Indus accumulates in the Tarbela dam, one of the two reservoirs in the Upper Indus basin, see figure 3 (Sharif et al., 2012). The Indus has an extensive upstream area of 40% of the total basin (Immerzeel et al., 2010).

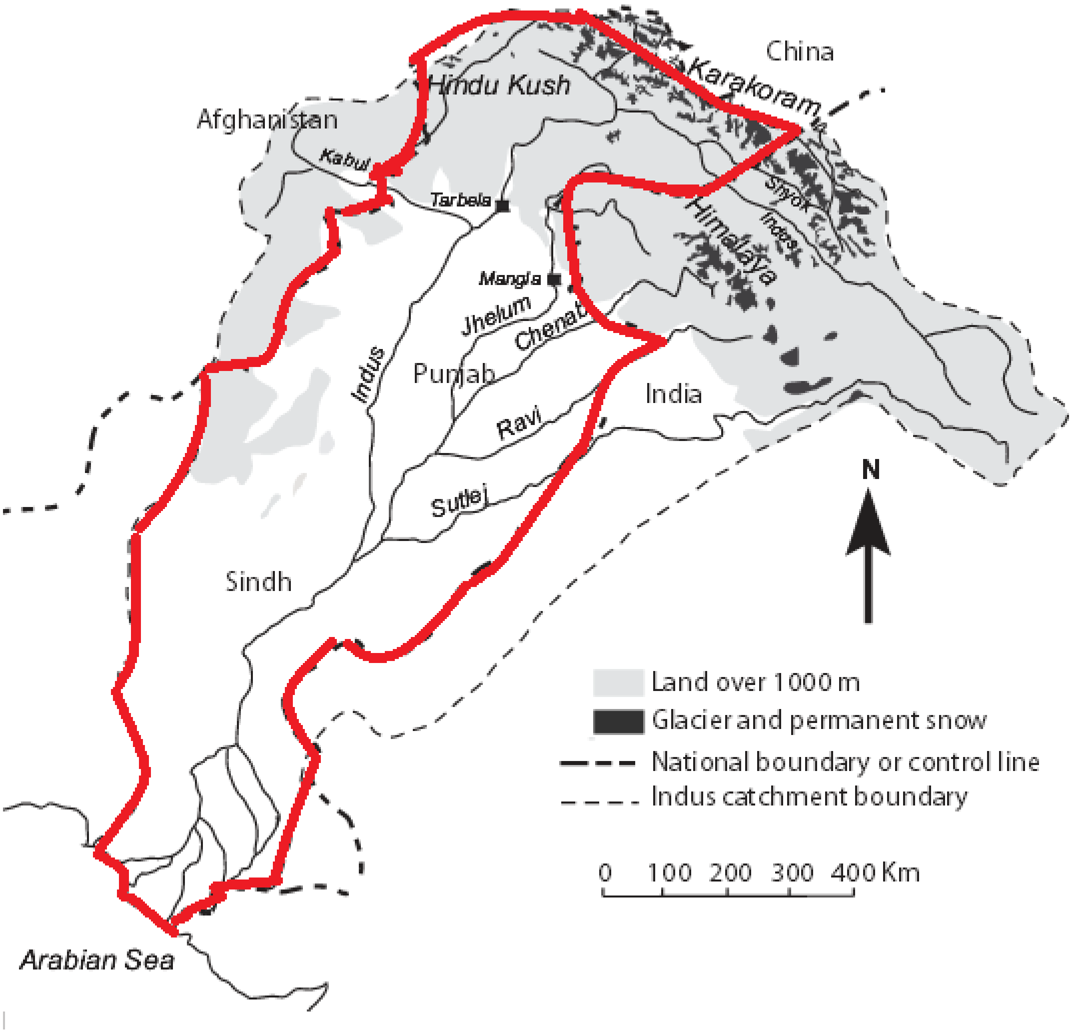

Figure 2 - The Pakistani Indus basin, within the red borders (Archer et al., 2010)

Despite the fact that the Indus mostly flows through the Karakoram and Hindu-Kush ranges, the Himalayan mountain range influences the climate in the Indus basin by acting as a barrier to intruding of the monsoon (Sharif et al., 2012). From now on, when referring to the region, all three mountain ranges are included. And when referring to the Indus basin or the Indus River, from now on only the Pakistani part of the Indus basin or River, which is the area within the red borders in figure 3, is included.

2.2 Analysis and data collection

I did a literature study to answer the main- and sub-questions. The analysis was carried out in the following steps:

a) Assessment of the water supply in the Indus basin and the role of melting water
b) Assessment of the freshwater demand
c) Analysis of the balance between supply and demand and the potential impact of changes in water supply as a result of higher melting rate for glaciers
d) Assessment of the anticipated impact on food production

Changes in the balance between fresh water supply by the Indus and fresh water demand in the basin are studied by analyzing the water balance of the Indus with inputs and outputs of the river system.

To enable this analysis, data were collected on:

- the water supply of the Indus
- the relation between glacier melt water from the Hindu-Kush Himalayas and the Indus flow
- the amount of water use of the Indus River for food production
- the total water demand of the Pakistani living in the Indus basin and water availability in the Pakistani part of the Indus basin
- predicted future changes in the hydrological system of the Pakistani Indus catchment
- predicted future changes of water use by the Pakistani living in the Indus basin

Figure 4 shows the data that I searched for in a conceptual model.

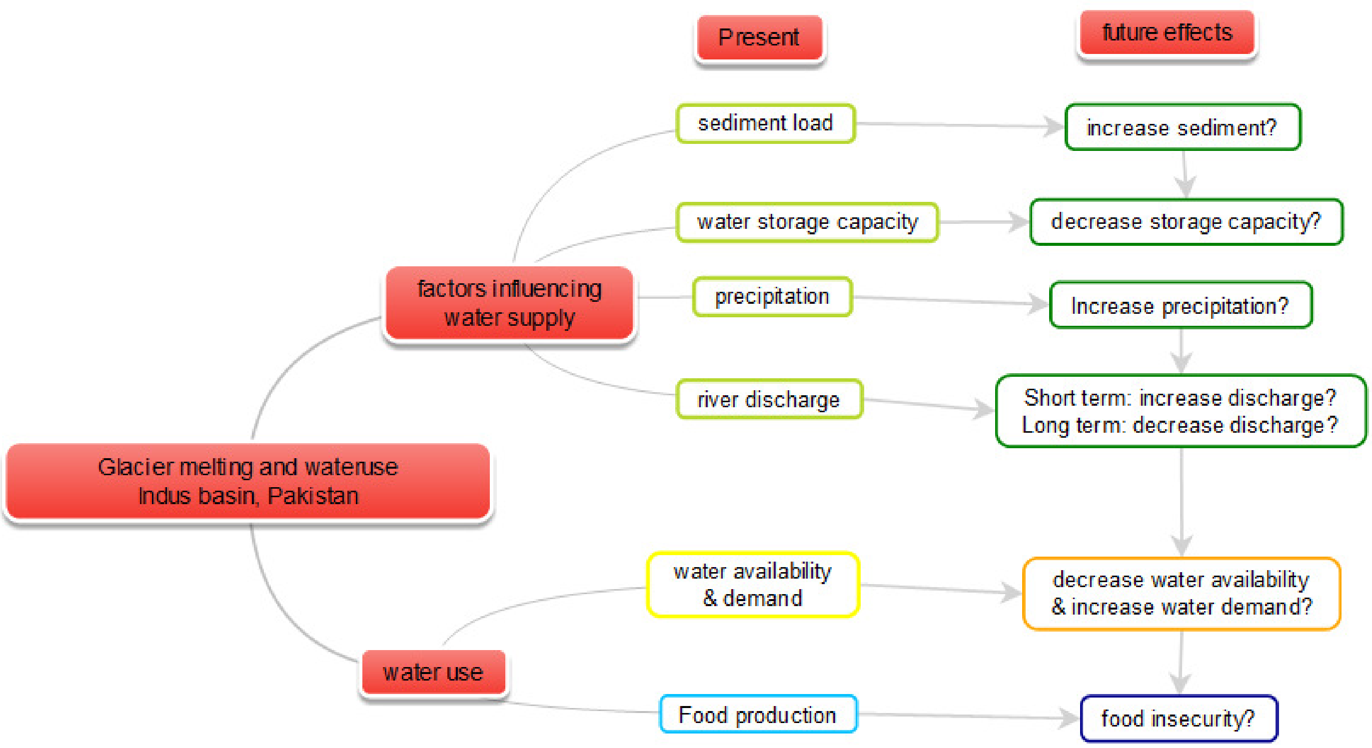

Figure 3 - Conceptual model

The light green boxes in figure 4 show the searched concepts to answer sub-question 1, which is explained in 3.1. An answer to sub-question two can be found in 3.2.1, and the used concept is shown in the yellow box in. The light blue box highlights the concepts searched for to answer sub-question 3, which is described in 3.2.2. The dark green boxes displays the data searched for to answer sub-question 4, which can be found in 3.3. The concepts searched for to answer sub-question 5 can be found in the orange box, and will be explained in 3.4.1. And last, the dark blue box shows the data searched for to answer sub-question 6, which is answered in 3.4.2.

I found the above mentioned data by searching through: Scopus, Web of Science, Scirus and Omega. I used both quantitative as qualitative data in my literature study.

I used the following keywords when searching for relevant data: Indus catchment, Indus basin, Hindu-Kush Himalayas (HKH), hydrology, water use, food production, agriculture, glacier melt, water storage, river discharge, runoff, Indus flow, melt water, and irrigation.

3. Results

3.1 Factors influencing the water supply of the Indus

3.1.1 Sediment load

Elevation influences the water flow speed of the Indus. Steeper hills have higher water speeds, and faster runoffs lead to increased sedimentation (Laghari et al., 2012). 60% of the sediment load in the Indus is glacier derived and comes from metamorphic rocks in the Karakoram range (Lu et al., 2010). The amount of sediment in the Indus depends on the amount of water draining through the Indus (Lu et al., 2010), which changes over time (Ahmed and Sanchez, 2010). The average annual sediment load of the Indus is about 291 million ton (Laghari et al., 2012). This high sediment rate makes the Indus one of the highest sediment load carrying rivers in the world (Laghari et al., 2012). Sedimentation influences the water availability, because it affects the water storage capacity (Archer et al., 2010). Due to high sediment load in water storage reservoirs, less water can be stored. Therefore, an increase in sediment load of the Indus decreases the water storage capacity (Archer et al., 2010). Sediment load of the Indus is projected to increase even more in the future, see 3.3.1.

3.1.2 Water storage capacity

'Water towers of the world' is what the Hindu-Kush Himalayas are called (Miller et al., 2012). Most of the water is stored as snow or ice (Miller et al., 2012). Northern Pakistan has a glacier coverage of about 13.000 km^2, with a coverage of one of the biggest glaciers greater than 700 km^2 (Bocchiola et al., 2011). Glacier recessions are observed among almost all glaciers in Northern Pakistan from the 20th century until 1995 (Akhtar et al., 2008). Since then some glaciers are stabilizing or advancing, while most are still declining (Akhtar et al., 2008), but not as fast as previously predicted (Hewitt, 2011).

The Indus basin has two big reservoirs, the Tarbela dam and the Mangla dam, which are used to store and release water to downstream areas when needed (Immerzeel et al., 2010). Both reservoirs are mainly fed by melt water from nearby mountains (Immerzeel et al., 2010). Pakistan has little water storage capacity, dams included, compared with other arid countries (Qureshi, 2011). The annual water storage capacity of the Indus per capita is 150 m^3 (Qureshi, 2011). For example, China has an annual water storage capacity per capita of 2200 m^3 (Qureshi, 2011). This small water storage capacity results in an increased risk of water shortage in dry periods.

3.1.3 Precipitation

Precipitation in the Indus basin is dominated by the westerlies (Bocchiola et al., 2011). The westerlies are defined as the west-to-east winds at the earth's surface between the 35° to 65° latitude (American Meteorological Society, 2012). They bring precipitation during winter and spring, upstream mostly in the form of snow (Panday et al., 2011). The average annual precipitation in the Indus basin is 423 mm (Panday et al., 2011), however variation occurs within regions. High-altitude and mid-altitude catchments are influenced by the westerlies, and foothill areas also derive precipitation in the monsoon season (Miller et al., 2012). Some years, the monsoon is strong enough to intrude upstream in the Indus basin and causes precipitation in summer (Ashraf et al., 2012). On average, the highest peak of precipitation is in April, and the lowest is at December (Ahmad et al., 2012).

Figure 5 shows the variation in precipitation in the Indus basin. The region within the red borders is the Pakistani part of the Indus basin. The southern slopes of the upstream area in the Indus basin are the wettest, with an Aridity Index Classification of humid (Laghari et al., 2012).

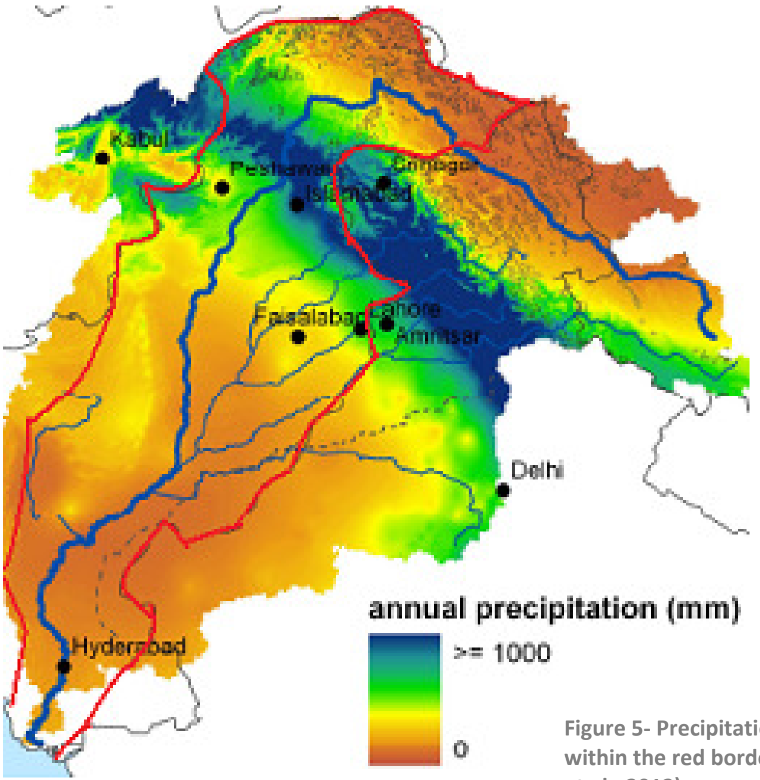

Figure 5- Precipitation in the Indus basin, with the area within the red borders being the Pakistani part (Laghari et al., 2012)

The lowlands and the high mountain ranges in Northern Pakistan are dry with annual precipitation close to 0 mm, and are classified hyper-arid (Laghari et al., 2012). The amount of annual precipitation varies from about close to 0 to 150 mm in the south to 1200 mm in the north of Pakistan (Abbas et al., 2013). The most vulnerable areas, to changes in glacier coverage, are the arid areas downstream and the areas in North-Pakistan.

3.1.4 River discharge

Figure 5 shows that a large part of the Indus basin is arid. Therefore, melt water is important to the Indus (UNEP and GEAS, 2012). The Indus can be divided into three regimes, based on importance of melt water:

- A glacial regime at high altitude catchments with runoff dependent on glacier melt water (Miller et al., 2012) and thereby on summer temperatures (Laghari et al., 2012).
- A nival regime at mid-altitude catchments, which has the biggest contribution to the total runoff of the whole basin (Laghari et al., 2012). In this regime, flow is dependent on the melting of seasonal snow and thus on precipitation in winter (Miller et al., 2012).
- A rainfall regime at the foothills of the Hindu-Kush Himalayas with runoff controlled by rainfall in winter and in the monsoon season (Miller et al., 2012).

These three regimes all have different dependencies on melt water to the river flow, with the glacial regime having the highest dependency on melt water. There have been attempts by different studies to calculate the exact percentage of melt water contribution to the Indus flow, presented in table 1.

Table 1- Different averages of melt water contributes to the total river flow

Study done by:	**Percentage melt water contribution to the total river flow of the Indus**
Bookhagen and Burbank (2010)	66%
Immerzeel et al. (2010	60%
Qureshi (2011)	80% at Tarbela dam

To indicate the importance of melt water for the Indus flow, the Normalized Melt Index (NMI) can be used, which is defined as the volumetric snow and glacier upstream discharge divided by the downstream natural discharge (Immerzeel et al., 2010). From table 1 can be concluded that melt water is of great importance to the Indus. Figure 6 confirms this statement by showing that the Indus has the highest NMI compared with four other major rivers in Asia.

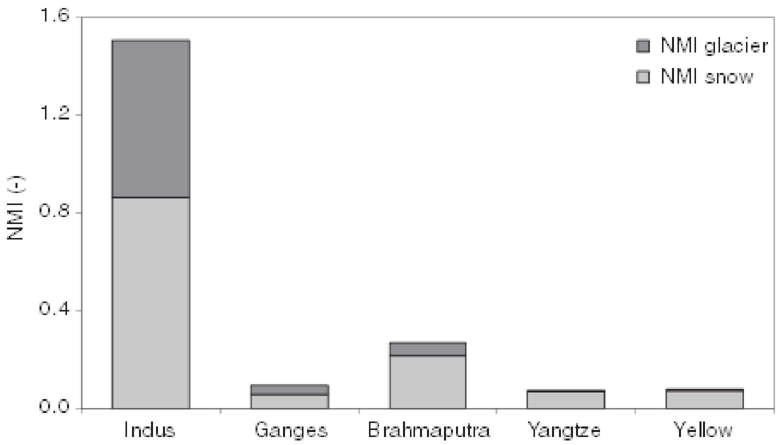

Figure 6 - The NMI of the Indus compared with four other major rivers (Immerzeel et al., 2010)

The Indus has the highest flows during summer due to increased rate of melt water and monsoon rainfall downstream (Laghari et al., 2012).

3.2 Water use

3.2.1 Water balance

The water availability, see table 3, is made up of inputs to the river system, while water use by several sectors, shown in table 2, can be seen as an output of the river system.

Irrigation is the largest sector of annual water use of surface and groundwater of the Indus basin, see table 2. Of the 180 km^3 water used by irrigation, a large part of both available surface water (128 km^3 of 175 km^3) as well as the available groundwater (52 km^3 of 63 km^3) is used, see table 3. Table 2 shows the relatively small amount of flow to the sea (35-64 km^3) of the total discharge of the Indus (165 km^3) which can be found in table 3. This indicates that a large amount of water from the Indus is used, and therefore that the outputs of the river system are relatively high with respect to the inputs.

Table 2 - Annual water use of surface and groundwater of the Indus. Numbers based on a study by Laghari et al. (2012).

	Annual water use in km^3
Irrigation	180
Domestic use	3,3
Industrial use	2,1
Remaining flow to the sea	35-64

Table 3 – Total annual water availability, and annual water use by irrigation based on study by Laghari et al. (2012).

	Annual water availability in km^3	Annual water use by irrigation in km^3
Surface water	175	128
Ground water	63	52
Discharge of the Indus	165	117-143

A study by Archer et al. (2010) confirms the statement that a huge amount of water is used from the total discharge of the Indus. Figure 7 below, shows the amount of water withdrawal from the Indus flow to canals, compared with the amount of flow that reaches the Arabic Sea, called 'escapages'.

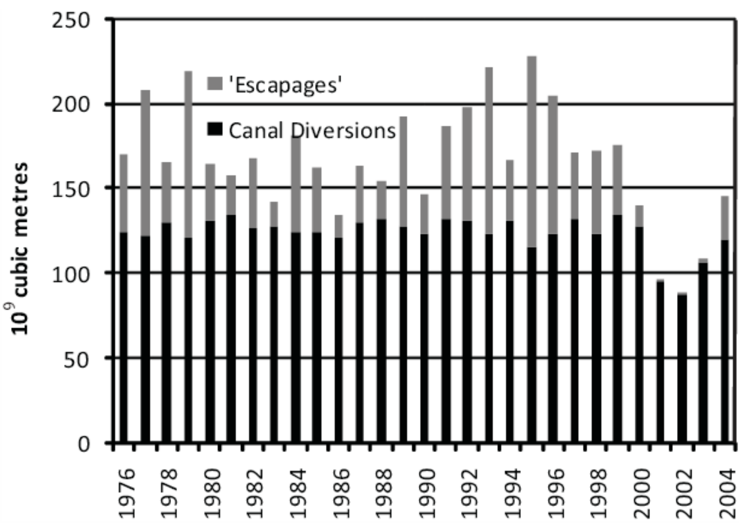

Figure 7 - Annual canal withdrawals from the total Indus flow and 'escapages' to the sea (Archer et al., 2010)

Between 2000-2004 almost the entire flow was used, due to extreme drought, see figure 7 (Archer et al., 2010). There was a negative water balance, meaning that the outputs to the river system were larger than the inputs. This led to water shortage.

The average annual surface water availability in the Indus basin is 175 km^3, see table 3. However, surface water availability varies monthly, with its peak in summer and the lowest availability in winter, see figure 8 (Laghari et al., 2012).

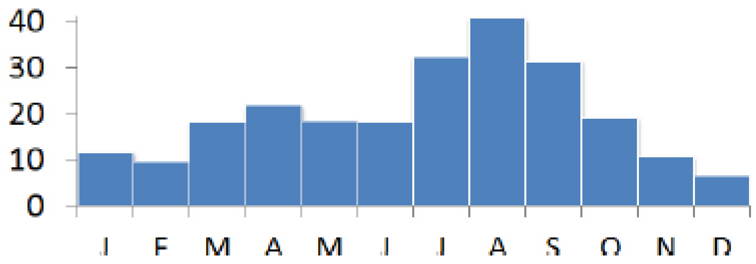

Figure 8 - The average monthly surface water availability for the Indus basin (Laghari et al., 2012)

The Mangla and Tarbela dam store water in the summer to release in wintertime during the drier period (Qureshi, 2011). Groundwater functions as an alternative to surface reservoirs like the Tarbela and Mangla dam (Archer et al., 2010), and is an important source for irrigation, see table 3. Especially in areas downstream, more than 40% of water use by agriculture is abstracted from groundwater (Laghari et al., 2012). Extensive groundwater use leads to an unsustainable annual decline of the groundwater table of 1,5 meter (Qureshi, 2011), draining aquifers faster than natural processes can replenish them (Laghari et al., 2012).

3.2.2 Food production

Agriculture is the largest economic sector in Pakistan and accounts for 25% of the gross domestic product, and 60% of the foreign earnings (Qureshi, 2011). It is also a large labor sector with about 45% of the Pakistani people working in agriculture (Archer et al., 2010). These numbers reflect the importance of irrigation not only for availability of food, but also for the Pakistani economy .

The irrigated area of the Pakistani irrigation system is about 137.216 km^2 (Laghari et al., 2012). Since 1960, when the Indus Water Treaty was signed, Pakistan began to develop the irrigation system with its storage reservoirs and canals from the western to the eastern tributaries (Archer et al., 2010). With the Indus Water Treaty, Pakistan got the exclusive rights of the three western tributaries of the Indus basin (the Indus, Jhelum and Chenab) and the eastern tributaries (Sutlej, Beas and Ravi) from their entry point in Pakistan (Archer et al., 2010). These developments made the transfer of surplus water from the wet summer period to the dry spring period possible (Archer et al., 2010). The irrigated areas of the Indus basin are shown in figure 9, within the red borders.

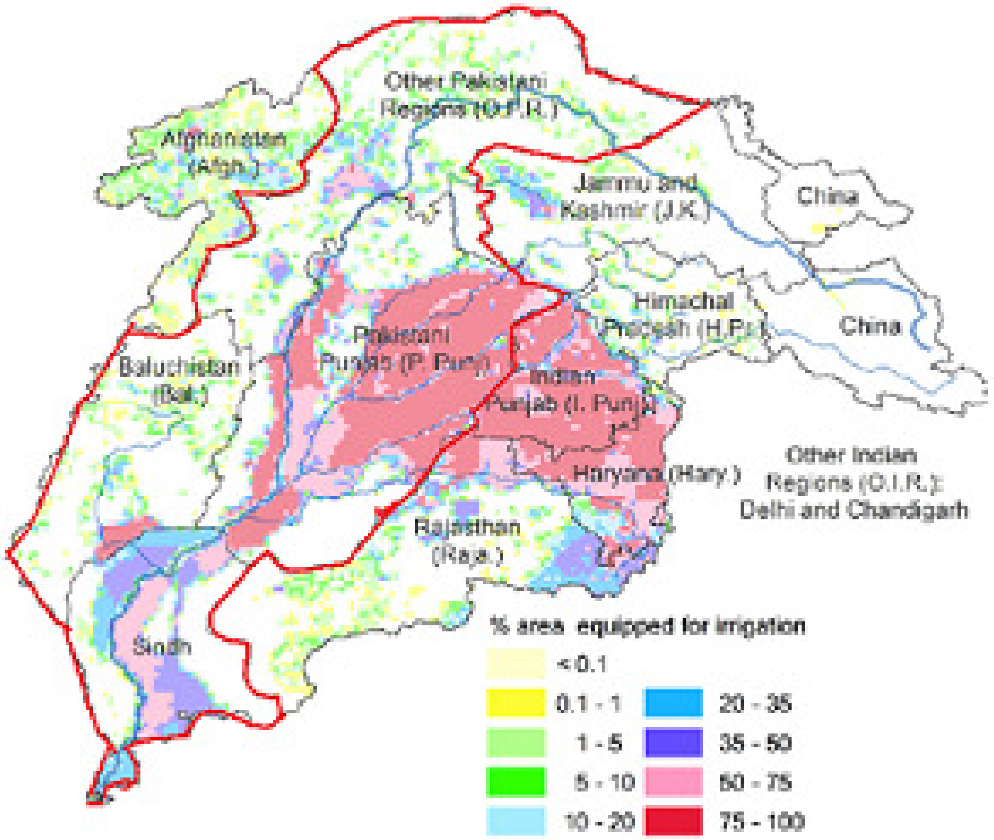

Figure 9 - Irrigated areas in the Indus basin, within the red borders (Laghari et al., 2012)

The provinces of Punjab and Sindh are the biggest irrigated zones in the Indus basin, see figure 9. For irrigation, as well as domestic and industrial use, there has been a shift from surface water to groundwater withdrawal during the last decades (Laghari et al., 2012). Over 80% of the groundwater exploitation in the Indus basin takes place through small capacity inexpensive private tube wells (Laghari et al., 2012). Abstraction of groundwater in Punjab has increased from 9 km^3 in 1965 to 52 km^3 in 2012 (Laghari et al., 2012).

Production of water dependent crops like rice, mainly grown in summer, result in high water demands and groundwater abstraction. Other crops grown during summer are cotton, sugarcane and maize (Laghari et al., 2012). In winter, mainly wheat is grown, which is the staple food for the majority of the Pakistani (Laghari et al., 2012). It has a planted area of over 8 million ha (Archer et al., 2010).

3.3 Future changes in factors influencing the water supply

3.3.1 Changes in sediment load and water storage capacity

Climate change leads to a greater risk of geomorphic hazards in the coming decades due to increasing glacier retreat and associated increase in flow because of shifting ice volume (Lu et al., 2010). These hazards lead to increases in sediment load in the Indus, especially in the first half of the 21st century when glaciers are projected to decrease (Immerzeel et al., 2010).

Sediment load in the Indus is also expected to increase due to mingling of sub-glacial sediment with melt water flowing into the Indus (Lu et al., 2010). Sediment is most times temporarily stored in downstream tributaries of the Indus (Lu et al., 2010). Because this sediment is stored outside the main flow, sediment in the main flow could further increase driven by increasing melt water (Lu et al., 2010). And last cause of sediment increase is increased erosion due to increased precipitation (Lu et al., 2010).

Increased sediment load in the Indus, affects the storage capacity of the Tarbela and Mangla dam (Archer et al., 2010). The Tarbela dam has an original storage capacity of 13,9 km^3 , that was reduced with 28% in 2000 due to sedimentation (Archer et al., 2010). Estimates indicated that the Tarbela dam would be totally filled with sediment by 2030 (Archer et al., 2010). The storage capacity of the Mangla dam was reduced by 20% in 2007 (Archer et al., 2010). These reductions influence the water supply downstream.

3.3.2 Changes in precipitation

A study by Ahmad et al. (2012) predicted an average precipitation increase in the Indus basin towards the end of the 21st century. This increase reflects a predicted increase in precipitation contribution to the Indus flow. Miller et al (2012) confirms this prediction by showing an increase in rainfall by 53% between 2071-2099. However, due to temperature increase in the region, more precipitation in winter will fall as rainfall than as snowfall compared with the current situation (Sharif et al., 2012). This rainfall will be added directly to the river system, instead of stored in the form of ice or snow in glaciers. Global warming also intensified the summer monsoon, and thereby enhances precipitation in summer, especially downstream of the Indus (Bocchiola et al., 2011). The Indus will become more of a rainfall dependent river towards the end of the 21st century, than a glacier dependent river (Sharif et al., 2012). However, an increase in precipitation will, at best, partly compensate the effects of glacier melting due to a decrease in storage capacity of glaciers on the long term.

3.3.3 Changes in river discharge

Temperature rise will lead to increased water availability in the short term due to increased melt water in the early decades of the 21st century (Laghari et al., 2012). An increase of the river flow of about 50% is predicted at Besham Qila, upstream in the Indus basin (Qureshi, 2011). However, water availability will decrease in the long term (Laghari et al., 2012). A study of Immerzeel et al. (2010) projected a decrease in river discharge of 8,4% by 2046-2065 to the reference period 2000-2007, see figure 10.

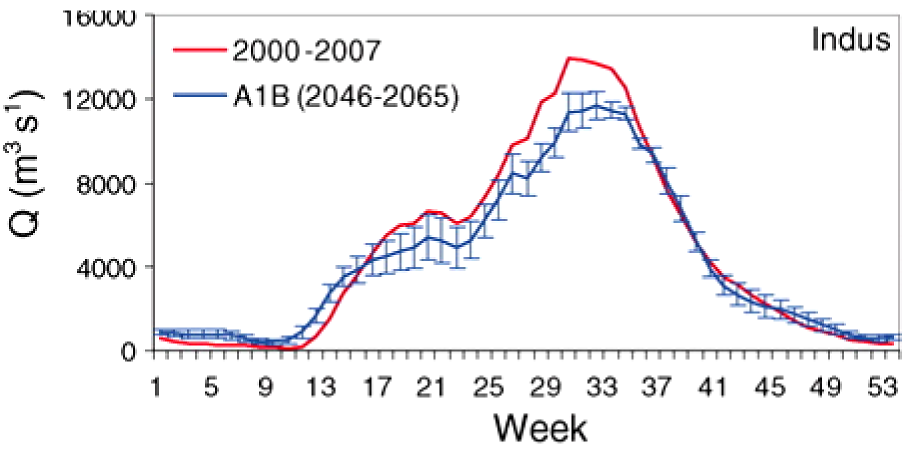

Figure 10- Predicted river discharge in 2046-2065 for the for the A1B SRES IPCC climate change scenario. Where Q is the river discharge. Glacier size is based on a best guess scenario. (Immerzeel et al., 2010)

The decreased water availability due to decreased melt water is partly compensated by increased precipitation, caused by climate change (Immerzeel et al., 2010). However, effects of climate change vary within the basin. Effects of climate change can be categorized among the nival, glacial and rainfall regimes. The nival regime will face reduced summer runoff in the coming decades, because of less potential of melting of seasonal snow due to an increasing winter and spring temperature combined with a decrease in winter precipitation (Archer et al., 2010). The glacial regime will face a sharp decline in runoff at the second part of the 21^{st} century when glacier coverage is decreasing (Archer et al., 2010). And the rainfall regime will have the least decline in river flow due to an increased summer monsoon (Archer et al., 2010).

3.4 Future changes in water use

3.4.1 Changes in the water balance

Future water demand is related to the number of people living in the basin. Figure 11 shows four different population growth trajectories estimated by the UN (2009), ranging from an increase of about 295 million people to 430 million people in 2050, and a maximum increase of about 250 million people in 2025 (Archer et al., 2009).

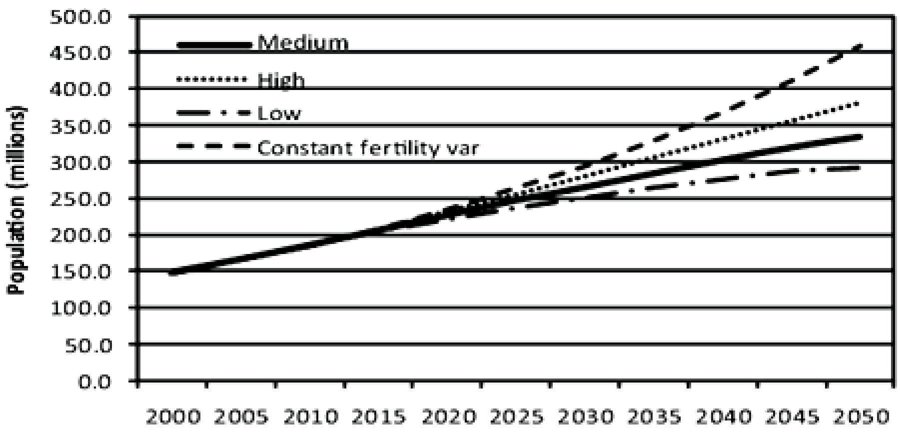

Figure 11 - Projected population growth in the Pakistani part of the Indus basin showing four trajectories based on UN (2009) estimates (Archer et al., 2010)

An increased population will lead to higher water demands, and thereby higher outputs of the water balance. Table 4 shows the predicted annual water use in 2025 in contrast with the current annual water use.

Table 4 - Predicted annual water use of the Indus. Numbers based on a studies by Laghari et al. (2012) and Qureshi (2011).

	Current annual water use in km³	Predicted annual water use in 2025 km³
Irrigation	180	250
Domestic use	5,4	14
Industrial use	2,1	4,9

The water demand by irrigation will compete with non-irrigation water demand in the long term future, since the water supply of the Indus, the input for the river system, will not rise (Qureshi, 2011). In the present situation, the Indus basin in Pakistan is already water stressed and is predicted to face water scarcity by 2035 (Archer et al., 2010). Basins are water stressed when their per-capita water availability is below 1700 m^3 a year, and facing water scarcity when per-capita water availability drops below 1000 m^3 a year (Archer et al., 2010). Figure 12 shows the water shortage threshold of 1000 m^3 compared with projected per capita water availability in the future based on estimates of the UN (Archer et al., 2010).

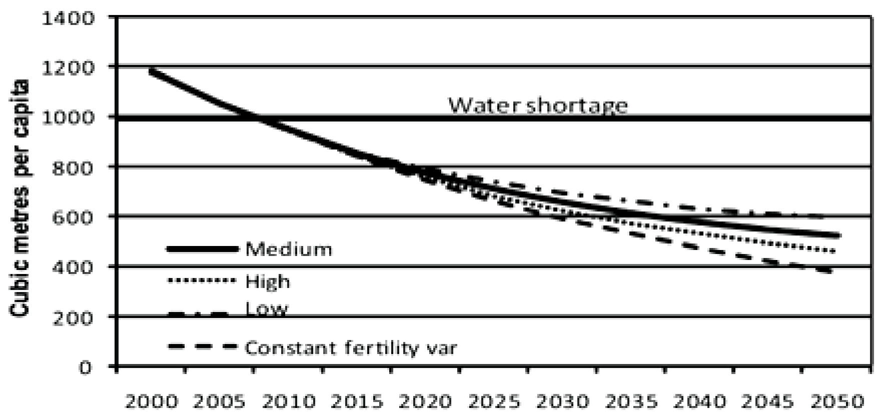

Figure 12 - Projected per capita water availability according to the four trajectories of population growth estimated by the UN (2009) (Archer et al., 2010)

Predicted per capita water availability ranges from 599 m^3 to 382 m^3 by 2050, see figure 12 (Archer et al., 2010). Especially in the dry months of early spring, water resources will diminish because of the lowered reservoir storage capacity due to increased sediment (Archer et al., 2010). To meet the water shortcomings in the future, the storage capacity of the Indus basin needs to be expanded. The Pakistan Water Sector Strategy estimates a necessary raise of at least 22 km^3 to meet the storage requirements of 165 km^3 in 2025 (Qureshi, 2011).

3.4.2 Problems for food production

Given the fact that agricultural land in the Indus basin is rain- or irrigation-fed, and the fact that the basin is already water stressed and predicted to face water scarcity, any climatic variation that affects the amount or timing of melt water contribution will affect food production and result in food insecurity (Malik et al., 2012). The changing hydrological system in the Indus, due to climate change, has impacts on production of rice, wheat and maize from 2010 to 2050 according to the International Food Policy Research Institute (Malik et al., 2012). Besides, the future predicted increase of domestic and industrial water demand will compete with water demand for irrigation (Archer et al., 2010). However, there will be variation among different regions in the Indus basin due to its highly diverse geographical and climatic features (Malik et al., 2012). Especially arid areas with little precipitation, like Sindh province or Northern Pakistan, are vulnerable to climate change. Water dependent crops, like rice, are mostly affected by lack of water availability for irrigation. There will be an average water shortage of about 60 km^3 by 2025 in the Indus basin (Qureshi, 2011). Adaptation strategies need to be developed to cope with this water shortage and to prevent severe food insecurity (Malik et al., 2012).

4. Discussion

After studying the effects of climate change and associated glacier melting in the Hindu-Kush Himalayas at the Indus basin in Pakistan on water availability and food production, I conclude that glacier melting is one of many factors that influence future hydrology. In addition future food production is also depending on a variety of factors. Therefore, the influence of glacier melting on future water supply and water use in the Indus basin needs to be placed in a broader perspective of a changing environment in Pakistan.

As explained in the results, climate change will indeed catalyze glacier melting and thus contribute to a decrease in runoff in the second part of the 21st century (Immerzeel et al., 2010). This will affect the water balance in a negative way, because of the high melt water contribution of the Indus (Archer et al., 2010). Besides, projected population growth in the basin will boost future water demand. The United Nations (2009) estimates population growth from 295 million to 430 million people by 2050, which is a doubling of the current population (Archer et al., 2010). The water availability per capita is estimated at minus 50% by 2050 (Archer et al., 2010). Population growth is possibly a greater influence to water availability than glacier melting.
Another factor, out of the scope of this thesis, that influences water availability is salinization. Salinization appears to be of great importance for the declining groundwater table. Water extracted for irrigation brings in about 33 million tons of salt, whereas the outflow to sea is only 16,4 million tons (Qureshi, 2011). A fraction of 6 mha of land within a total of 22 mha cultivated land in the basin is affected by salinization (Abbas et al., 2013). Abstraction of saline groundwater enhances the salinization process of the soil in these areas (Archer et al., 2010).
The discussed projected increase of precipitation also influences the future water supply of the Indus. However, the interaction between precipitation, temperature and ablation or accumulation of glaciers needs to be investigated in future research. It is uncertain if the projected increased precipitation will compensate the decreased Indus flow due to glacier melting.
A last factor influencing water supply of the Indus is the high irrigation inefficiencies. Water demands can be decreased if the irrigation system was more efficient. The productivity of water in Pakistan is about the lowest in the world (Qureshi, 2011), with irrigation efficiencies ranging from 35% to 40% (Qureshi, 2011). A large part of the irrigation water is wasted or leaked to the groundwater (Laghari et al., 2012). The influence of population growth, salinization, increasing precipitation and irrigation inefficiencies are possibly of greater influence on fresh water supply of the Indus in the future than glacier melt is. This needs to be studied in further research.

Using the water balance analysis I discovered that some hydrological data about the region is missing due to lack of monitoring and knowledge about glacial behavior. The region is named 'a white spot' by the IPPC Assessment Report (2007), indicating that there is little knowledge on glacier processes, water use and changes in the hydrological system of the Indus (IPCC, 2007). The World Meteorological Organization (WMO) recommends one gauge per 250 km^2, whereas the actual density of gauges in the Upper Indus basin is less than one gauge per 5000 km^2 (Archer et al., 2010). There also has been no long-term monitoring of glacial melt contribution to the Indus basin (UNEP and GEAS, 2012). This lack of long-term information combined with little information about current glacial behavior in Pakistan results in inconsistencies between various studies in the area. Hewitt

(2011) and Immerzeel et al. (2010) stated that some glaciers in the Karakoram range expanded since the 1990s. This atypical behavior complicates making future predictions of glacier behavior (UNEP and GEAS, 2012). I assumed, when writing this thesis, that despite inconsistencies among several studies, there is a consensus of a general decrease in glacier coverage in the Pakistani part of the Hindu-Kush Himalayas (Immerzeel et al., 2010). However, a more adequate program of observations and measurements of glacier behavior in Pakistan is necessary to draw a more certain conclusion to the research question stated in this thesis.

Furthermore, the Pakistani part of the Indus basin covers a broad range of variations within hydrological characteristics. For example, in paragraph 3.1.3, the amount of annual precipitation ranges from 0 to 150 mm in the south to 1200 mm up north (Abbas et al., 2013). Therefore, expected future changes in precipitation are average changes and can vary among different sub regions in the basin. Although I made a distinction between three regimes, glacial, nival, and rainfall regime, results are still based on averages of these three regimes. Further research could use more site specific data to estimate local effects. The same accounts for changes in sediment load, water storage capacity and river discharge. Further research needs to be done to estimate local effects, of melting glaciers, on fresh water supply of the Indus.

5. Conclusion

Climate change and associated glacier melting in the Hindu-Kush Himalayas at the Indus basin in Pakistan leads to a decrease in fresh water availability at the end of the 21st century and thereby to a water shortage for food production. Changes in the hydrological system due to glacier melt influence the water availability in the future. Increased sedimentation and decreased groundwater availability lead to a decreased water storage capacity. These two tendencies result in water shortage in the dryer periods of early spring and autumn. Because the Indus has a high Normalized Melt Index, changes in the amount of melt water in the future are of great influence to the water supply of the Indus. However, climate change will cause an increase in precipitation in the area (Qureshi, 2011) and thus partly compensate the effect of melting (Immerzeel et al., 2010). Due to increased precipitation and decreased melt water, caused by glacier melting, the Indus will change from a glacier dependent river to a more precipitation dependent river at the end of the 21st century. The dependency of food production on the Indus, results in problems in meeting the food demand with less water available in dry seasons and less water storage capacity. An additional issue concerning water demand is the expected rising population in the basin. The water demand is expected to rise, while the water availability is expected to decrease at the second half of the 21st century. This results in water shortage and the inability to meet food demands. Future research needs to be done to predict exact local amounts of water shortage in the basin and to design adaptation strategies and water management programs.

The research question of this thesis is: *What effects can be anticipated from the impact of global climate change and associated glacier melting in the Hindu-Kush Himalayas on food production at the Indus basin in Pakistan?*

The research question can be answered by accepting the hypothesis, as follows:
There will be a decrease of glacier coverage in the coming decades as a result of global warming. This will lead to an increase in water availability on the short term, in the coming decades, due to an increase in melt water. However, the water availability will decrease on the long term, at the second half of the 21st century. This decrease in water availability combined with a projected increased water demand, will cause water shortage for irrigation and thus food insecurity.

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