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The Indus basin in the framework of current and future water resources management

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The Indus basin in the framework of WRM

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Abstract

The Indus basin is one of the regions in the world that is faced with major challenges for its water sector, due to population growth, rapid urbanisation and industrialisation, environmental degradation, unregulated utilization of the resources, inefficient water use and poverty, all aggravated by climate change. This paper gives a comprehensive listing and description of available options for current and future sustainable water resources management (WRM) within the basin. Sustainable WRM practices include both water supply management and water demand management options.

1 Introduction

The Indus river basin is one of the most depleted basins in the world (Sharma et al., 2010). During certain periods of the year, water even doesn't really reach the sea any more, making it a closing basin (Molle et al., 2010). Already today it faces large problems with respect to water resources. These will only become more challenging in the next decades, due to population growth, rapid urbanisation and industrialisation, environmental degradation, inefficient water use and poverty (economic water shortage), all aggravated by climate change.

Different aspects of the water cycle in the Indus basin have been the subject of several studies, e.g. hydrology and available water resources (Winiger et al., 2005; Archer, 2003; Immerzeel et al., 2010; Kaser et al., 2010), the impact of climate change on glaciers and the hydrological regime (Akhtar et al., 2008; Immerzeel et al., 2010), agricultural water demands and productivity (Cai and Sharma, 2009; Cai and Sharma, 2010), groundwater management (Kerr, 2009; Qureshi et al., 2009; Scott and Sharma, 2009; Shah et al., 2006), reservoir sedimentation (Khan and Tingsanchali, 2009), ecological flows and the Indus delta (Leichenko and Wescoat, 1993), water policy (Biswas, 1992; Miner et al., 2009; Shah et al., 2009; Shah et al., 2006; Sharma et al., 2010) and water resources management (Archer et al., 2010; Qureshi et al., 2009).

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Within the two latter publications the major challenges facing the Indus basin were described, as well as recommendations for sustainable water management. However, both papers have certain limitations. They both focused only on Pakistan, although 40% of the basin's surface area is located within 3 other countries. Qureshi et al. (2009) focused on groundwater. The recommendations for sustainable water management within (Archer et al., 2010) were far from complete, as not all available options were accounted for. This paper gives a comprehensive listing and description of all available water resources management options and does not restrict itself to the Pakistani part of the Indus basin. Especially the Indian part of the basin is also included in the analysis.

2 The Indus basin

The Indus basin is located in 4 countries, of which the largest part in Pakistan, and substantial upstream parts in India, China and Afghanistan (Table 1). More than 40% is located at an elevation higher than 2000 m a.s.l. The total original basin – as defined by the International Water Management Institute (IWMI) – is displayed in Fig. 1. However, the modern Indus basin is smaller, as the Sarasvati River (or Ghaggar River) flowing through the Thar desert in Indian Rajasthan, instead of flowing to the Indus river, now flows directly to the Arabian Sea respectively dries up in the Thar desert. Within this paper it will therefore be referred to the modern Indus basin, e.g. in Table 1.

Of a total population of about 193 million, Pakistan accounts for 72% and India for 23%. Another 5% live in the Afghani part of the basin, and the Chinese population is very little due to the rough Himalayan landscape character of this part of the basin. Of the irrigated area about 74% is located in Pakistan and about 24% in India. The Indus Basin Irrigation System (IBIS) is the largest irrigation system in the world. Water demands are thus by far the highest in Pakistan followed by India. The focus of this paper will therefore be one these two regions.

The wettest regions of the Indus basin are on the southern slopes of the Himalaya-Karakoram-Hindu kush (HKH) mountain range (Fig. 2). The high mountain ranges in the north of the basin – like Ladakh in India – are very dry, as well as the lowlands. The aridity index within the basin ranges from humid to hyper-arid. The glacial area is very large, i.e. 37 134 km^2 according to the DCW database (Raup et al., 2000). Within the GLIMS-Database (Armstrong et al., 2005) glaciers from India and Pakistan are missing. However, other sources that refer to this database indicate within the Indus basin a glacial area of about 22 000 km^2 (Immerzeel et al., 2010) or 20 325 km^2 (Kaser et al., 2010).

The major agricultural zones are located in the Pakistani and Indian provinces of Punjab (Fig. 3). Also the Sindh province in Pakistan is an important agricultural area. In these regions the major irrigation system is located. Irrigated agriculture currently accounts for more than 90% of blue water requirements in the Indus basin. Large regions within the basin – with extensive agriculture – are rainfed.

3 Major challenges

3.1 Introduction

Major challenges are foreseen for the water sector in the Indus basin. The region is under extreme pressures of population and poverty, unregulated utilization of the resources and low levels of productivity (Sharma et al., 2010). Population within the basin is projected to increase – with resulting higher water demands – and changes in water availability are predicted (Archer et al., 2010). Whether the effect of climate change on water resources will have a positive or negative effect on water resources remains uncertain. Following gives an overview of challenges for the Indus basin:

- Population increase and increased urbanisation and industrialisation, resulting in higher water demands for domestic and industrial purposes, food production and energy.

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- Unregulated utilization of resources; a shift from surface water to groundwater use resulting in rapid depletion of groundwater resources – an observation made for both the Indus and Ganges basins.
- Low water productivity in food production.
- Declining reservoir storage due to sedimentation.
- Water logging and salinity, loss of productive agricultural land, land degradation, contamination of surface and groundwater resources.
- Change in water availability due to climate change.
- Increase in environmental flows to sustain ecosystems within the rivers and the Indus delta, but also to prevent further salt water intrusion in the delta.
- Tension between riparian countries.

3.2 Water resources changes and climate change

Water from the sparsely inhabited upstream mountains in the Indus basin is essential for the densely inhabited semi- to hyper-arid lowlands (Fig. 2) with its extensive irrigation system. In many basins with mountainous regions the seasonal storage of water in snow and ice is very important for the lowlands so that water resources management analyses need to be conducted on at least a seasonal level (Vanham et al., 2008). Immerzeel et al. (2010) showed that meltwater is extremely important in the Indus basin. They showed that in the Indus the difference between basin precipitation (415 mm, Table 2) and net irrigation demand (908 mm) is extremely high. For the present day climate discharge generated by snow and glacial melt is 151% of the total discharge naturally generated in the downstream areas. About 40% of the meltwater originates from glaciers, 60% from snowpack. Also Kaser et al. (2010) stresses the importance of glacial melt water to the Indus flow. An overview on hydrological regimes in the Indus basin is given by Archer (2003):

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– A nival regime at middle altitudes with flow dependent on the melting of seasonal snow. The greatest contribution to total flow comes from this regime.

– A glacial regime at very high altitudes with river flow closely dependent on summer temperatures.

– A rainfall regime dependent on runoff from rainfall mainly during the monsoon season. This regime dominates on the southern foothills of the Himalayas (Fig. 2) and also over the plains but with much reduced total amounts.

Climate change will definitely affect the temporal and spatial availability of water resources, however the effects in the Indus basin remain uncertain. A listing of potential effects and studies conducted on the three hydrological regimes is given in Archer et al. (2010). Also Immerzeel et al. (2010) indicates that upstream snow and ice reserves of the Indus basin, important in sustaining seasonal water availability, are likely to be affected substantially by climate change, but to what extent is yet unclear. A new study by Scherler et al. (2011) actually indicates that debris coverage may be a missing link in the understanding of the decline of glaciers in the HKH. Controversy about the current state and future evolution of Himalayan glaciers has been stirred up by erroneous statements in the fourth report by the IPCC. According to Scherler et al. (2011), glaciers in the Karakoram region are mostly stagnating. However, glaciers in the Western, Central, and Eastern Himalaya are retreating. Half of the studied glaciers in the Karakoram region are stable or even advancing, whereas about two-thirds are in retreat elsewhere throughout High Asia. This is in contrast to the prevailing notion that all glaciers in the HKH are retreating. This stresses the uncertainty in future water availability forecasts for the Indus basin and the need for further research.

3.3 Increase in water demands

Water demand increases for domestic and industrial purposes, food production and energy, relate primarily to the predicted population increase in the basin, associated with

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an increase in urbanisation and industrialisation but also an increase in living standards. The population of Pakistan, currently at 185 million, is projected by the UN (UN, 2011) to increase to 246 million in 2025 and 335 million in 2050 (medium population estimates). For 2050 the different population growth trajectories range from a low estimate of 293 million to a high estimate of 459 million. Also in the Indian part of the basin a population increase is predicted. In the dominant Indian agricultural province of Punjab, the current population of 27 million (60% of the Indian population in the Indus basin, Table 1) is projected to increase to 29 million in 2025 and 28 million in 2050 (average variant), or to stabilise at 29 million for 2025 and 2050 (high variant) (Mahmood and Kundu, 2008). About 10 million people live in the Afghani part of the Indus basin (Table 1). The UN forecasts a growth of the national population from currently 29 million people to 45 million in 2025 and 74 million in 2050 (medium population estimates). For 2050 the different population growth trajectories range from a low estimate of 66 million to a high estimate of 82 million. Kabul is located in the Indus basin, and its population has tripled in size since late 2001, to approximately 4.5 million people, making it perhaps the world's fastest-growing city in the last eight years (Lashkaripour and Hussaini, 2008; Setchell and Luther, 2009). The number of people that live in the Chinese part of the basin is extremely low.

3.4 Shift from surface water to groundwater use

During the last decades there has been a shift from surface water resources to groundwater resources within the Indus basin, for irrigation but also for domestic and industrial purposes. On demand availability of groundwater has transformed the concept of low and uncertain crop yields (before predominantly fed with surface water) into more assured crop production (Qureshi et al., 2009). The availability of inexpensive drilling technologies allows even poor farmers to access groundwater. Over 80% of the groundwater exploitation in Pakistan takes place through small capacity private tube wells. During the last decades, the number of tube wells in the main agricultural zones of the Indus basin has increased dramatically. By the early 1960s, an estimated 23% of

Pakistan's land suffered from waterlogging and crop root zone salinity. Initial response was through the SCARP-project, which aimed at lowering the groundwater table by means of the instalment of 13 500 publicly owned and operated tubewells (Qureshi et al., 2008). However, the main change came by the independent decision of farmers to use groundwater as a substitute or to supplement for direct surface water irrigation.

The IBIS is a gravity run system with minimum management and operational requirements (Qureshi et al., 2009). Its operation is based upon a continuous water supply and is not related to actual crop water requirements. Despite significant increases in storage capacities, it is essentially a supply-based system. It can thus not accommodate changing water demands during the crop season. Groundwater exploitation has enabled many farmers to supplement their irrigation requirements and to cope with the uncertainties of surface supplies. The access to the natural buffer of groundwater resources has helped poor farmers not only to increase their production and incomes, but also enhance their opportunities to diversify their income base and to reduce their vulnerability against seasonality of agricultural production and external shocks such as droughts.

However, current groundwater exploitation rates are unsustainable in many regions. There is a large imbalance between extraction and replenishment. Water tables are falling at alarming rates, both on the Pakistani (Qureshi et al., 2009; Tiwari et al., 2009) and Indian sides (Rodell et al., 2009; Sundarajan et al., 2008; Tiwari et al., 2009). For the Indus basin Tiwari et al. (2009) estimated a change (loss) of terrestrial water storage of about 10 $km^3 yr^{-1}$ between April 2002 and June 2008. Excessive lowering of the groundwater table has made pumping more expensive. As a result, many wells have gone out of production, yet the water table continues to decline and salinity increases.

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4 Recommendations in the framework of water resources management (WRM)

Literature on solutions and alternative policy options for future sustainable WRM in the Indus Basin and India in general include (Gupta and Deshpande, 2004; Kumar et al., 2005; Sharma et al., 2010; Thakkar, 2008). According to Sharma et al. (2010) the needs are: (1) development policies that are regionally differentiated to ensure resource sustainability and high productivity; (2) immediate development and implementation of policies for sound groundwater management and energy use; (3) improvement of the fragile food security and to broaden its base; and (4) policy changes to address land fragmentation and improved infrastructure. Meeting these needs will help to improve productivity, reduce rural poverty and improve overall human development.

Sustainable WRM practices include the management of water supply and the managing of water demands. Applicable practices for the Indus basin are given in Table 2 and discussed in the following paragraphs.

4.1 Water supply-availability management

4.1.1 Water storage, rain water harvesting and artificial ground water recharge (AGWR)

Due to the monsoonal characteristic of precipitation and the seasonal character of melt water flow in the basin as well as the seasonal changes in crop water demands, the storage of water and rain water is essential. In the past large reservoirs have been built (e.g. the Tarbela Dam) and farmers gradually shifted from surface water usage to groundwater for irrigation to cope with these natural conditions. The use of the natural buffer of the groundwater reservoir has however led to an unsustainable fall of the groundwater table, draining aquifers faster than natural processes can replenish them (Qureshi et al., 2009; Rodell et al., 2009; Tiwari et al., 2009).

Both multipurpose dams and decentralised rainwater harvesting are essential in the Indus basin. Rainwater harvesting also prevents soil erosion. It can focus on

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(1) capturing water for domestic use (e.g. by rooftop rainfall collection); (2) replenishing green water (e.g. through stone bunds on the contour line); or (3) increasing blue water availability locally (e.g. through small check dams that increase recharge to the groundwater or store water in small reservoirs). Decentralised water harvesting is definitely an important factor for poor communities. Kumar et al. (2006) however indicates limitations of this practice. The storage of water should be implemented in the framework of IWRM, in order to avoid massive disproportional storage in upstream parts of the basin on the expense of downstream regions. Environmental flows should be maintained.

If suitable aquifers are accessible, AGWR has many benefits when compared to other storage options, e.g. low evaporation rates, natural treatment and storage capacity to buffer seasonal supply and demand variations. Basically the aquifers in the Indus basin have large reservoir capacities. The observed gradual depletion of the ground water table can be (partly) compensated by AGWR. Again, this storage has to be conducted in the framework of IWRM.

Natural floodplains of the Indus and its tributaries should be maintained as much as possible. Due to increased population pressure these floodplains are gradually more inhabited and inundation space for the rivers during monsoon season becomes sparser. With sustainable floodplain management, large water quantities of monsoon floods could be temporarily stored and groundwater reservoirs thereby replenished.

4.1.2 Reservoir management

A decline of reservoir storage due to sedimentation is observed in the Indus basin. The Indus river and its tributaries carry a very high sediment load which has seriously affected the storage capacity of the two principal control dams, Tarbela and Mangla, on the Indus and Jhelum (Archer et al., 2010). For more details on handling the sedimentation problem it is referred to the latter publication.

Reservoir management needs to be sophisticated to maximize yield from a given catchment and storage combination; the desire to minimize evaporative losses, and the demand for optimum water quality outcomes. There should be a multipurpose controlled management for hydropower generation, other uses and flooding control.

4.1.3 Water quality conservation and investment in wastewater infrastructure

The conservation of water quality and investment in wastewater infrastructure are a necessity in order to maintain the already quantitative scarce water availability. This includes the implementation of water pollution prevention strategies (legislation, polluting taxes, ...) for the different polluters (Kumar et al., 2005). Society and individuals in the riparian countries should have a greater knowledge and ability to bring about the required changes and mentality.

Deteriorating groundwater quality is also a big issue in the Indus basin. The quality of groundwater in the basin varies from fresh to saline. Salinity remains a serious problem especially in the irrigated areas of the Sindh province, where much of the groundwater is naturally saline (of marine origin) and thus unsuitable for irrigation as a substitute for canal water. The joint management of surface and groundwater is a key requirement. Farmers need to be educated about suitable crops that can be grown under the conjunctive management of surface water and groundwater resources (Qureshi et al., 2009). In the Punjab provinces farmers largely rotate crops of wheat and paddy over the year. Since the Green revolution these intensive monocultures of wheat and paddy have displaced other crops. The immediate impact of intensive monoculture cultivation practices is seen on the soils, farmers have started using much larger doses of chemical fertilisers and pesticides in the last 50 yr. After Andhra Pradesh, per hectare application of fertilisers is the highest in Indian Punjab. These substances have contaminated water bodies. Additionally groundwater in the Punjab is contaminated by urban runoff, seepage from contaminated industrial sites, and industrial discharges (Singh, 2001). A more green approach in farming is required and the policies that impose them. Quantification and timing of fertilisation has to be managed carefully in order to avoid water pollution.

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4.1.4 Use of alternate water resources

Alternate water resources include the recycling of wastewater and desalination. Since both domestic and industrial water demands will increase substantially in the basin, so will the potential for recycled wastewater. A general discussion on recycling of wastewater in India is given by Kumar (2009). In the Sindh Province there are substantial deposits of brackish water in the underground. As the cost of desalinisation is falling (Kumar et al., 2005), the prospects of desalinating brackish water – and also seawater for the coastal communities – are becoming more attractive. Studies done in Pakistan and India have also shown that brackish water can be used for irrigating different crops under different soil types and environmental conditions (Qadir et al., 2001; Sharma and Rao, 1998).

4.1.5 Land use planning and soil conservation

These practices include a change of land use, reforestation and the reduced sealing of areas in order to prevent erosion and high surface flow coefficients.

4.2 Water demand management

4.2.1 Managing conjunctive use of surface and groundwater

The explosion in groundwater use has led to an unsustainable depletion of groundwater resources. Due to the enormous number of wells installed by small farmers, licensing is not the best option to resolve this, as observed in both Pakistan and India (Qureshi et al., 2009). The conjunctive use of surface and groundwater by farmers should be managed as described by Qureshi et al. (2009).

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4.2.2 Rehabilitation and modernization of existing infrastructure

Existing infrastructure for domestic, industrial and agricultural water supply should be rehabilitated and modernised. Leakage reduction in domestic water use should be addressed. A major task is adapting yesterday's irrigation systems to tomorrow's needs. Modernization, a mix of technological and managerial upgrading to improve responsiveness to stakeholder needs, will enable more productive and sustainable irrigation. The average irrigation efficiency in India is about 40% for surface and 60% for groundwater irrigation (Singh, 2007). Irrigation efficiencies in the IBIS are also very low (Archer et al., 2010). An increase in irrigation efficiency (e.g. by installation of drip or sprinkler irrigation, by reducing irrigation canal leakage) can have a huge impact on reducing water demands.

4.2.3 Increasing water productivity (WP) for agriculture (irrigated and rainfed)

Gaining more yield and value from less water can reduce future demands for water, limiting environmental degradation and easing competition for water. Increasing the productivity of the rice-wheat (RW) system in the Indus basin is critical for food security. Average WP for rice and wheat in the Indo-Gangetic basin is 0.84 and 1.36 $kg\,m^{-3}$, respectively (Cai and Sharma, 2009, 2010). Approaches to increase water productivity include (1) providing appropriate quantum of fertiliser to the crop to realize yield potential; (2) cropping planning and diversification; (3) increasing the value per unit of water by integrating livestock and fisheries in irrigated systems; (4) appropriate timing and quantification of water delivery for the different growing stages of the plants; (5) in situ soil and water management and water harvesting techniques (bunds, terracing, contour cultivation, land levelling, etc.). At present crop yields are low in India (e.g. 1756 kg per ha for cereals during 2005–2006) as compared internationally (e.g. > 5000 kg per ha for cereals in France, Germany, USA and Japan in 1996). Cropping planning and diversification includes the growing of crops in regions where or at times of the year when ET requirements are lower.

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4.2.4 Economic instruments (e.g. water pricing)

According to Singh (2007), part of the reason for the low irrigation efficiencies is the highly subsidized price of irrigation water that encourages the excessive application of water to crops. An overview of potentials, problems and prospects for water pricing for irrigation is given by Reddy (2009), and particularly for the Indus basin by (Shah et al., 2009, 2006).

4.2.5 Restriction of water uses during drought periods

This is a practise which is for example applied in Australia. During drought periods, there is a restriction on watering the garden or washing the car.

4.2.6 Virtual water import-export

There are opportunities for trading agricultural products from water abundant and highly productive areas to water-short areas (virtual water trade). According to Verma et al. (2009), the state of Punjab is amongst the largest net virtual water exporters (total amount 20.9 $km^3\,yr^{-1}$) within India. Basically large amounts of crops produced are consumed elsewhere in the country, outside the Indus basin. Proponents of the virtual water trade argument that if certain policies – where farmers receive highly subsidized agricultural inputs (including water for irrigation) and are assured high prices for the wheat and rice they produce as in Punjab – were to be revised in favour of the wetter Indian states, water rich states would no longer have to import virtual water from water scarce states (Verma et al., 2009). Mekonnen and Hoekstra (2010) discuss the water footprint of wheat production in the Indus and Ganges river basins. Almost all wheat production (98%) in Pakistan comes from the Indus river basin. About 89% of India's wheat is produced in the Ganges (62%) and the Indus basin (27%). The total water footprint of wheat production in the Pakistani part of the Indus basin is 48 $km^3\,yr^{-1}$ (25% green, 58% blue, 17% grey). In the period 1996–2005, the blue water export to

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other countries from the Indus river basin was and 1 $km^3 yr^{-1}$. Since wheat is a low-value crop, one may question whether water allocation to wheat production for export in states such as Punjab is worth the cost (Mekonnen and Hoekstra, 2010). Especially for products that are exported out of the Indus basin, an evaluation of benefits (economically and livelihoods) to costs (depletion of water resources) should be made.

4.2.7 Changing food demand patterns and limiting post-harvest losses

Influencing diets towards more water-efficient food mixes, such as less meat can be a demand management practise. Diets can be influenced through advertising campaigns and appropriate pricing of foods to reflect the scarce resources used in food production (de Fraiture and Wichelns, 2010). The food requirements of diets based on meat from grain-fed cattle may require twice the water required to support vegetarian diets. A diet without meat requires an estimated 2000 l per day to produce, while a diet high in grain-fed beef requires 5000 l of water (Renault and Wallender, 2000). Thus, the potential to reduce pressure on water resources by changes in food consumption patterns seems high. However, in both rural and urban India, the demand for non-grain food crops (vegetables, fruits, oil crops, ...) and animal products (milk, chicken, eggs, fish, ...) is increasing (Amarasinghe et al., 2008). Increasing income and urbanization will further increase the demand for non-grain food products in the Indian and Pakistani diet.

Post-harvest losses can be reduced by improving transportation and storage infrastructure and systems. Estimates of agricultural produce lost in the steps between production and consumption are between 40% and 50% (Lundqvist et al., 2008).

4.3 International collaboration

For nearly 50 yr a relatively stable Indus Water Treaty (IWT) moderated competition for the Indus water between Pakistan and India (Miner et al., 2009). Rising demand for water in each nation could unsettle this stable relationship. For the benefit of their

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people, Pakistan and India could coordinate unilateral development and resolve issues rather than defer them.

5 Conclusions

The Indus river basin – shared by Pakistan, India, China and Afghanistan – is one of the most depleted river basins in the world. Irrigated agriculture is by far the most important water demand stakeholder, but water demands for domestic and industrial purposes are increasing, due to population increase, increased urbanisation and industrialisation and the rise in living standards. Also water demands for food production and energy will increase. Other challenges include the unregulated utilization of resources and a shift from surface water to groundwater use resulting in rapid depletion of groundwater resources. Food production is characterised by low water productivity. Reservoir storage is diminishing due to sedimentation. Water logging and salinity, loss of productive agricultural land, land degradation and the contamination of surface and groundwater resources are challenges as well as a predicted change in water availability due to climate change. A required increase in environmental flows to sustain ecosystems within the rivers and the Indus delta will put pressure on other demand stakeholders. These challenges can put tension between riparian countries.

Sustainable WRM practices to meet these challenges include both water supply management and water demand management options. A comprehensive listing and description of available options for the Indus basin within these two concepts is given.

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Table 1. Basic data on the modern Indus basin.

	Total (and % of basin area)	Country				Source
		Pakistan	India	China	Afghanistan	
Area (km^2)	920 445	60%	23%	9%	8%	
Elevation > 2000 m a.s.l.	40.6%	21.6%	57.5%	100%	67.1%	
Total population in 2005 (10^3)	192 896	72%	23%	0%	5%	GPWv3 dataset (CIESIN)
Population density in 2005 (persons km^{-2})	210	252	212	0.7	128	GPWv3 dataset (CIESIN)
Irrigated area (km^2)	184 584 (20%)	73.9%	23.8%	0.0%	2.3%	Siebert et al. (2005)
Glacial Area (km^2)	37 134 (4%)	43.9%	45.3%	10.0%	0.8%	Raup et al. (2000)
Annual precipitation (mm)	415	328	633	303	583	Hijmans et al. (2005)
Annual precipitation (km^3 or bcm)	382	182	132	26	42	Hijmans et al. (2005)
Annual precipitation volume per person (m^3)	1980	1308	2941	448 368	4456	

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Table 2. Sustainable water management practices applicable for the Indus basin.

Supply-availability increase	Demand management

– Water storage, rain water harvesting and artificial ground water recharge (AGWR).
– Reservoir management.
– Water quality conservation and investment in wastewater infrastructure.
– Use of alternate water resources:
  – Recycling of wastewater
  – Desalination
– Land use planning and soil conservation.
	– Managing conjunctive use of surface and groundwater.
	– Rehabilitation and modernization of existing infrastructure.
	– Increasing water productivity (WP) for agriculture (irrigated and rainfed).
	– Economic instruments (e.g. water pricing).
	– Restriction of water uses during drought periods.
	– Virtual water import-export.
	– Changing food demand patterns and limiting post-harvest losses.

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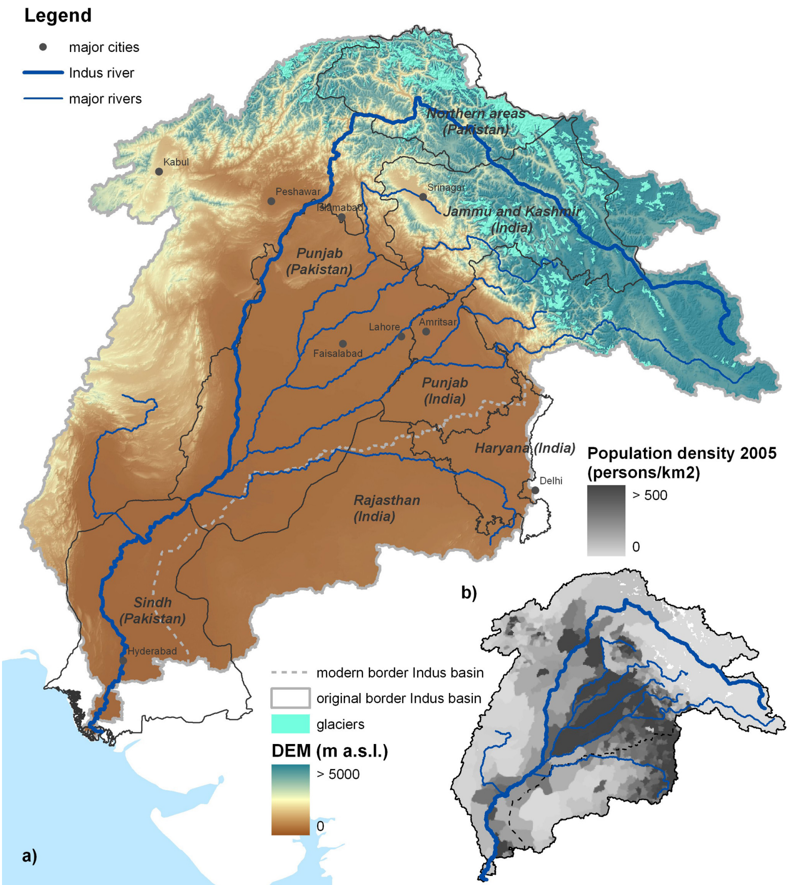

Fig. 1. **(a)** Overview of the Indus river basin within its original boundaries based upon topography, as provided by the IWMI, and with its modern day basin boundary; **(b)** population density (persons per km^2) in 2005 according to CIESIN (2005).

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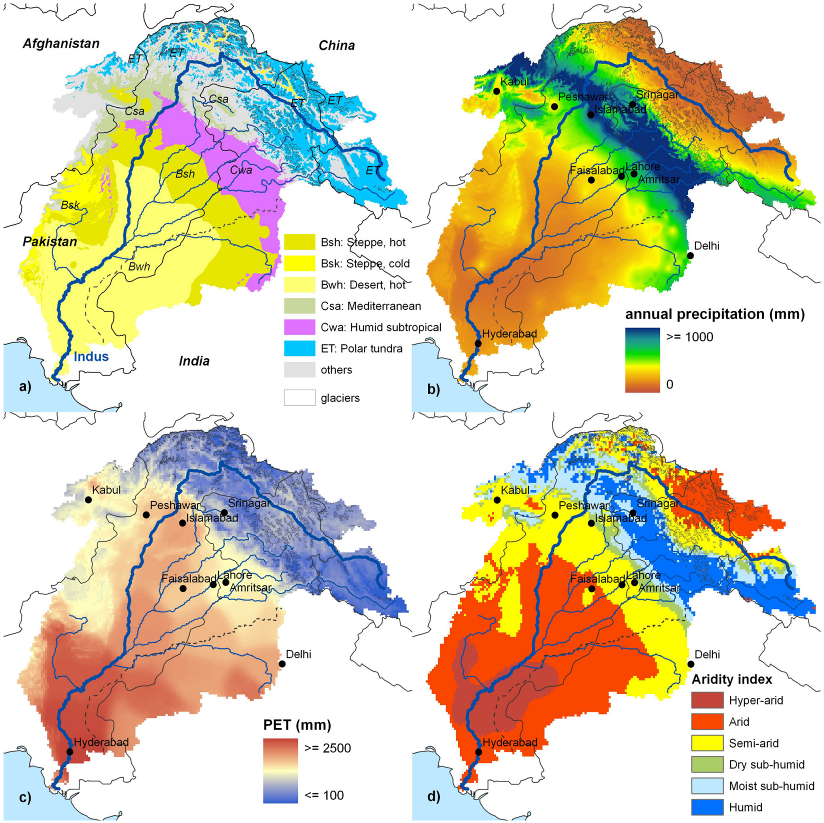

Fig. 2. Climatology within the Indus basin: **(a)** major climatic zones 1950–2000 – the Köppen-Geiger system of climate classification (Köppen, 1936) adapted according to Hijmans et al. (2005) by de Bie (2007); **(b)** average annual precipitation (mm) for the period 1950–2000, according to Hijmans et al. (2005); **(c)** average annual potential evapotranspiration PET in mm (interpolated surface from FAOClim-Database) calculated as ETo after the FAO Penman-Monteith equation (Allen et al., 1998); **(d)** aridity index (AI = PET/P) as defined by UNEP (1992).

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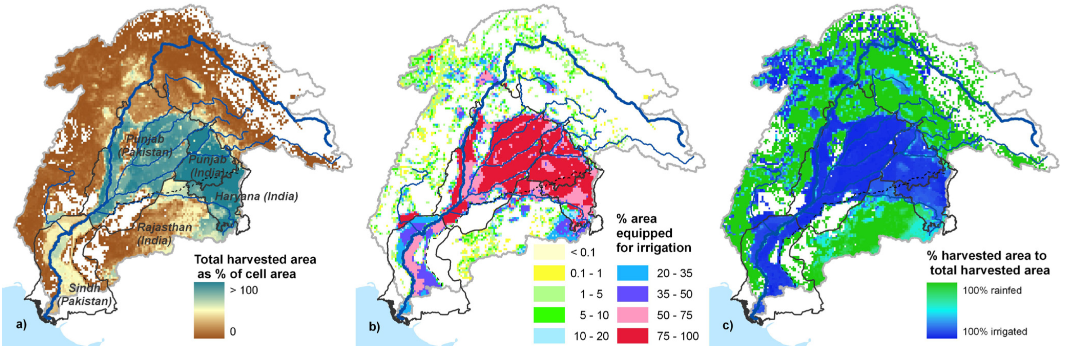

Fig. 3. Agriculture within the Indus basin: **(a)** total harvested area of both irrigated and rainfed crops as percentage of cell area (spatial resolution of 5 arc min (about 9.2 km at the equator)), representation of MIRCA2000-data (Portmann et al., 2010); **(b)** % of area equipped for irrigation (FAO-database, according to Siebert et al., 2005); **(c)** relative contribution (%) to total global harvested area by irrigated crops and rain fed crops, representation of MIRCA2000-data (Portmann et al., 2010).

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