Impact of Climate Change on Water Resources and Agricultural Production in the Indus Basin, South Asia

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Abstract

Annual flow in the Indus is 120-230 km^3 (1957-97) with only about 10% net discharge to the sea, and with glacier melt providing stream flow in the upper basin. Our analysis using Water Evaluation and Allocation Policies (WEAP) modelling with a special sub-routine for glacial and snow melt showed that the average contribution from glacier melt is 47.2 km^3/year (64% of total) at Tarbela dam and 44.2 km^3/year (54.1%) at Sukkur barrage in Pakistan. The simulations showed that an increase of 1°C to 3°C over the next 20 years may change the annual flow by +9 to +31% at Tarbela dam and +10 to +34% at the Sukkur barrage. This is likely to have very serious implications for the water resources availability and use in the short and long term. In the short and medium term large investments may be made in creation of water infrastructure to avoid flooding in the upper reaches and the plains. In the medium to long term, water efficient cropping and irrigation methods, and possible reduction in the irrigated areas in the basin shall be required.

Keywords: Climate change, Indus basin, WEAP modelling

Introduction

The Indus basin covers an area of about 1.10 m km^2 distributed between Pakistan (63%), India (29%), and China and Afghanistan (8%) (Jain et al., 2009). Indus River originates in Mount Kailash (Mansarovar Lake) in Tibet (China) and consists of Upper Indus and Lower Indus- the portions upstream and downstream, respectively of Guddu barrage in Pakistan. The Indus has two main tributaries, Panjnad from the east formed by five rivers Jhelum, Chenab, Ravi, Beas and Sutlej; and Kabul River on the west (Fig.1). The upper reaches of the Indus are in the high Karakoram and Himalayan mountains with many peaks over 7000 m amsl (above mean sea level). Annual flow in the Indus is 120-230 km^3 (1957-1997) with only about 10% net discharges to the sea. Glacier melt provides most of the stream flow in the upper basin. More than 40% of the basin is located at an elevation higher than 2000 m amsl. The wettest regions of the Indus basin are on the southern slopes of the Himalaya-Karakoram-Hindu Kush (HKH) mountain range. The high mountain ranges in the north of the basin – like Ladakh in India – are very dry. The glacial area is very large, i.e. 37,134 km^2 according to the DCW database (Raup et al., 2000). However, other sources that refer to this database indicate within the Indus basin a glacial area of about 22,000km^2 (Immerzeel et al., 2010) or 20,325 km^2 (Kaser et al., 2010). An overview of the hydrological regimes in the Indus basin is given by Archer (2003):

i. A nival regime at the middle altitudes with flow dependent on the melting of seasonal snow. The greatest contribution to the total flow comes from this regime.
ii. A glacial regime at the very high altitudes with river flow closely dependent on summer temperatures.
iii. A rainfall regime dependent on runoff from rainfall mainly during the rainy season. This regime dominates on the southern foothills of the Himalayas and also over the plains but with smaller total amounts.

As such, impact of climate change in the form of rise in temperatures and snow and glacial melt shall be of significant consequence in the Indus basin.

The Indus basin houses the largest contiguous irrigation network in the world, Indus Basin Irrigation System (IBIS) in Pakistan, serving 17 Mha. The system diverts almost 75% of the annual river flows into the irrigated areas of the basin. The system consists of 15 barrages, 45 main canals and 14 river-link canals. The capacities of the main canals range from 15 to 425 m^3/s and inter-river canals have capacities ranging from 142 to 624 m^3/s. IBIS draws about 130 billion cubic metre (BCM) of surface water for irrigation. Structural development in the basin area has greatly enhanced the irrigation water availability. In the Indian part of the Indus basin, the Bhakra- Nangal project is the biggest multi-purpose project with cultivable command area of 2.37 M ha and an installed power capacity of 1200 megawatt.

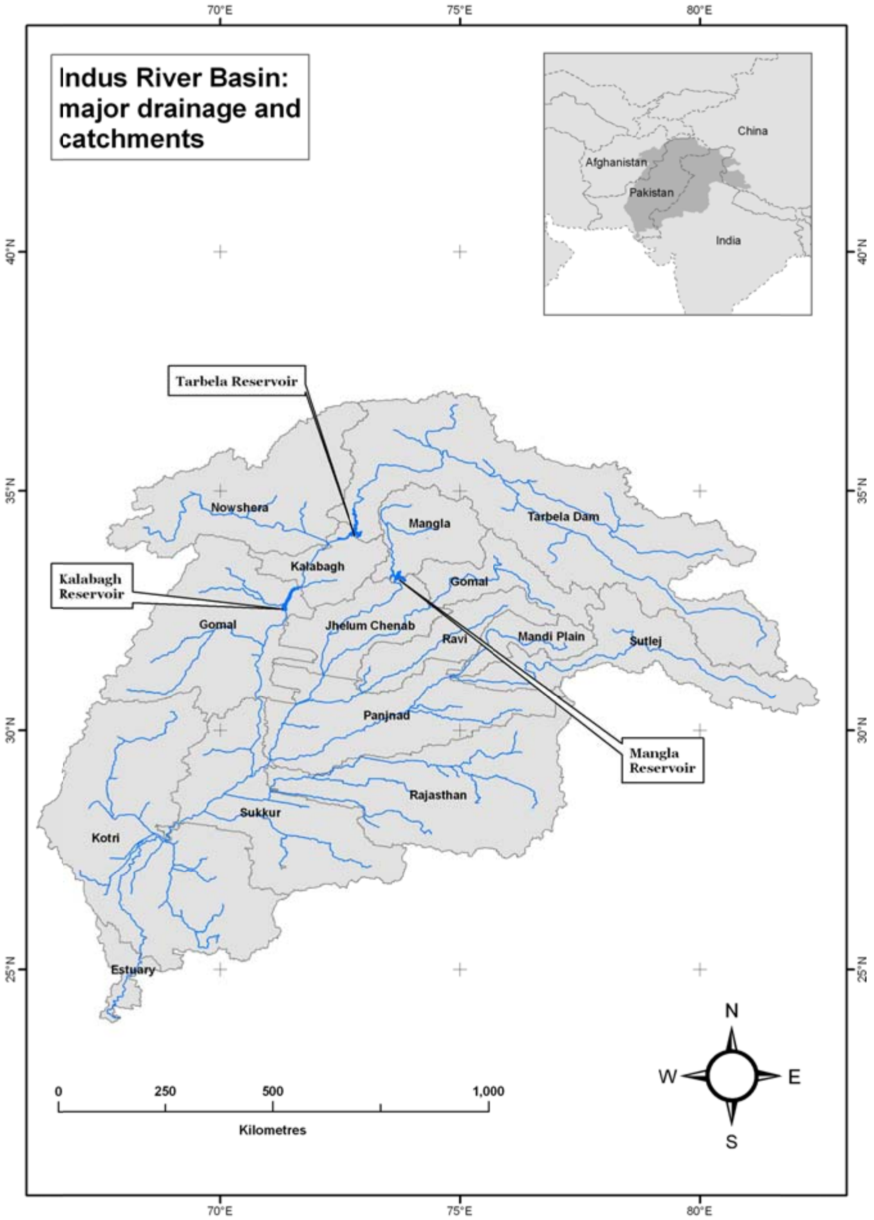


Figure 1. The Indus Basin, with its major catchments and tributaries (Source: Eastham et al., 2010; http://www.waterandfood.org/uploads/publication_pictures/1289974689_CPWF_BFP_WP_07.pdf)

The World Bank mediated Indus Water Treaty (1960) governs trans-boundary water sharing of the Indus system between India and Pakistan. The Indus basin has also witnessed an unprecedented exploitation of its groundwater resources. Groundwater contributes to almost 99% of the increase in total irrigated area. In Indian Punjab, tubewell irrigated area has outgrown canal irrigated area since 1970. Canal irrigated area in Haryana state of India increased by 49 % in the last 35 years, whereas the tubewell irrigated area increased by more than 500 % (Dharmadhikary, 2005). Groundwater potential and its use in the Indus basin are shown in Table 1. This was also confirmed through findings of the GRACE satellite project which showed significant and continual water table decline in the region (Rodell et al., 2009). Tiwari et al (2009) and Laghari et al. (2011) also showed that the use of natural buffer of groundwater reservoir has led to an unsustainable fall of the groundwater table; draining aquifers faster than natural processes can replenish them. The Indus basin is now practically closed with near zero environmental flows in most years.

Table 1. Groundwater availability and its use in the Indus basin

Countries/ Basin	Available groundwater, BCM	Annual groundwater draft, BCM			Stage of groundwater development, %
		Irrigation	Domestic, industrial & others	Total	
India	30.2	36.4	1.6	38.0	126
Pakistan	55.1	46.2	5.1	51.3	93
Indus basin	85.3	86.2	6.7	89.3	105

Water Demand and Food Security in the Indus Basin

The Indus basin presently inhabits about 200 million populations, with projections of significant increase in the future. Demographic pressure and industrial development influence the distribution of water between sectors. The share of agricultural water use, which presently uses about 95.5 % of the total water use, is under stress to relieve the resources for enhanced industrial and domestic water demands (Amarasinghe et al., 2007). The Indus basin is the seat of Asian Green Revolution and the surplus food produced in this basin meets the food requirements of several other food-deficit basins. Therefore, any impact on the water resources shall have serious implications for the food security not only in the Indus basin but South Asia region as a whole.

Table 2. Water demands in the Indus basin (down to Kotri in Pakistan)

Irrigation, km^3 /year (%)	Domestic, km^3 /year (%)	Industries, km^3 /year (%)	Total, km^3 /year
168.7 (95.5)	4.4 (2.5)	3.4 (2.0)	176.5

The Indus basin ranked in the top ten of the world’s most vulnerable basins with inflows predicted to fall by 27% by 2050 (IPCC 2001). Glacier melt is the major water source for the Indus and hence of water for irrigation. Reduced glacier melt will therefore impact food production in the Indus basin. There was an overall de-glaciation of 21% since 1962 in 462 glaciers in the Chenab, Parbati and Bapsa basins. Existing studies show that the combination of glacial retreat, decreasing ice mass, early snowmelt and increased winter stream flow suggest that climate change is already affecting the Himalayan cryosphere (Kulkarni et al. 2007). Reduced surface runoff will reduce groundwater recharge and affect the groundwater dynamics in the region, which will be critical in the western region where most irrigation is from groundwater. We shall now examine the impact of climate change on water resources in the Indus basin, and its implications on agricultural production.

Contribution of Snow and Glaciers

Significant proportions of annual precipitation fall as snow in the high Himalayan-Karakoram mountains and over long periods of time, the snowfall has built up into glaciers which are semi-permanent reservoirs of water preserved as ice. Snowpacks accumulate during the winter periods to be released as meltwaters during spring and summer giving the streams a distinct seasonal rhythm to annual flow regimes. Release of water stored as glacier ice is particularly significant in years of low precipitation and during the late summer period when seasonal snowpacks have largely melted. Thus glaciers provide a buffering effect on streamflow, acting as regulators and providing insurance against times of low flow. However, while in the short-term glacier melt will provide extra water to the rivers, in the longer term when those ice masses melt out, the extra water will no longer be available and all-important buffering effect will disappear. The information required for the glaciers module of WEAP used in this study is the time variation of glaciers' area. The required information for some of the glaciers was obtained from *World Glaciers Monitoring Service*. However, these are punctual observations while spatial coverage is required. On the other hand, the *Global Land Ice Measurement from Space (GLIMS)* and GIS files from the IGB ToolKit provide this coverage although these are snapshots at a given date. The glaciated areas for the sub-basins of Mangla dam, Tarbela dam and for the whole basin are given in Table 3 and Fig. 2.

Table 3. Distribution of glaciers area within the partly glaciated important sub-basins of the Indus, down to Kotri

Sub-basin	Area ,km^2 and (%) in elevation-band of the sub-basin					
	Total	3000-4000 m	4000-5000 m	5000-6000 m	6000-7000 m	7000-8000 m
Mangla dam	42	-	8 (1%)	34 (>> 100%)	-	-
Danyour bridge	4,861 (37%)	419 (16%)	1,500 (28%)	2,454 (65%)	441 (100%)	47 (101%)
Tarbela dam	20,450 (13%)	490 (2%)	4373 (7%)	13,662 (26%)	1,876 (81%)	49 (75%)
Whole basin	35,297 (4%)	1255 (2%)	10,220 (9%)	21,195 (27%)	2,719 (81%)	109 (86%)

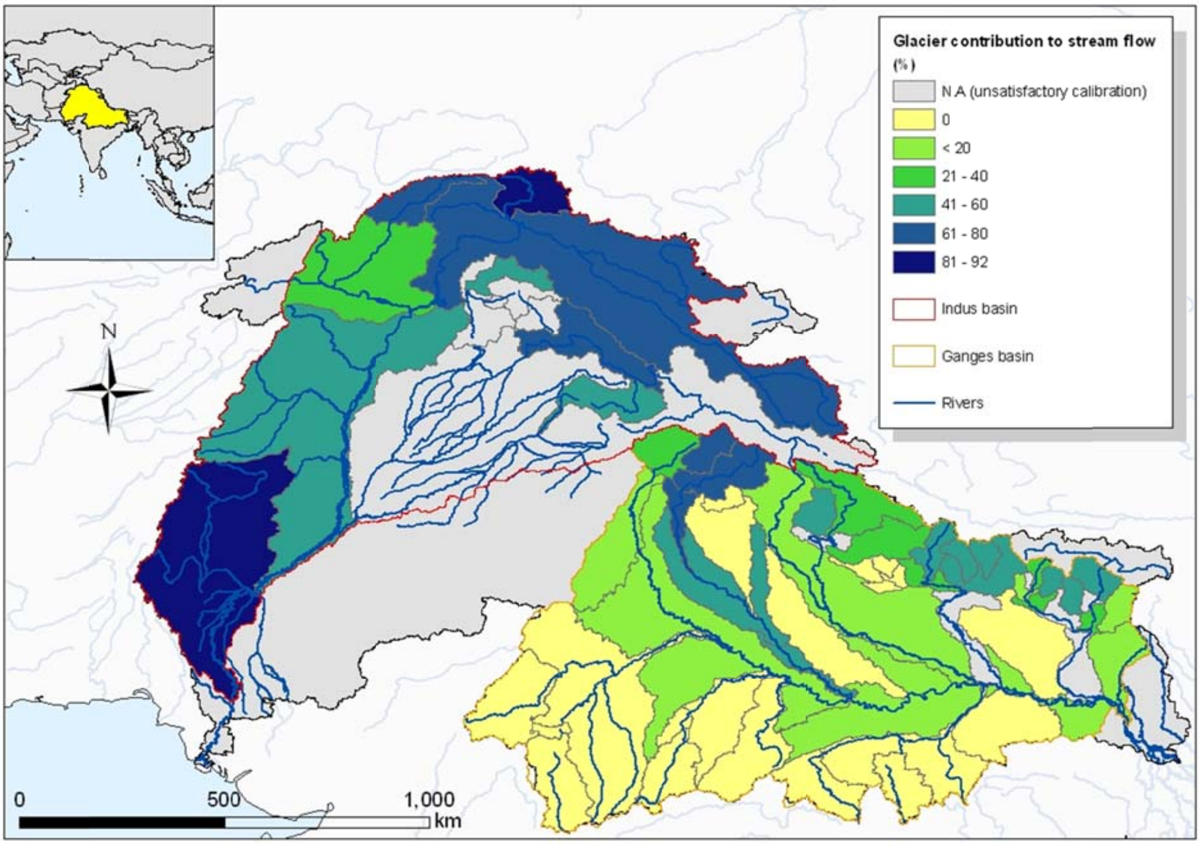


Fig. 2. Percent contribution of glaciers to streamflows in the Indus and the Ganges basins

As is evident from the data about 4% of the whole basin area of Indus (upto Kotri) is covered by glaciers which is quite large as compared to just 1 % of the whole basin area (upto Farakka) of the neighbouring Ganges basin.

Setting-up of a basin-wide WEAP model

We set an application of the model *Water Evaluation and Planning* (WEAP) which contained experimental glaciers module that accounts for snow and glacier processes in the Indus basin, i.e. seasonal mass variations and contributions to streamflows. This model helped to (i) simulate the surface water resources in the Indus basin with special focus on the contribution from snow and glacier melting, as well as the anthropogenic utilisation of the resources, and (ii) enable the development of prospective scenarios to climate change (increase in temperature). The first step was to gather the input data, such as the digital elevation model (DEM), the land-use, the climate-time series, observed streamflows, glaciers coverage and water uses in the basin. In the second step WEAP was calibrated and partly validated on the observed streamflows. As time-series of observed streamflows and glaciers area were scarcely available, the WEAP application developed in the study could not model precisely the processes and provided instead general trends. In a third step, we applied WEAP to analyse the current context of the surface water resource in the Indus basin, in particular the contribution from melting of glaciers. We also examined possible impacts of an increase in temperature of +1, +2, or +3° C over 20 years.

The data for the streamflows were obtained from Global Runoff Data Centre (GRDC 2008); Global River Discharge (RivDIS, Vorosmorty et al., 1998), and the Research Data Archive (RDA) maintained by the Computational and Information Systems Laboratory (CISL) at the National Centre for Atmospheric Research (NCRA), U.S.A; the dataset ds552.1 was chosen. The digital Elevation Model (DEM) was the version of Shuttle Radar Topography Mission (SRTM) pre- processed by Jarvis et al., (2008). The information required for the glaciers module of WEAP is the time variation of glaciers area. The Global Land Ice Measurement from Space (GLIMS) and GIS files from Indo-Gangetic Basin Tool Kit (IGB Tool Kit, www.iwmi.org) provide the glacier coverage at a given date. These sources were chosen eventually, though there are certain differences between both dataset. WEAP glaciers module also requires the degree-day coefficient for ice and snow governing the melting rate from snow packs and glaciers. The values found in the literature are compiled in Table 4. Lastly, the recurrent value for the rain-snow temperature threshold read in three references (Hasnain 1999; Singh et al. 2008; Thayyen et al. 2005) for the region is 2°C.

Table 4: Some values for the degree-day coefficient governing the melting rate from snow packs and glaciers.

Source	**Degree-day coefficient**
Singh et al. (1995)	Ice: 5.4 mm/°C/6h
Singh et al. (1999)	Ice: 8 mm/°C/day; Snow: 6.3 mm/°C/day
Singh et al. (2008)	Ice: 2.5 to 9 mm/°C/day

Following the approach of Condom et al. (2007), the Indus basin was further discretised with respect to elevation so as to account for the variation with altitude of the glaciers coverage and the climate.

The basic unit of modelling were the sub-basins subdivided by elevation bands. The analysis proceeded per river system, from upstream to downstream, with a monthly calculation time step. In each of this sub-unit were placed (Fig.3):

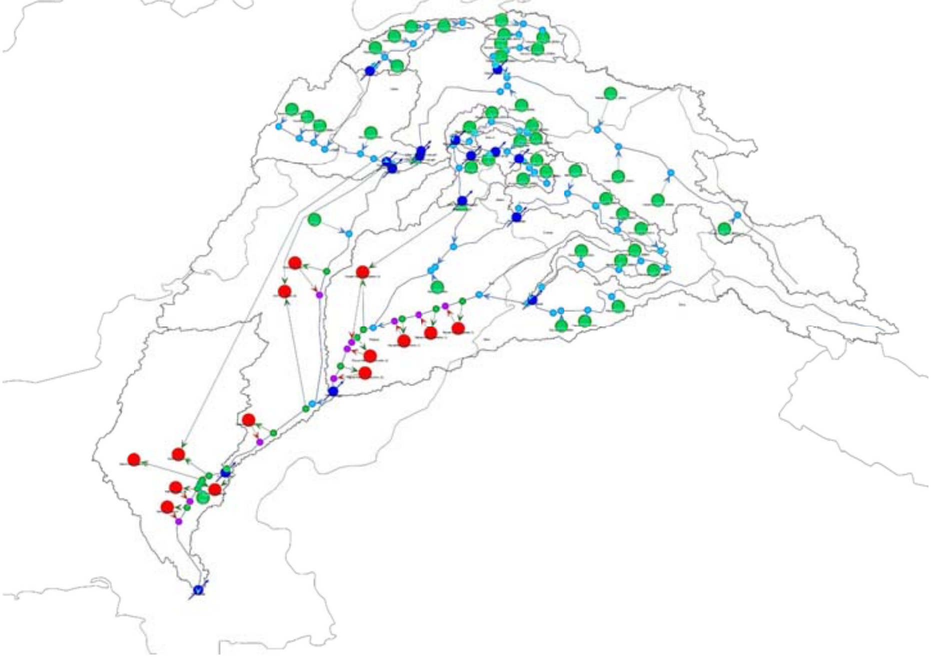


Fig. 3. Scheme of setting-up of the WEAP-Indus

i. An hydrological unit that stimulates(a) glaciers and snow melting and (b) land-use related rainfall/ runoff from input of climatic data,
ii. Water infrastructures and demand objects that account for water uses.

Setting WEAP- Indus meant calibrating and possibly validating the hydrological objects so as to reproduce the observed stream flows at the outlet of a given sub-basin. Concretely, calibration was achieved by tuning the parameters of the hydrological objects that pertain to:

(a) The glaciers, i.e., the degree-month coefficient, calculated by multiplying the degree-day coefficient by 30, and the rain-snow temperature threshold. As initial values, we referred to values mentioned in Table 4.
(b) Land-use related rainfall / runoff process, i.e., the land parameters such as the soil layers retention capacities, their conductivity and a runoff coefficient. The initial values were those plausible for the given land-use.

Whenever large time-series of observed data were available, i.e., more than 10 recent years, part of this time-series was kept aside for validation. We also evaluated the quality of the WEAP- Indus and found that the setting was 'very good to good' in the western part of the Indus(along the Indus river) and were 'bad' in the eastern part due to flow behaviour of the Jhelum river and unavailability of stream flows data for Ravi and Sutlej rivers.

Limitations of the WEAP-Indus

The following were some of the important limitations of the current version of the WEAP-Indus:

i. This version does not cover the entire basin but only upto Kotri barrage in Pakistan.

ii. No time-series of glacier coverage was available, hence calibration of WEAP glaciers module only aimed at reproducing the streamflows while an additional target could be the variation in glacier area.

iii. Description of glaciers is based on a simple conceptual model, which may not capture all the glacier processes. In particular, the variability of degree-day coefficient was not considered (Singh et al., 2008).

iv. Finally, these first settings did not include snow melting in the un-glaciated areas, which may be significant hydrological processes in medium to low mountainous ranges.

As a consequence, the WEAP-Indus can provide only the average trends and not more detailed information on monthly or annual time scale.

Model Simulation and Results

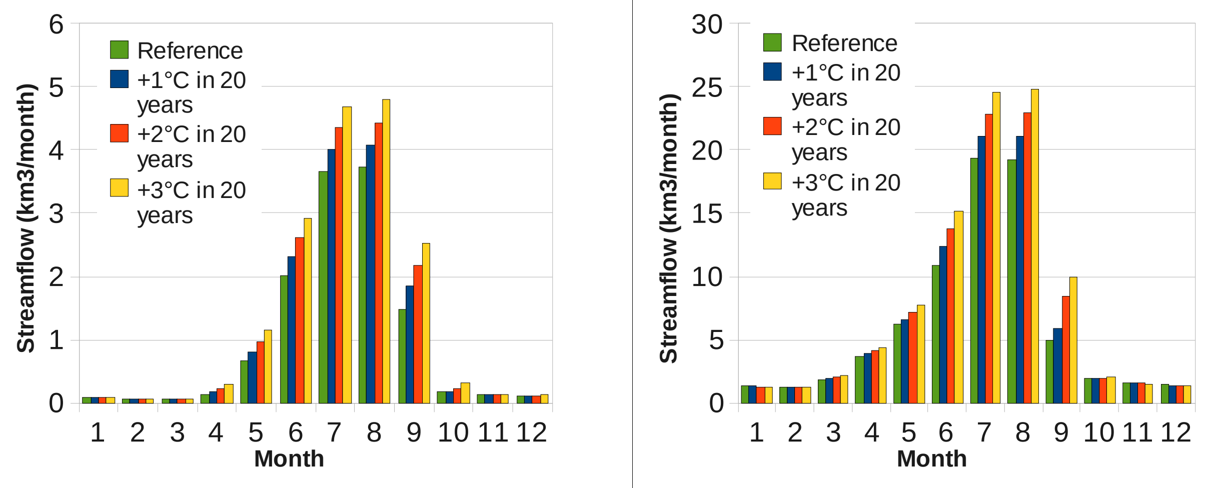
The chosen simulation period for the study is 20-years of the latest CRU data (1982-2002). Irrigation demands have a much greater impact in the Indus basin. The total water demands of 169 km^3 /year represent roughly 83% of the surface water resources. This is a tremendous share, although in reality a good part of this stress is on the groundwater, not considered in this analysis.

Contribution from melting of glaciers

The contribution of glaciers to the stream flows is critical in the Indus basin as it equals 91% at Danyour bridge, 64% at Tarbela dam and 90% at Kotri (Fig. 4). Fortunately, the contribution from glaciers is dispersed in the Indus basin as it is available all the year round, although it is greatest between June to September (Fig. 5). The particularly high values of this contribution at Kotri (90%) can be explained by viewing the monthly values. However, the canal withdrawals are all the year round, in particular during the low flow season when contribution of glaciers is small. Hence the relative contribution of glaciers is greater after withdrawals from canals as at Kotri. As discussed earlier the results indicate that glaciers apparently buffer against inter-annual variability of rainfall. As shown in Table 5, annual streamflow contributions from glaciers have a smaller inter-annual coefficient of variation than annual flows generated by rain and thus tend to smooth the inter-annual variability of total annual streamflow. Immerzeel et al. (2010) have also indicated that upstream snow and ice reserves of the Indus basin, important in sustaining seasonal water availability, are likely to be affected by climate change.

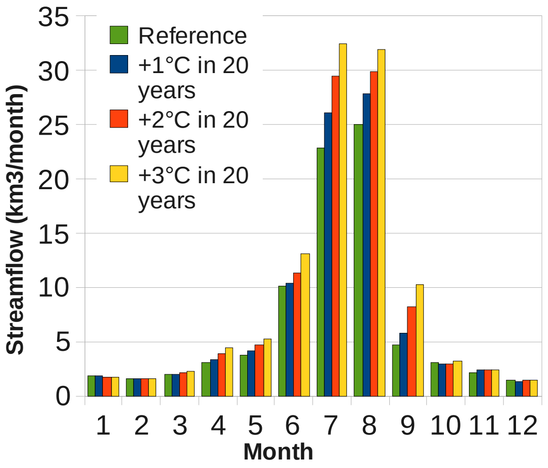
Table 5: Components of annual streamflow at Tarbela dam as simulated for the period 1982- 2002, Indus basin

Parameter	Tarbela dam		
	Total	Rainfall/ runoff	Glaciers
Average contribution, km^3 / year	73.7	26.5	47.2
Coefficient of variation	14%	28 %	15 %



Danyour bridge

Tarbela dam



Sukkur Barrage

Fig.4 Average monthly contribution of glaciers at some important locations in the Indus basin, as simulated for the period 1982-2002.

Analysis of Possible Scenarios

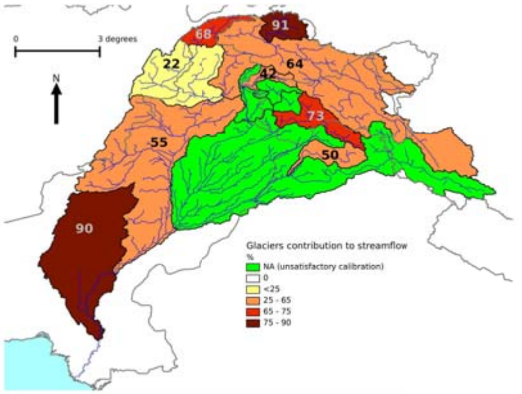
Increase in temperature

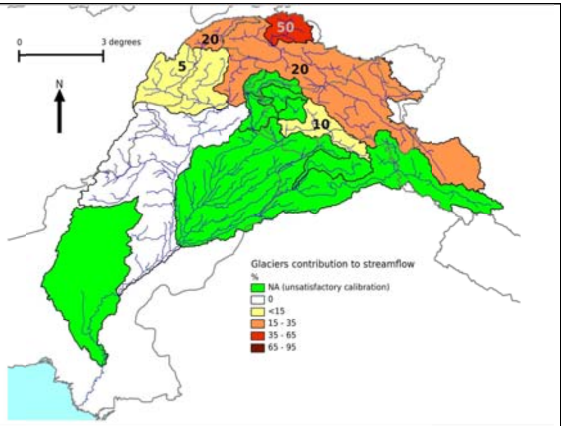
The report by Christensen et al. (2007) from the Intergovernmental Panel on Climate Change (IPCC) indicates that in the Tibetan region the temperature increase at the end of the century could be +3.8^{O}C. ICIMOD (2009) also provides information of the same order and as such the scenarios considered here were based on the same trend. More precisely, the following trends were considered:

i. an increase of 1°C after 20-years, i.e., a rate of +0.05°C/year,
ii. an increase of 2°C after 20-years, i.e., a rate of +0.10°C/year,
iii. an increase of 3°C after 20-years, i.e., a rate of +0.15°C/year.

The last scenario should be considered as the extreme scenario. As calibration of the glaciers parameters was based solely on observed streamflow data, we only analyzed simulated streamflows and not, for instance, on variations in glaciers' area. In each scenario, the temperature was raised gradually every year. Rise in temperature increases the quantity of snow and ice melt in the glaciated areas and thus augments the streamflows. However, the impact decreases from upstream to downstream, as (i) enhanced contribution from rainfall dilutes flows from glaciated areas, and (ii) increased temperature also leads to greater evapo-transpiration in the plains and thus smaller streamflows.

The amount of extra flows is quite significant both at the Tarbela dam and the Sukkur barrage (Table 6). As the glaciers contribution is high during the high flow season, the streamflow and the risks of additional floods, especially at Sukkur barrage are high during May to October (Fig. 5).





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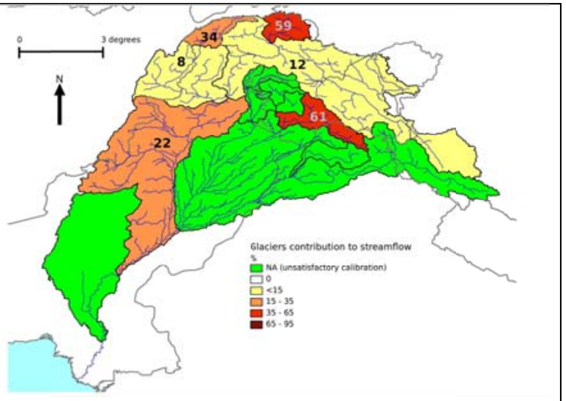

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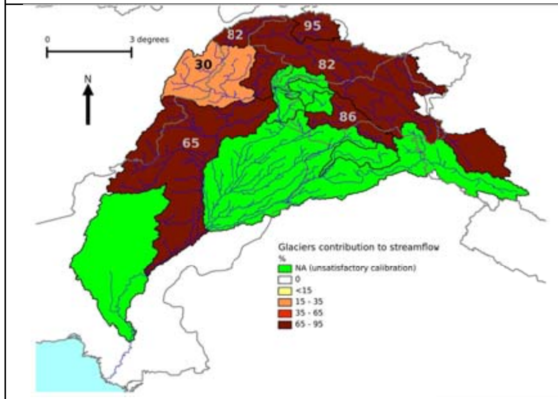

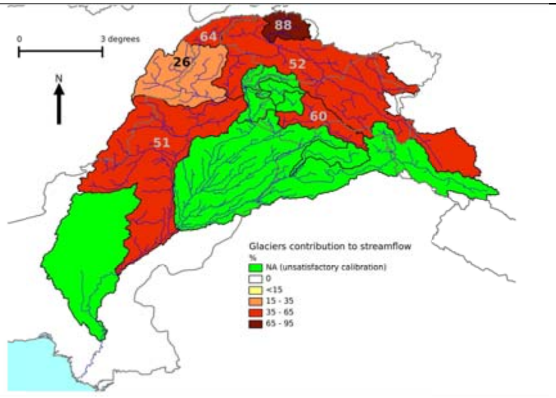

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Table 6: Simulated average change in annual streamflow at selected locations of the Indus basin when temperature increases gradually over 20 years, as compared to the reference scenario.

Change in temperature	Inflow to Tarbela dam, km^3 /year	Flow at Sukkur barrage, km^3 /year
+1° C over 20 years	+6.6 (+9%)	+8.1 (+10%)
+2° C over 20 years	+15.2 (+21%)	+18.4 (+22%)
+3° C over 20 years	+22.6 (+31%)	+28.5 (+34%)

Potential Opportunities and Threats

The extra water from the glaciated areas in the short to medium term presents a set of potential opportunities and some serious threats. The extra water can be successfully used for intensification of the surface water use, augmentation of the groundwater aquifers and thus intensification of agriculture and improvement of land and water productivity.

i. *Surface Water Resources:* The extra water from the glaciated areas presents a real good opportunity for the water scarce Indus basin, especially in the Pakistan part. As the existing storages are almost fully utilized, it shall be worth consideration of early completion of the on-going large storage projects at Chashma and other suitable locations. The plans may also be developed for extending the irrigation commands beyond Punjab which receives the largest share of irrigation waters. The following strategies are worth consideration:

   a. This extra water could be captured by additional reservoirs/dams, both small and large reservoirs. This water may be used locally or in the context of trans-boundary agreements between the riparian countries. Water storage, in its various forms, provides a mechanism for dealing with variability (and extra flows) which, if planned and managed correctly, increases water security, agricultural productivity and adaptive capacity (McCartney and Smakhtin, 2010).

   b. *Threat of Floods*: The Pakistan part of the Indus faces a serious threat of additional flood volumes reaching the plain areas (command areas of Tarbela dam, Sukkur barrage etc.) during the high-flow monsoon season. The recent floods in Pakistan may be considered as an indicator of the looming future. Rather than coping with the floods on ad-hoc basis, comprehensive flood management strategies comprising both of high level structural interventions and intensive adaptive and flood mitigation strategies need to be put in place to avoid large scale hardships to the populations and loss of lives and infrastructure facilities. As Indus basin is presently nearing closure, new policies should be devised to allocate water to meet the environmental water demands in the delta regions of the Indus which shall also help in checking the fast spread of the salinization and loss of inland fisheries, wetlands and bio-diversity.

   c. The increased flows in May and June (early melting of snow and glaciers) could be the most beneficial in terms of water uses as this happens just after the dry season. Technically and financially, this presents a good possibility to capture the magnitude of this extra flow at this time. This additional water shall be highly useful for irrigation of rice nurseries, and short-duration pulse and vegetable crops and more importantly for satisfying the very high demands from the domestic and industrial sectors during the hot summer season.

ii. *Groundwater resources:* Over the last 50 years, groundwater has become an important source of water for irrigation. The need to produce more food in the near- to medium-term within the available water resource constraints, compounded by the challenges and uncertainties associated with climate change strongly points towards increased and more efficient use of groundwater as one of the key solutions. The northwestern regions of the Indus basin are witnessing an unprecedented growth in ground water use (Sharma et. al., 2010). By virtue of its nature, groundwater presents an excellent opportunity for augmenting the recharge during the high availability period and a planned use during the low/ no availability of the surface supplies. Managed Aquifer Recharge (MAR) (Gale et al., 2007) is the practice of purposefully recharging aquifers via surface spreading, or through wells and dykes - for subsequent utilization. Large regional programs in the basin and adjacent areas can be successfully implemented with the extra water made available through melting of snow and glaciers upstream.

iii. *Improving land and water productivity:* The Indus basin meets a significant part of the food requirements of both Pakistan and India and is thus critical for South Asian regional food security. It is true that productivity levels of both rice and wheat are already high in the Indus basin. However, the analysis reveals that high productivity is limited to a rather narrow region of the Indian and Pakistan Punjab and the vast regions outside this food-basket continue to have low water and land productivity. Sharma et al. (2010) and Cai and Sharma (2010) showed that the bright spot for both rice and wheat in Indian Punjab and adjacent areas , with only 5 per cent of the IGBs' area cropped to rice and wheat has high water productivity of US\$ 0.190/m^3 . If the basin average of US\$0.131/ m^3 could be increased to the same as in bright spots, the basin could use 31% less water for the same production or increase production by 31% with the same amount of water. Presently, there are many constraints to achieving this potential, but with additional supplies of surface and groundwater, there are clearly possibilities to increase land and water productivity of the existing cereal crops, diversify the agricultural systems to meet the changing income and diet patterns and thus make the regional food security more sustainable.

Conclusions

The Indus basin in South Asia is one of most depleted transboundary basin with most of its water (~95%) being used for mega irrigation projects and through exploitation of groundwater. Surplus food produced in this basin meets the food deficits of several other adjoining basins and is thus crucial for regional food security. However, the Indus River- especially in the upper reaches, receives a significant part of its streamflows through melting of snow and glaciers. Existing studies show that these glaciers are retreating with serious impacts in the medium and long term basis. Results from the Water Evaluation and Planning (WEAP) model with a special sub-routine for the glacier melt showed that the contributions from the catchments with large presence of glaciers shall change. The prospective scenarios of $+1^o$ C to $+3^o$ C increase in temperature over a 20-year period predicted an increase of +9 to +31% flows at Tarbela dam and +10 to +34% at Mangla dam in Pakistan. These additional flows present a set of potential opportunities and serious threats for the water and agriculture development planners in the region. In the short term large investments need to be made in water infrastructure to use these supplies for additional food production, extend the command areas and allocate additional water resources to meet the ecosystem requirements. This may be achieved through construction of small and large storage structures and sharing of water among the riparian countries and also through large scale managed aquifer recharge schemes for augmenting the depleted groundwater aquifers. There may also be enhanced threat of floods during the high flow season, especially in the upper reaches of the basin, which needs to be managed properly to minimise the losses of lives, infrastructure facilities and the agricultural production.

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