Impact Assessment of Hydroclimatic Change on Water Stress in the Indus Basin

by
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Submitted to the Engineering Systems Division
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Abstract

Ninety percent of Pakistan's agricultural output is produced in fields irrigated by the Indus basin irrigation system, the world's largest network of canals, dams, barrages and tubewells. River flows, primarily fed by snow and glacial melt, are highly seasonal and fluctuate between intense floods and droughts. Built storage is relatively small, with withdrawals averaging at 70% of annual availability. Climate change, growth in sectoral water demands, and changes in water management infrastructure could have a profound impact on water stress in the coming decades. The interplay and contribution of these influences is explored using a model of the managed Indus River basin. To account for key hydro-climate shifts, I translate temperature rise and glacier cover scenarios into river runoff in 2050. I also project sectoral water demands to 2050. I then use an optimization model to estimate dam releases and project water stress to 2050. I find that climate change will cause decreases in peak river flows, but the changes in runoff will be comparable to current interannual variability. The most significant increase in water stress is caused by a scenario of 1-2.5°C warming and 1% annual glacial retreat. However, rises in demand have a greater impact on water stress than climate-induced changes in runoff which can be either positive or negative. The stabilization of global greenhouse gas emissions checks the rise in water demand and thus lowers future water stress. Effective adaptation options to an increase in water stress include building more storage capacity, relaxation of water allocation to allow interprovincial water trading, and adaptation of the cropping calendar to the natural hydrological cycle.

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Acronyms

BCM	billion cubic meters
CSIRO	Commonweath Scientific and Industrial Research Organisation
EPPA	Emissions Prediction and Policy Analysis
GCM	General circulation model
IPCC	Intergovernmental Panel on Climate Change
IRSA	Indus River System Authority
KPK	Khyber Pakhtunkhwah
MAF	million acre feet
MCM	million cubic meters
NARD	National Agro-Ecological Resources Database
NAS	National Academy of Sciences
NCAR	National Center for Atmospheric Research
PARC	Pakistan Agricultural Research Council
PMD	Pakistan Meteorological Department
PMF	probability mass function
PNAS	Proceedings of the National Academy of Science
WAPDA	Water and Power Development Authority
WRS	Water Resource Systems

1 MAF approximately equals 1233.45 MCM.

1 BCM = 1000 MCM

1 INTRODUCTION

The Indus river and its tributaries irrigate one of the world's most fertile and populous regions in modern day Pakistan and northwestern India. The rivers originate in the Western Himalaya, Karakoram and Hindukush mountains bordering the northwest of the Indian subcontinent. The upper Indus basin boasts the highest concentration of peaks above 8000 m in the world, including the K-2 (figure 2). The rivers flow through the Indian province of Punjab in the east and Pakistan's Khyber Pakhtunkhwa (KPK) province in the west, before coming together in Pakistan's province of Punjab. The Indus river forms a delta in the Sindh province before entering the Arabian sea in the south of Pakistan near Karachi (figure 1).

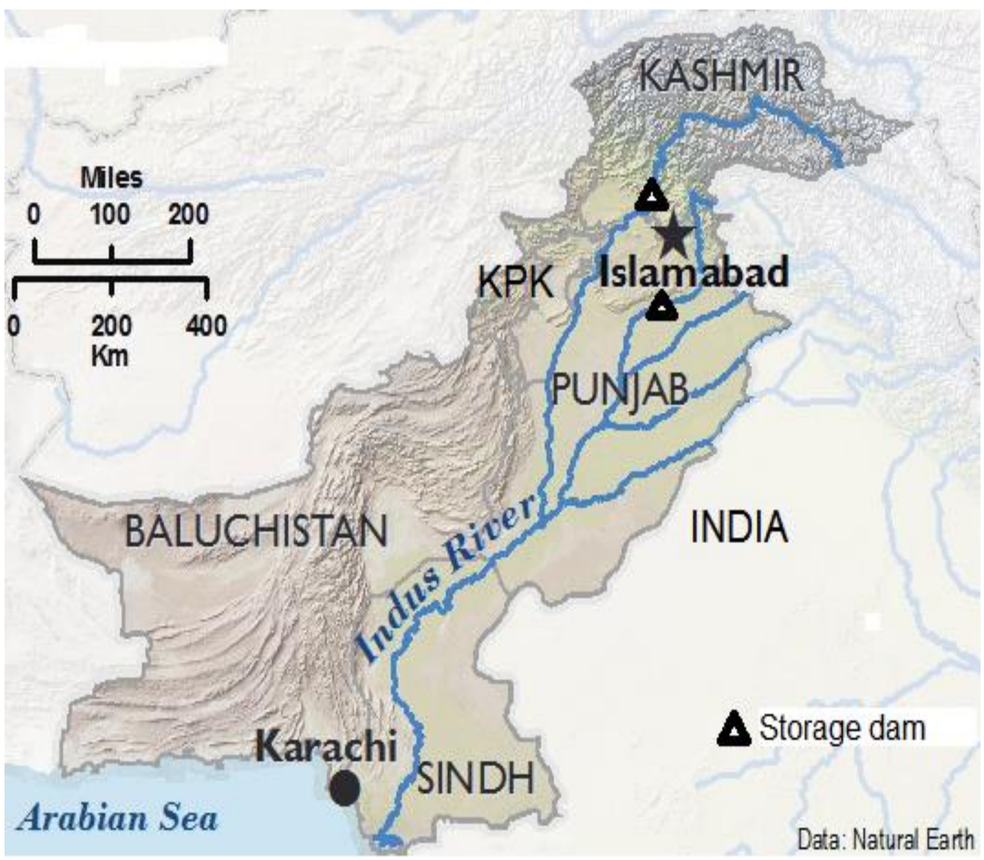


Figure 1: The geography of the Indus basin. Three western rivers, not shown, join the Indus from Afghanistan. (Source: http://nathazmap.com/news)

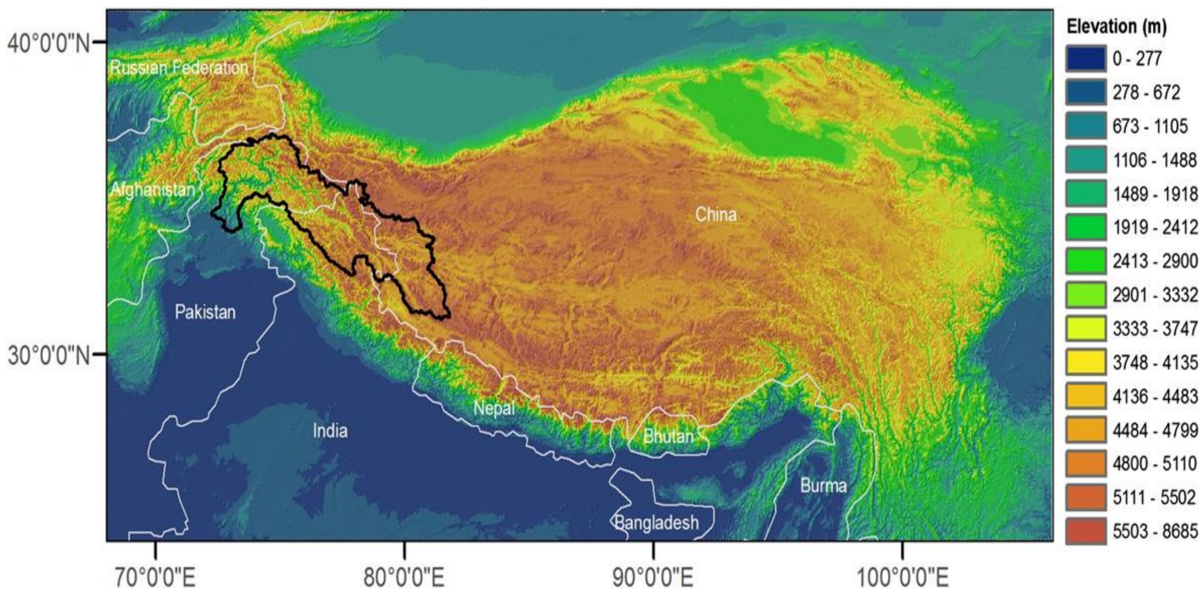


Figure 2: An elevation map of the Himalayan region in which the black polygon outlines the upper Indus basin. Source: Immerzeel et al. (2009).

More than two hundred million people live in the Indus basin today. This work focuses on the Pakistani portion of the Indus basin where about 170 million live. Agriculture employs 40% of Pakistan's labor force and directly contributes 22% to the GDP (World Bank, 2011). Yet, its climate is arid, with annual rainfall below 250 mm in the agricultural heartland of Punjab, Sindh and central KPK (Wildlife of Pakistan, 1994). Ninety percent of agricultural production takes place on irrigated land. The lush farmland of the Indus basin is flanked by the Balochistan desert to the west and the Cholistan desert in the east. Much like the Nile valley, Pakistan would have been a desert if not for the Indus river system. (See the satellite photo in figure 3 for an illustration.)

'Punjab' literally means five rivers, i.e. Indus, Chenab, Jehlum, Ravi, Sutlej and Beas. This river system is augmented by a vast and intricate network of irrigation infrastructure. Punjab is home to more than half of Pakistan's population and produces 60% of both the country's GDP and agricultural output. Northern Punjab is at the foothills of the Himalayas with relatively high rainfall and a temperate climate. However, central and southern Punjab are hot, semi-arid and flat agricultural plains, where vast acres of farmland are dotted with densely populated towns. Like the rest of the country, Punjab's farmers practice two major cropping seasons: *kharif* (April-September) and *rabi* (October-March). Wheat dominates the winter season, whereas cash crops like sugarcane and cotton are grown in the summer.

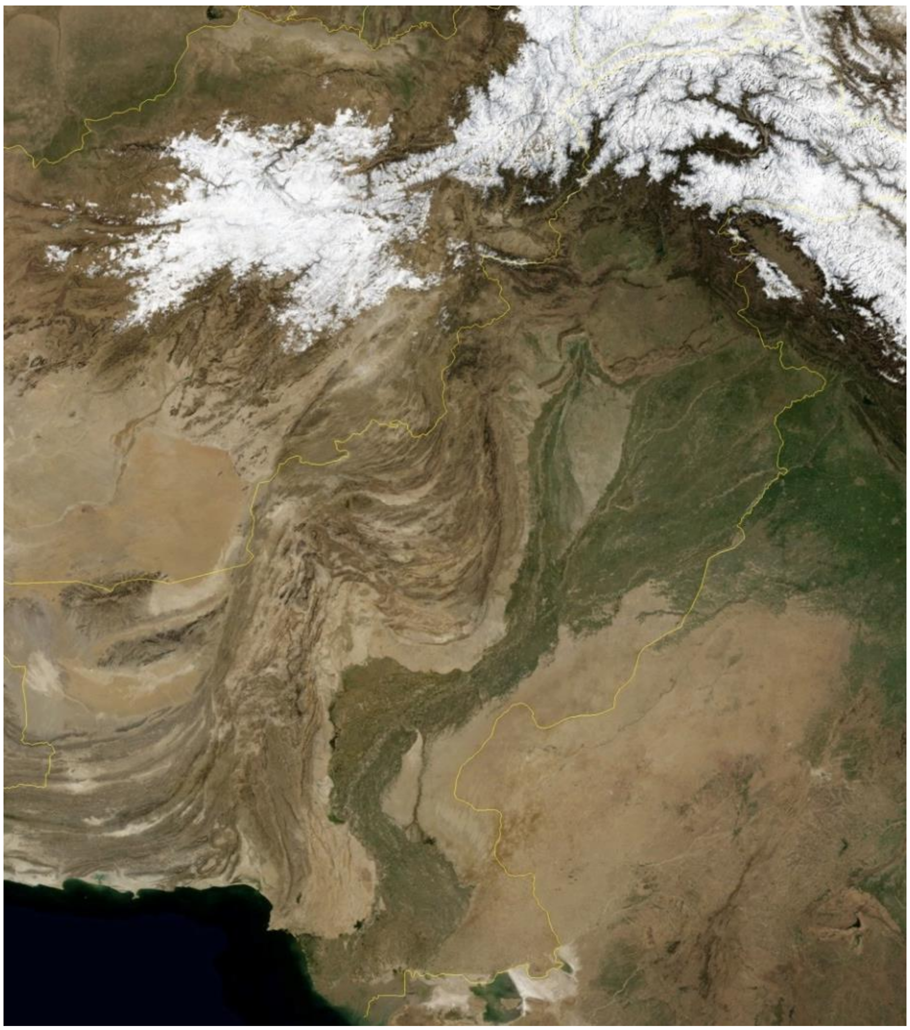


Figure 3: A satellite photo shows the Indus basin as a strip of green flanked by deserts on both sides. Notice also the glaciers in the north. Source: Briscoe and Qamar, 2007.

KPK in the northwest has relatively little arable land. Most of its landscape is dominated by mountains. However, the Peshawar valley is an important agricultural region with major population hubs.

Sindh is the most downstream province on the Indus river. In local languages the Indus is called "Sindh" – the province identifies itself with the river. While eastern Sindh is a desert, western and southern Sindh feature irrigated farmland with chronic problems of water-logging and salinity. Though the banks of the Indus host major towns like Hyderabad, Sukkur and Karachi, most of Sindh's population is rural.

Balochistan is Pakistan's largest province by area, though its harsh and arid landscape make it the most sparsely populated one (figure 4). With the exception of important towns like Quetta and Ziarat, the spread of the population makes the provision of essential services difficult. Consequently, Balochistan remains the poorest of Pakistan's provinces. The Sulaiman and Kirthar mountains along the Afghan and Iran borders feed a river system independent of the Indus basin hydrology. For this reason, I have not included Balochistan in the analysis that follows.

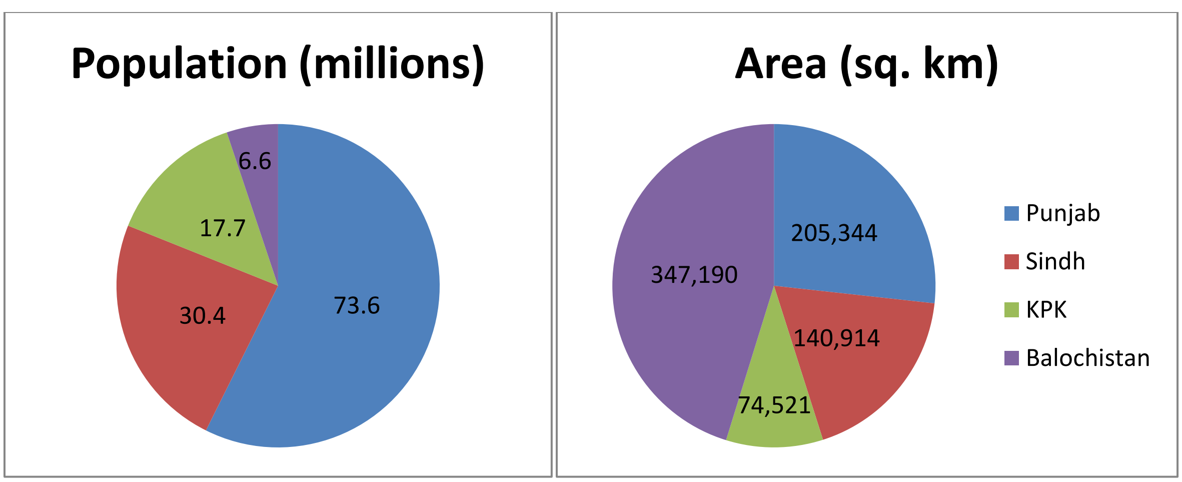


Figure 4: Pakistan's provinces by share of area and population. Source: Pakistan Bureau of Statistics 2012

1.1 Historical Background

One of the world's earliest civilizations developed 5200-4500 years ago on the banks of the Indus river. The Indus valley civilization was agrarian but developed large, architecturally complex urban centers. The Harappans as they are called, after the first excavated city of Harappa, did not attempt to control water resources by large-scale canal irrigation. Harappan agriculture was sustained by monsoonal rivers. Urbanism flourished in the western region of the Indo-Gangetic Plain for approximately 600 years, but since circa 3,900 years ago, the total settled area and settlement sizes declined, many sites were abandoned, and there was a significant shift in site numbers and density towards the east.

This decline of the Indus valley civilization was probably owing to climate change, claim Giosan et al. (2012) in the PNAS. The authors found that "fluvial landscapes in Harappan territory became remarkably stable during the late Holocene. This fluvial quiescence suggests a gradual decrease in flood intensity that probably stimulated intensive agriculture initially and encouraged urbanization around 4,500 years ago. However, further decline in monsoon precipitation led to conditions adverse to both inundation- and rain-based farming. As the monsoon weakened, monsoonal rivers gradually dried or became seasonal, affecting habitability along their courses." Forced to choose between building irrigation infrastructure and abandoning their settlements, it is thought the Harappans chose to relocate to upper Punjab, Haryana and Uttar Pradesh.

1.1.1 Colonial Era and the Building of the Indus Basin Irrigation System

The British built the canal system in western Punjab in the late nineteenth century. Punjab was a vital frontier between British India and the Russian Empire. Canal building was seen as “a civilizing lever… to induce roving predatory tribes… to take peaceful agricultural pursuits…” (Gilmartin, 1994). This British infrastructure relied on diversion barrages and not on storage dams. As an irrigation network emerged in arid western Punjab, the British transported large numbers of Punjabis from eastern Punjab westward. These settlers were given small landholdings and recruited in the army. This military-agricultural complex persists to this day, with Punjab dominating the Pakistani military and the military receiving generous gifts of land.

On the other hand, Sindh became agrarian only after the construction of the Sukkur Barrage in 1935. Sindh was thus the ‘latecomer’ in utilizing the Indus water. Benazir Bhutto, a former prime minister who hailed from rural Sindh, writes in her book *Reconciliation* (Bhutto, 2009):

“My grandfather had long struggled for the severance of Sindh from Bombay. The British said that the waterlogged, saline Sindh lacked sufficient revenues to be independently governed as a separate administration… My grandfather then initiated the Sukkur Barrage project to turn the arid lands of upper Sindh fertile. With the completion of the Sukkur Barrage, Sindh gained sufficient revenues for my grandfather to argue that Muslim Sindh be separated from Hindu India. He was successful, and Sindh once again emerged as a separate entity under British rule.”

The Indus basin irrigation system (figure 5) today has three major multi-purpose storage reservoirs, 19 barrages, 12 inter-river link canals, 45 major irrigation canal commands (covering over 18 million hectares), and over 120,000 watercourses delivering water to farms and other productive uses (Yu et al., 2013). The total length of the canals is about 60,000 km, with communal watercourses, farm channels, and field ditches running another 1.8 million km.

These canals are unlined and leaky, and operate in tandem with a vast and growing process of groundwater extraction from over a million private tubewells (Punjab Development Statistics, 2012).

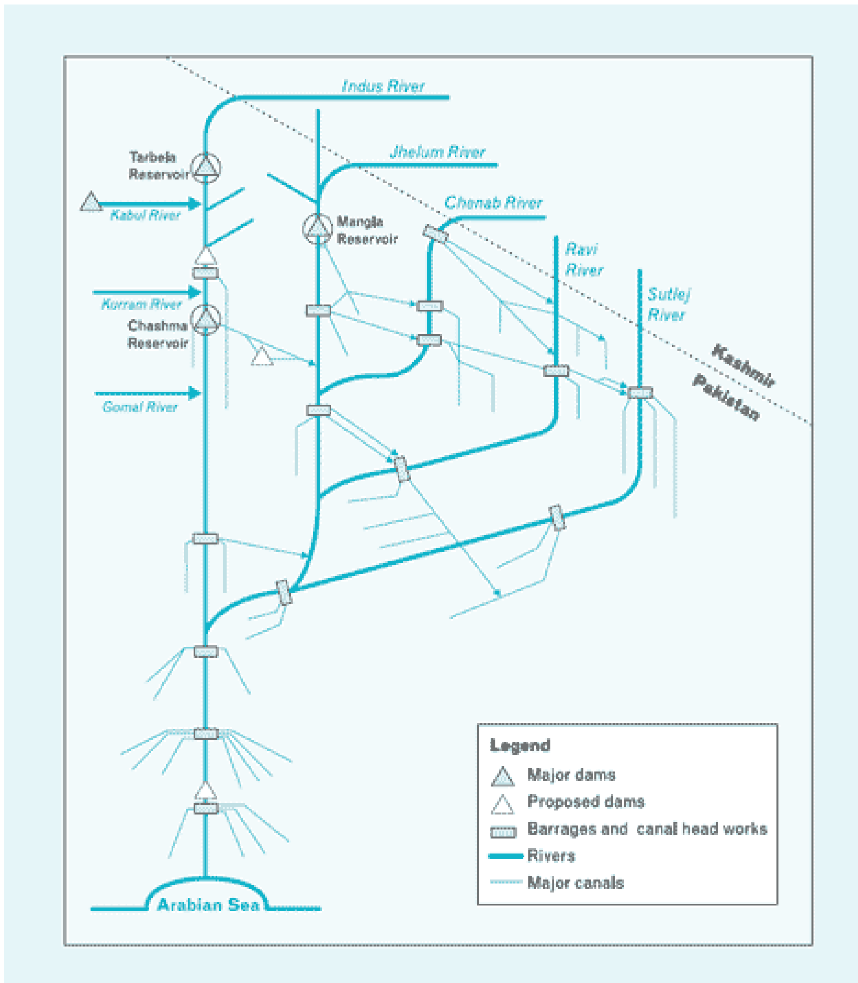


Figure 5: Schematic diagram of the Indus basin irrigation system. Source: Briscoe and Qamar, 2007

1.1.2 Partition and the Indus Waters Treaty

Sir Cyril Radcliffe's partition line (1947) between India and Pakistan left the headworks of all major rivers that fed Pakistan in India. The settlement of this problem was a feat of international diplomacy. In 1960, the World Bank brokered the Indus Water Treaty whereby India claims rights to the eastern rivers of Beas, Sutlej and Ravi, and Pakistan claims rights to the western rivers of Chenab, Jhelum and Indus. Pakistan was left with 75% of its natural river flows – by all measures a success for the lower riparian, but still enough of a shock to potentially quell Pakistan's agriculture. Therefore, with monetary help from the World Bank and, remarkably, India, Pakistan built what is called the "Indus Basin Replacement Works". 'Link canals' and barrages were constructed to divert water from the western rivers towards areas previously irrigated by the eastern rivers. Most significantly, India partially paid for the construction of Tarbela Dam on the Indus and Mangla dam on the Jhelum (Briscoe and Qamar, 2007), which have enabled year-round availability of water to the plains of Pakistan.

1.2 Storage Infrastructure in the Indus Basin

The two existing dams on Pakistan's rivers, Tarbela on the Indus and Mangla on the Jehlum, were built in the 1960's. They have been silting up and need replacement. The plan was to build a reservoir every decade thereafter. However, fifty years later, barring small projects, the total storage capacity in the Pakistani portion of the Indus basin has seen an overall decrease (figure 6). The reason for the deadlock has been the proposed Kalabagh dam, a bone of contention among Pakistan's provinces since the 1960's. The primary reason for the controversy is that the project is located in Punjab, by far the wealthiest and most populous province. The Legislative Assembly of every province except Punjab has passed resolutions against the Kalabagh Dam (Kheshgi 2012).

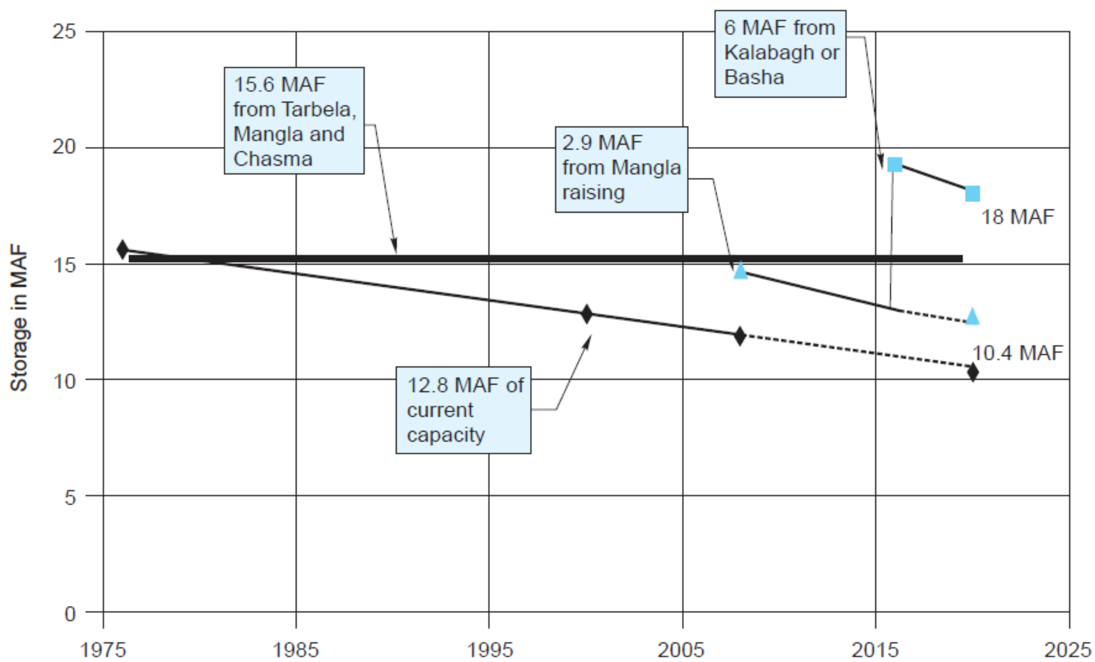


Figure 6: The impact of siltation on built storage capacity on the Indus river system since 1975. Source: Briscoe and Qamar, 2007.

Pakistan is in desperate need of another hydropower reservoir. A World Bank report (Briscoe and Qamar, 2007) makes a strong case for more storage, estimating that Pakistan withdraws more than 70% of its mean annual freshwater supplies. In a river system marked with strong seasonality and inter-annual variability, averages are deceptive. In drought years like 1974 and 2000, the Indus hardly reaches its delta, jeopardizing the mangrove forests and fishing communities that inhabit the delta (see figure 7). Since 2010, however, Pakistan has had three consecutive flood years. Pakistan routinely faces gaping electricity shortages, making hydropower attractive and popular.

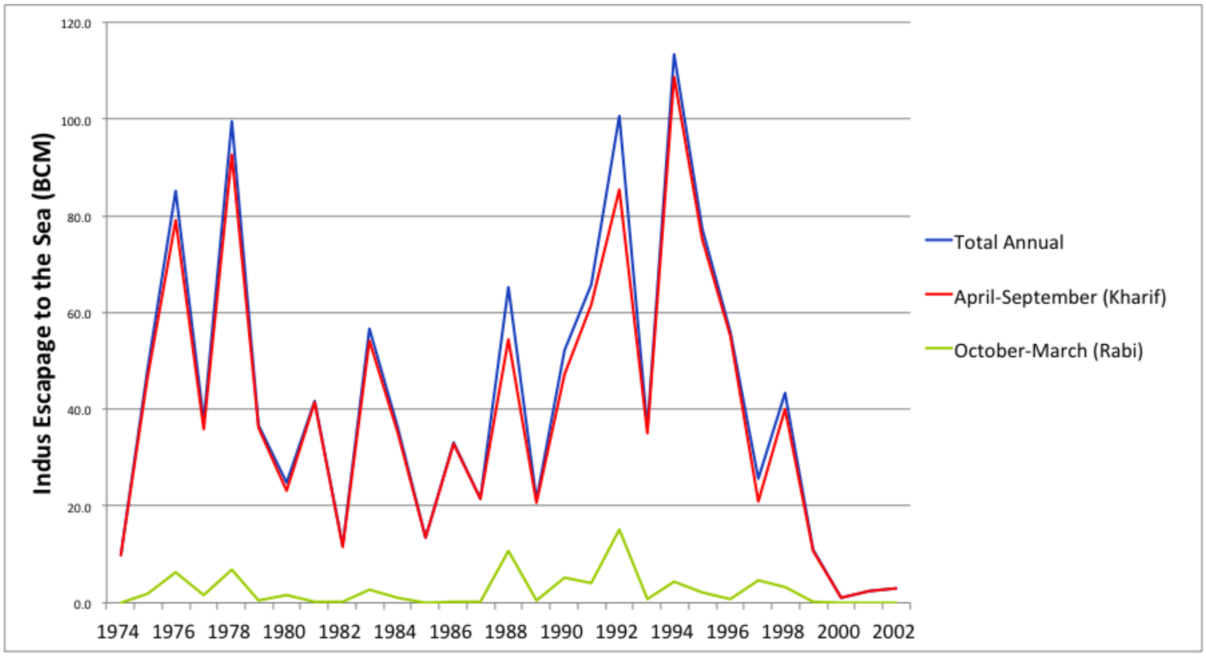


Figure 7: Annual volume of the Indus river reaching the Arabian sea. Sindh claims that minimum annual environmental flow requirements in the Indus delta are 10 MAF (12.3 BCM). Source: NARD

Since river flow is variable, storage is required so that the supply of water can more closely match water demands every year, and the oscillation between floods and droughts can be modulated. Relative to other arid countries, Pakistan has very little water storage capacity. Figure 8 shows that the dams of the Colorado and the Murray-Darling rivers can hold 900 days of river runoff. South Africa can store 500 days in its Orange River, and India between 120 and 220 days in its major peninsular rivers. By contrast, Pakistan can barely store 30 days of water in the Indus Basin. Similarly, whereas North America and Europe have tapped over 70% of their hydropower potential, Pakistan has tapped only 13% to date (Figure 9).

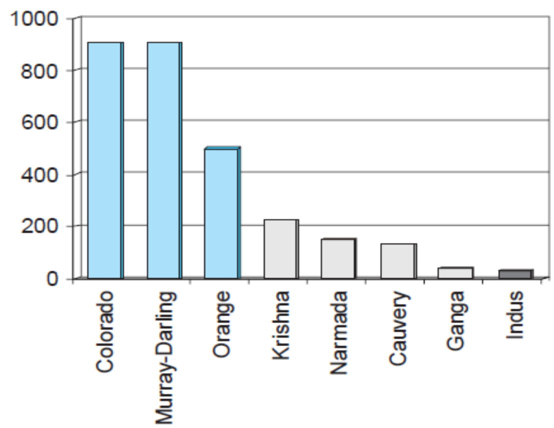


Figure 8: Days of river flow that can be stored in comparable semi-arid river basins. (Briscoe and Qamar, 2007)

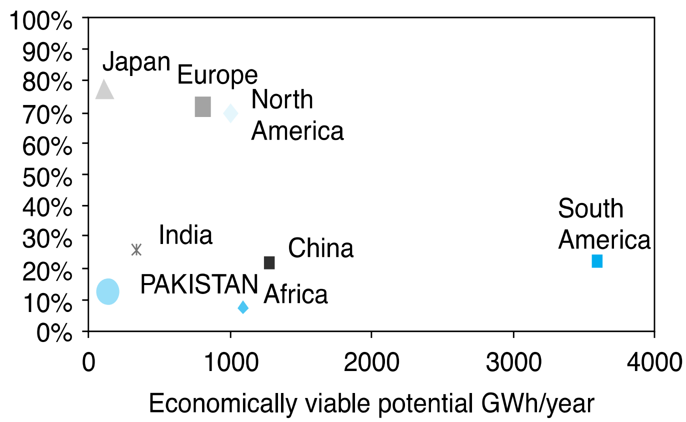


Figure 9: Percentage of hydropower potential Pakistan has developed, framed in a global context. (Briscoe and Qamar, 2007)

1.3 Scarcity and Climate Change

Per capita water availability in Pakistan is one of the lowest among comparable semi-arid countries, says the World Bank (figure 10). The National Academy of Science, in its recent report on hydrology in the Himalayan region (NAS, 2013), states, "even without climate change affecting water availability, Pakistan would have a significant challenge providing enough water to meet its needs under traditional projections". The simplest measure of physical water scarcity is per capita water availability in a region. One common set of thresholds defines regions with more than 1,700 m^{3} person^{-1} yr^{-1} as "water sufficient", while those below this threshold have some degree of water stress (<1,700 m^{3} person^{-1}yr^{-1}), chronic scarcity (<1,000 m^{3} person^{-1}yr^{-1}), or absolute scarcity (<500 m^{3} person^{-1}yr-^{1}) (Falkenmark, 1989; Falkenmark and Lindh, 1974; Falkenmark et al., 1989; Falkenmark and Widstrand, 1992). Using this metric, with population growth (ignoring potential changes in water availability), the National Academies estimate that Pakistan will move from water stress in 2000 (1,400 m^{3} person^{-1}yr^{-1}) to chronic scarcity in 2030 (900 m^{3} person^{-1}yr^{-1}) and 2050 (700 m^{3} person^{-1}yr^{-1}), even without factoring in climatic changes to regional hydrology. Any reductions in flow in the Indus caused by climate change would further intensify this scarcity.

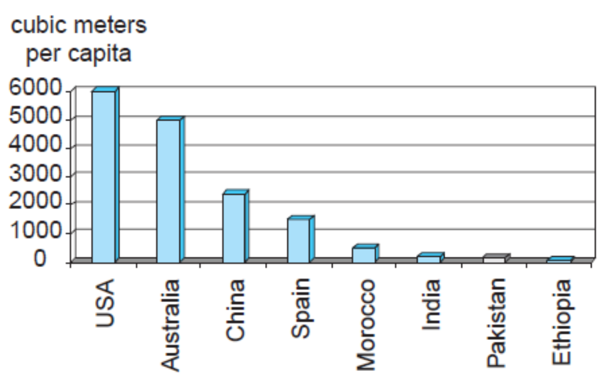


Figure 10: Water Availability Per Capita in Comparable Semi-Arid Countries (Briscoe and Qamar, 2007)

Another way to define physical scarcity is the ratio of water use to water availability. By this metric, and ignoring potential changes to water availability, the National Academies deems the Indus basin the most likely of any of the basins in the Himalayan region to face water scarcity.

The rivers of the Indus Basin have glaciated headwaters and snowfields that, along with monsoon runoff and groundwater aquifers, provide the major sources of water for Pakistan. Currently, about 50-80 percent of the total average river flows in the Indus system are fed by snow and glacier melt in the Hindu-Kush-Karakoram part of the Himalayas, with the remainder coming from monsoon rain on the plains. There are more than 5,000 glaciers covering about 13,000 km^2 in the Upper Indus river basin catchment (Yu et al. 2013). The supply of water stored in glaciers and snow is projected to decline globally during the 21st century. However, the patterns of depletion and accumulation vary regionally and locally. Some glaciers in the upper Indus basin are increasing in depth and size, in contrast with the more general (but still variable) pattern of glacial retreat in the Himalayan range to the east (Gardelle et al., 2012).

The World Bank recently issued a report (Yu et al., 2013) on the impacts of climate change on the Indus basin. This report suggests that the Indus basin is already experiencing historically unprecedented hydroclimatic phenomena. It cites the years from 2009 through 2011 as examples of current challenges of water and food security, likely to be worsened by climate change. A weak monsoon hampered agricultural production in 2009. Drought was an extensive problem throughout the country. Rainfall was 25-50 percent below normal and melt waters were 15-30 percent below normal. These water constraints delayed winter wheat sowing until December 2009, posing risks to that staple food crop. At that time, diminished irrigation supplies led to questions about potential impacts of climate change and the associated concerns about the future of the glaciers in the Upper Indus. Increasing transboundary conflict over water development on the Jhelum and Chenab rivers exacerbated these concerns. Pakistan's increasing vulnerability to water scarcity was also highlighted in the literature (for example, Archer et al. 2010; Immerzeel et al., 2010; Laghari et al., 2011). Around that time, the Government of Pakistan also issued a report of the Task Force on Climate Change (GPPC 2010).

In January 2010, a large landslide near the village of Attabad dammed the Hunza River valley, a tributary of the Upper Indus, inundating villages and destroying 19 km of the Karakoram Highway. But these resettlement and reconstruction efforts were eclipsed by devastating floods later in the year.

As late as June 2010, the Pakistan Meteorological Department (PMD) forecast a "normal (+10 percent)" monsoon. In late July, however, heavy rains fell over the Upper Indus main stem and the adjoining tributaries in the Kabul basin, causing extensive flash flooding in KPK that cascaded through the districts that line the Indus from Punjab to Sindh and parts of Balochistan over the following month. Additionally, flash floods and landslides caused severe damage to infrastructure in the affected areas. More than 1,980 were killed and 2,946 injured. A joint Asian Development Bank and World Bank (ADB and World Bank 2010) Flood Damage and Needs Assessment estimated that the total direct damages and indirect losses amounted to about US$10 billion; the agriculture, livestock, and fisheries sectors suffered the highest damages, calculated at US$ 5 billion.

As the 2011 monsoon season approached, the PMD forecast a slightly below normal (–10 percent) monsoon, with some areas expected to experience slightly above normal rainfall (+10 percent) (PMD 2011). However, heavy rains flooded the lower Indus Basin districts in Sindh and Balochistan, adversely affecting 5 million people, damaging 800,000 homes, and destroying 70 percent of the crops on flooded lands in what were already the most food insecure provinces in Pakistan (UNOCHA 2011). Although very different in hydroclimatic terms, the two floods of 2010 and 2011 had compounding damages on agricultural livelihoods and food security in the lower Indus basin.

1.4 Modeling Global Change Impacts on Water Stress

This work builds on two lines of literature on water resource modeling. The first is the World Bank's decades-old optimization modeling effort in the Indus Basin (the 'Indus Basin Model' (IBM), Lieftinck et al., 1968; Duloy and O'Mara, 1984; Ahmad, Brooke and Kutcher, 1992). The second is the MIT Joint Program for Global Change's water resource systems model (WRS: Strzepek et al., 2013 and Schlosser et al., in press).

The first major application of a multi-objective planning model for the Indus Basin was the World Bank's Indus Special Study of 1964-68, published as the three-volume report on Water and Power Resources of West Pakistan: A Study in Sector Planning (Lieftinck, et al., 1968). It was an early use of linear programming and optimization modeling to weigh investment alternatives, which included Tarbela Dam and irrigation and agricultural development projects. Later, Duloy and O'Mara (1984) would develop the first version of the Indus Basin Model (IBM). At about the same time, WAPDA and USEPA studied general circulation model (GCM) scenarios alongside Pakistan's development alternatives. The scenarios were arbitrary +2°C to +4.7°C warming and +/-20% change in precipitation. The economic effects of all but the +2°C, +20 percent change in precipitation were negative. The Global Change Impact Study Centre (GCISC) in Pakistan undertook a number of adaptation studies (for example, Ali et al., 2009). Using a sophisticated crop model, these studies focused primarily on examining how climate change may impact wheat and rice yields and production (Iqbal et al. 2009a, b, c).

Recently, a joint effort among the World Bank, the University of Massachusetts and IFPRI (Yu et al., 2013) has used IBMR (where 'R' stands for 'Revised') and a snow and ice hydrology model to study the interdependences among climate, water and agriculture of

Pakistan. They use a computable general equilibrium (CGE) model for the Pakistani macro-economy, and an agro-economic optimization model to generate the optimal crop production across the provinces every month, subject to a number of physical and political constraints. From a review of available GCM's, they conclude that temperatures in the winter will rise more than in summers, at worst by 3°C. Precipitation changes in GCM's are inconclusive even regarding direction. However, they find that streamflow variations due to climate are in general comparable to current interannual variations. Therefore, the primary impact of all but the most extreme climate change scenarios could be a shift in the timing of peak runoff, and not a major change in annual volume. They calculate that climate change could decrease GDP by 1.1%, and result in a rise in food prices which will leave non-farming households worse off. They further find that a relaxation of the current Interprovincial Water Accord could increase the total agricultural revenues.

The MIT Joint Program for Global Change developed the Water Resource Systems model (WRSm see Schlosser et al., in press) as an enhancement to its integrated global systems model (IGSM) to study the effects of climate change on managed water resource systems. WRS resolves 282 river basins globally, of which the Indus basin is one. Temperature and precipitation were downscaled from the zonal representation of the IGSM to regional (1' latitude x 1' longitude) scale, and the resulting surface hydrology was translated to runoff at the scale of river basins. This model of water supply is combined with the analysis of water use in agricultural and non-agricultural sectors and with a model of water system management that allocates water among uses and over time and routes water among basins.

The output of WRS is water stress, a measure of water adequacy developed by Smakhtin et al. (2004). Water stress is defined simply as the ratio of total water withdrawals to surface water availability in a basin. Figure 11 shows the estimates of water stress in 2000 by WRS. In the dark blue regions, less than 30% of the available water is being used, whereas dark brown regions are where more water is being withdrawn than is sustainably available, either by the mining of fossil water or by desalination, etc. However, a comparison with FAO-AQUASTAT (FAO, 2012) shows that WRS overestimates water stress in the Indus basin. A few reasons for this are: (a) coarse representation of the Indus basin as one unit; (b) imperfect representation of glacier ice-melt in the upper Indus basin which leads to an underestimate of Indus runoff; and (c) the farming practices in Pakistan, which differ from the cropping calendar assumed in CliCrop – the irrigation demand model in IGSM (Fant et al., 2012). Crucially, by leaving out the groundwater aquifer on which over a million tubewells in Pakistan rely (Punjab Development Statistics, 2012), one is bound to overestimate water stress.

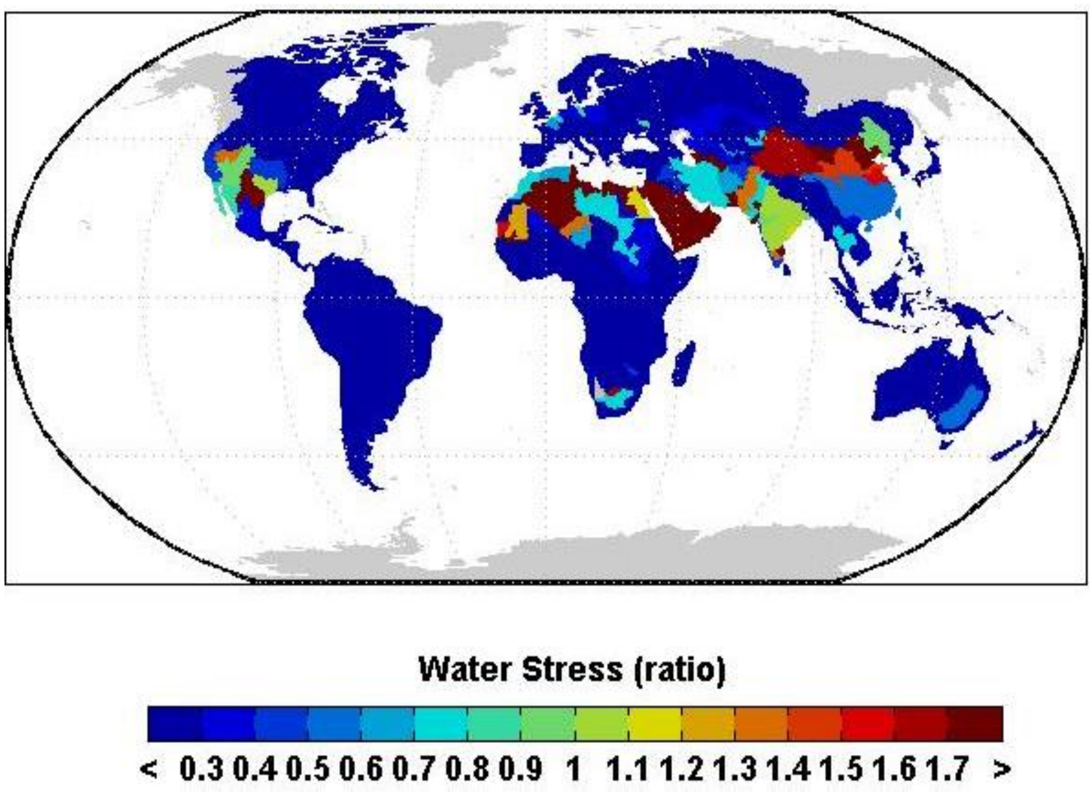


Figure 11: Water Stress estimates for 2000 by WRS. Source: Strzepek et al., 2013

1.5 Scope of This Work

The purpose of this work is to introduce greater geographic and hydroclimatic specificity in WRS-Global's depiction of the Indus basin. My projections of water stress are informed by regional politics, sensitive to local hydroclimate, and geographically specific. I have resolved the Indus basin into four sub-basins: the upper Indus basin catchment area, Punjab, KPK and Sindh. I estimate water supply using official historical data for river flows and sustainable groundwater yields. I estimate province-wise water demand using official figures for irrigation demands and cultivated areas. These data are inputs into an optimization model which I describe in chapter 2. The objective function is the minimization of water stress, taking into account political constraints like the Interprovincial Water Accord and Pakistan's emphasis on food security. Thus, I estimate province-wise water stress in the base-year of 2000.

In chapter 3, I project changes in temperature and glacier cover in the upper Indus basin, and translate these parameters into changes in Indus runoff. I also use the Joint Program's Emissions Projection and Policy Analysis (EPPA) model to project water demand for 2050. Using these projections, I estimate changes in water stress in Pakistan in 2050. Finally, in chapter 4, I compare the efficacy of various adaptation options in combating water stress, including augmented storage, interprovincial water trading, and modification of the cropping calendar.

2 WATER MANAGEMENT IN PAKISTAN

Pakistan's water managers are faced with a complex task. The flows in the Indus and its tributaries are not only highly seasonal (85% of annual flows occurs in five summer months, see figure 12) but also variable from year to year (figure 13.) Rainfall diminishes to a trickle as you move south from the Himalayan foothills to the hot Indus plains. Although winter precipitation is diminutive, the staple crop, wheat, is grown in the winter for historical reasons. So the summer peak flows must be stored to irrigate winter wheat. Wheat is key to food security in Pakistan. Therefore, winter (or "rabi") irrigation takes precedence over summer (or "kharif") cash crops like sugarcane, cotton and rice in water management (Pakistan Agricultural Research Council, 2005).

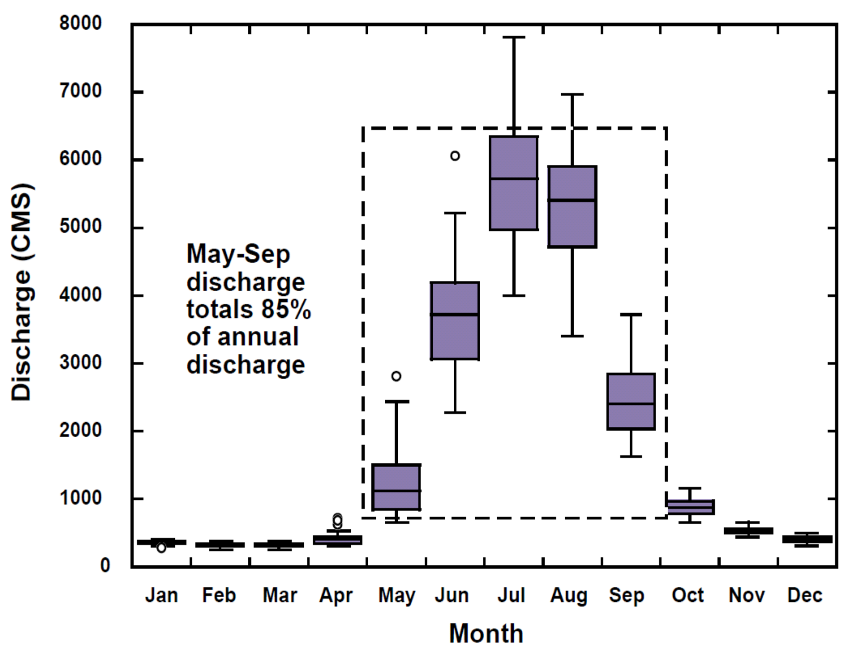


Figure 12: The monthly hydrograph of the Indus river just before it reaches the Tarbela Dam from 1962-2000, measured in cubic meters per second (CMS). It shows the acute seasonality of the Indus river, with 85% of flows occurring in five months. Source: National Academy of Sciences, 2013

The water managers have resort to only two major storage reservoirs to ensure adequate supply to winter wheat. Built on the Indus and the Jehlum rivers, respectively, these dams can together store only 30 days of total annual flows of these rivers. (For comparison, the Colorado river has nearly 1000 days of built storage). Dam construction has been on moratorium since the Tarbela dam (10500 MCM) and the Mangla Dam (5950 MCM) were constructed in 1970.

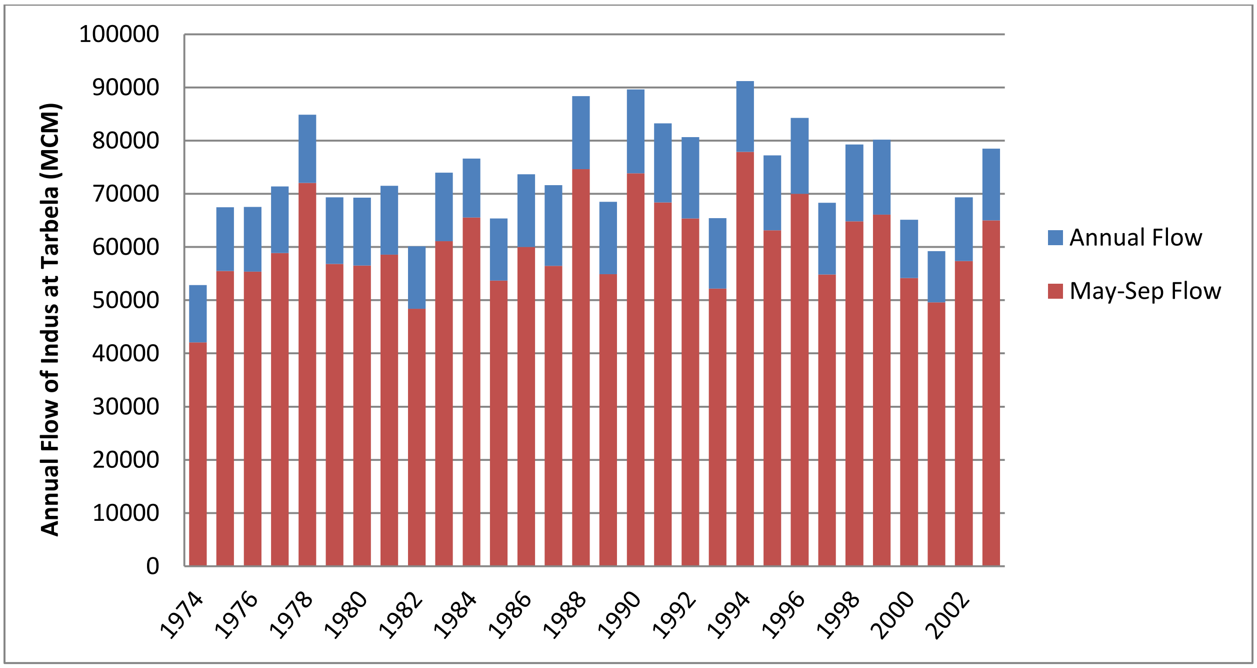


Figure 13: The annual variability of Indus Flows in million cubic meters (MCM). Standard deviation is 12% of mean annual flow. (Source: PARC 2003)

A low built storage capacity forces Pakistan's water managers to keep reservoir levels low in the monsoon months lest a flood should occur. Already, we see that the objectives of storing the peak flows for the winter and keeping room in the reservoir for possible floods are competing objectives that leave water managers in a quandary. Take the example of the year 2010 when rains were relatively low until July. The water managers did not empty Tarbela. However, the last week of July saw three months' worth of rain (NASA, 2010). Unable to store it all, Tarbela passed on the deluge downstream in the form of a historic flood.

A third objective is producing hydropower. Demand for electricity peaks in the summer and water managers are under pressure to release as much as they can down the spillway to the powerhouse from June-August. However, Pakistan's water managers resist this pressure in favor of food security. As a water manager explained to me in Pakistan, effectively one equation (governing the operation of Tarbela dam) is being used to solve for three variables in Pakistan (irrigation, hydropower and flood management).

The Indus River System Authority (IRSA) governs the apportionment of water among the canals that irrigate the Indus plains according to the surprisingly parsimonious Interprovincial Water Accord (IWA, 1991). Rather than maximizing overall economic output, the IWA reflects (a) only agricultural uses of water and (b) political expediency in a strong federation and historic uses by upstream and downstream users. It is not a demand-based system, i.e. water is not released in a canal upon demand. Rather, it is a supply-based system, i.e. the farmers have to make do with whatever is released in the canal and furnish the rest with groundwater pumping.

2.1 A Management Model of the Indus Basin System

To explore how Pakistan's dams are operated, I have built a GAMS model that optimally allocates available water with the objective of minimizing water stress around the year to the four provinces of Punjab, Sindh, KPK, and Baluchistan. The objective of the model is to match water supply with demand in each month and each province. Water stress is defined as the withdrawal/availability of total surface and groundwater. The withdrawals include the water needed for domestic, industrial and irrigation sectors in the baseline year of 2000, accounting for the seepage losses from canals. The available water is estimated as the sum of the monthly releases from the dams in the model, the incoming flows of the undammed rivers, and groundwater. The surface component of the available water is allocated among the provinces according to the interprovincial water accord.

2.1.1 Estimating Monthly Water Supply

I obtained monthly river flow data from the Government of Pakistan (2003 edition) and from the Pakistan Water Statistics Handbook (2006) for 1974-2002 (the post-Tarbela period) at the heads of the six rivers of Indus, Jehlum, Chenab, Ravi, Sutlej, Swat and Kabul. (See table and figure 14 for flow details.) Of these, the Indus and Jehlum flows are regulated by the Tarbela and Mangla dams, respectively, whose storages can be manipulated in the model on a monthly basis. The monthly reservoir releases are the decision variables. While I have used the natural (or 'un-managed') flows of the Indus, Jehlum, Kabul, Swat and Chenab rivers, the flows of Ravi and Sutlej are taken as released by India.

Widespread groundwater pumping augments the surface supply of water. The canals in the Indus Basin irrigation system are mostly unlined, causing large seepage losses. However, these losses are more than fully recovered by the thick network of over a million tubewells pumping groundwater across Pakistan's irrigation plains (Punjab Development Statistics, 2012). Although the exact amounts of groundwater extraction and recharge are little known, it is estimated (Qazilbash, 2007) that about 51 billion cubic meters (BCM) of groundwater is sustainably available annually in the Indus Basin to augment surface water supply. This amount of groundwater is made available in the model to the provinces every year. They end up pumping water mostly in the winter months (November-February), with Punjab claiming an average of about 45.5 BCM in the model.

River	Mean Flow (MCM)	Minimum Flow (MCM)	Maximum Flow (MCM)
Indus	74,838	52813	91213

Jehlum	28,553	14618	39470
Chenab	33024	22486	40507
Kabul	25507	13774	42198
Swat	5784	-	-
Ravi	5094	-	-
Sutlej	3195	-	-
Total	175995	-	-

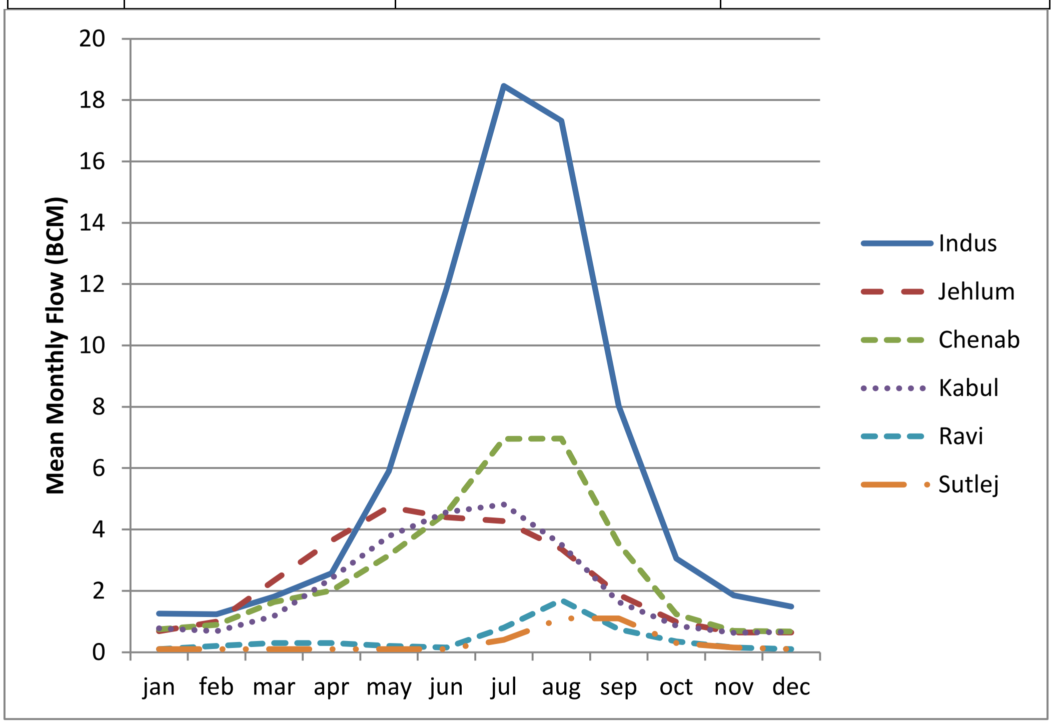


Table and Figure 14: Annual hydrographs of the six major rivers in Pakistan over 1974-2003. Of these, the Indus, Jehlum and Kabul rivers are dammed. All these rivers flow together before reaching the sea. Data source: Government of Pakistan, 2013

2.1.2 Estimating Monthly Water Demands and Withdrawal Requirements

Crop irrigation requirements – obtained from the National Agro-Ecological Resources Database (NARD), a project of the Pakistan Agricultural Research Council (PARC) – are fed into the model as millimeters of irrigation water needed per crop per season for each province (table 1). Averaged over the years 2000-2002, these numbers already account for monthly average rainfall and reflect irrigation requirement only. The crops I consider are wheat, rice, sugarcane, cotton, sorghum, millet, potato, vegetables, mango, citrus, maize and chickpea. Figure 15 shows the spatial distribution of crops.

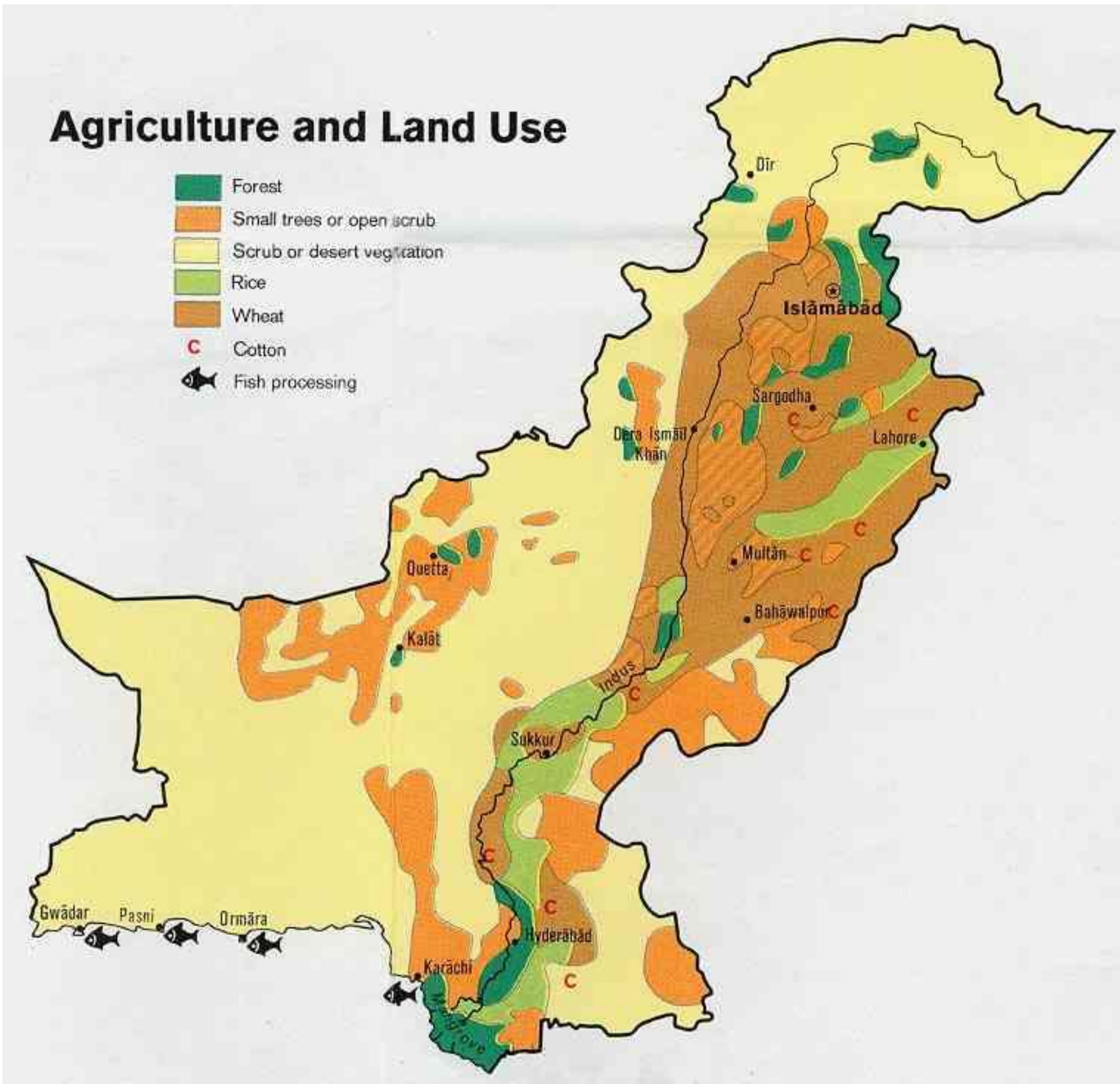


Figure 15: Map showing prime farming regions for the major crops of wheat, cotton and rice. (Source: The *Pakissan* Forum 2013)

The purpose of the model is to understand the interplay of unmanaged river flows with the irrigation network, and chart future water stress under climate change. So I have used the per unit area irrigation requirements and the cultivated areas of crops in the "base" period of 1998-2002 as constant, and applied them against the flows of 1974-2003. I have calculated irrigation water demands by taking the cultivated areas under each crop in each province in the year 2000 – as reported by NARD and the Pakistan Bureau of Statistics (table 2) – and multiplying them by the irrigation requirement per crop per unit area per month. In other words, for each crop in each province:

Volume of irrigation water needed = (Area cultivated) x (irrigation requirement in mm per unit area)

Pakistan's Meteorological Department (figure 16a-c) defines Pakistan's agro-climatic zones as coinciding with provincial boundaries. This conveniently lends itself to our provincial water analysis. The provinces vary not only in their irrigation requirement but also in their sowing and harvesting calendars. I have taken the official crop calendars for each province from the Pakistan Meteorological Department's webpage (see figure 16a-c). Using this calendar, I have distributed the total irrigation requirement of the crop through the planting and growing seasons. Figure 16 shows major winter (wheat and vegetables) and summer crops (cash crops, fruit and cereals). It also shows that Sindh is the first to plant wheat and KPK is the last to plant sugarcane.

	Punjab	**Sindh**	**KPK**
Cereals			
wheat	400	450	420
rice	1000	1100	900

maize	375	400	400
chickpea	280	300	280
millet	320	350	350
sorghum	370	400	400
barley	370	300	300
Total	**3115**	**3300**	**3050**
Cash Crops			
cotton	650	650	650
sugarcane	1200	1200	1000
Total	**1850**	**1850**	**1650**
Fruit and Vegetables			
mango	1100	1100	1100
citrus	1100	1100	1100
potato	600	600	600
vegetable	600	650	550
Total	**3400**	**3450**	**3350**

Table 1: Irrigation requirements in mm for each crop in its full cultivating season during 1998-2002. The requirement accounts for precipitation and field losses of water. In distributing this total seasonal requirements over the full cultivating season, the demand was skewed more towards the growing than the harvesting season. Source: NARD

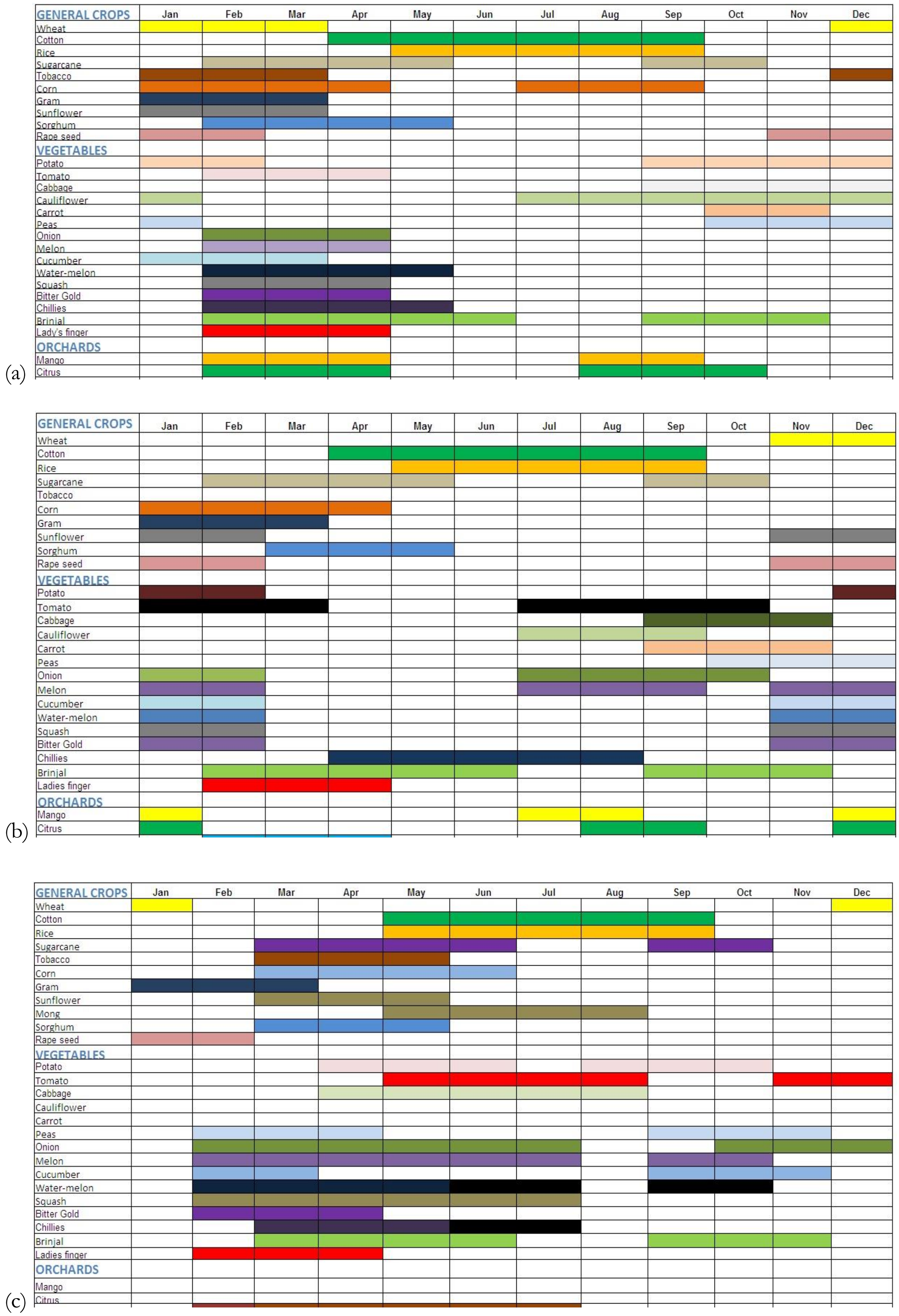
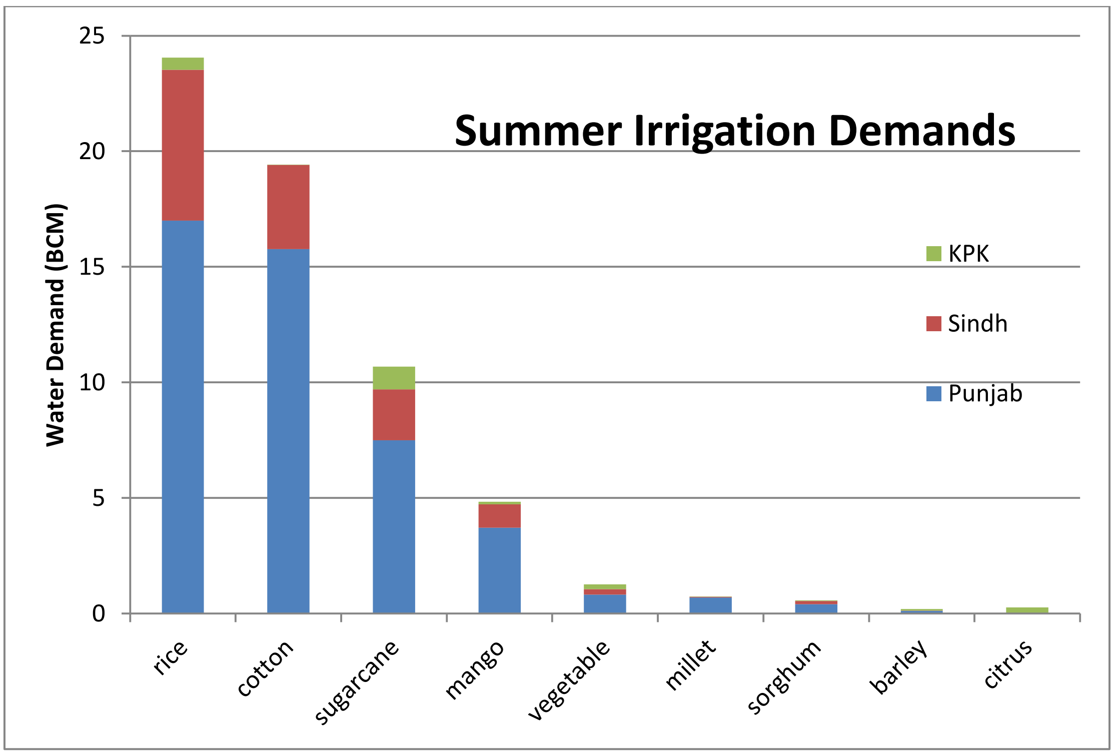


Figure 16: Official crop calendars for (a) Punjab, (b) Sindh and (c) KPK provinces. Source: PMD

	Punjab	Sindh	KPK
wheat	5726	933	311
maize	370	2	380
chickpea	360	20	19
potato	104.5	0.4	9.8
rice	1700	593	59
cotton	2426	560	2
sugarcane	625	183	99
mango	338.1	92	9.2
vegetables	136	37	37.7
millet	218	5	5
sorghum	110	35	7
barley	29.5	6	25
citrus	0.8	0.1	22.8

Table 2: Mean area of each crop under cultivation in each province in 1998-2002 in 1000 hectares. Source: Pakistan Bureau of Statistics



(a)

(b)

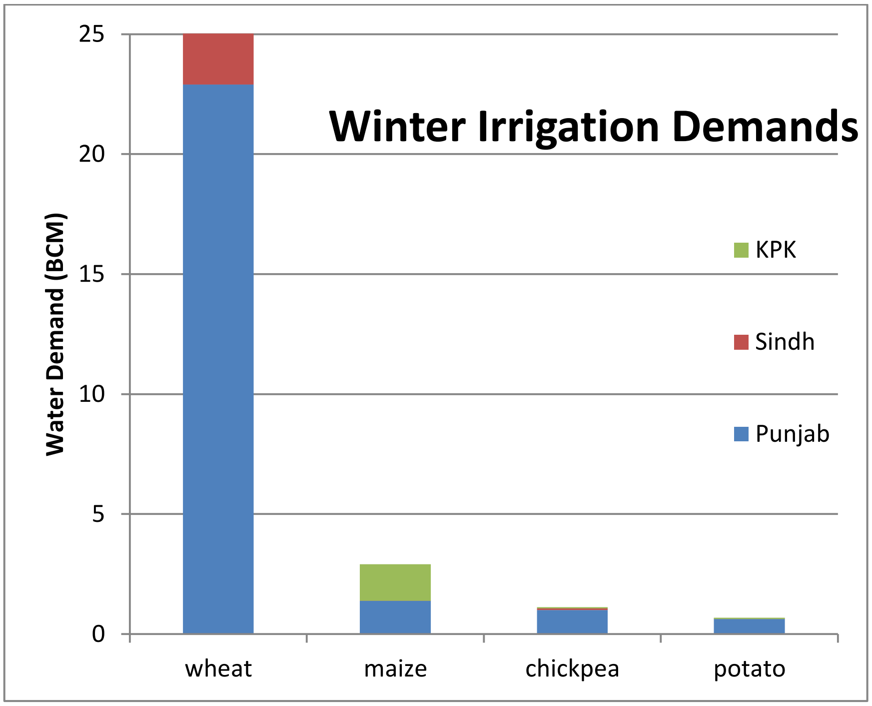


Figure 17: Irrigation demands in the summer (kharif) and winter (rabi) seasons for the base year, 2000. These demands are a product of the irrigation demands per unit area of each crop and the total area cultivated (tables 1 and 2).

Pakistan's industrial and municipal water requirements are small in comparison to irrigation demands which constitute 92% of total demands. I use the municipal and industrial demands by province from 2002 as baseline (Zakaria, 2007, table 3), and assume for simplicity that they are uniform throughout the year.

	Urban Household	Rural Household	Industrial	Total
Punjab	1740	3064	720	5524
Sindh	857	1000	360	2217
KPK	192	997	79	1268

Table 3: Annual household and industrial demands for water in MCM. Source: Zakaria, 2007

Getting from crop water demands to withdrawals from the river requires an estimate of conveyance efficiency of the canals in the Indus basin irrigation system. Shahid Ahmed (2007) estimates that at least 17.3 BCM are lost from the river to the farm due to leaky canals, and do not replenish the groundwater aquifer. This is about 18% of the crop water demands in 2000 of Punjab, Sindh and KPK which total roughly 95 BCM. Therefore, as a first order approximation, I magnify the total water demand at the field by 18% to estimate withdrawal from the river (figure 18).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Punjab	5781	6480	5282	6437	10076	6954	5054	8722	5692	527	5269	5269	71544
Sindh	312	650	451	1016	1377	1246	1651	923	594	374	2301	2409	13304
KPK	529	137	625	615	918	711	261	261	418	303	368	513	5660
Total	6623	7268	6358	8068	12371	8911	6966	9906	6704	1204	7938	8191	90507

Table 4: Total demand for water (sum of irrigation, domestic and industrial demands) in MCM in 2000 (not to be confused with withdrawals below (Figure 18), which include conveyance losses).

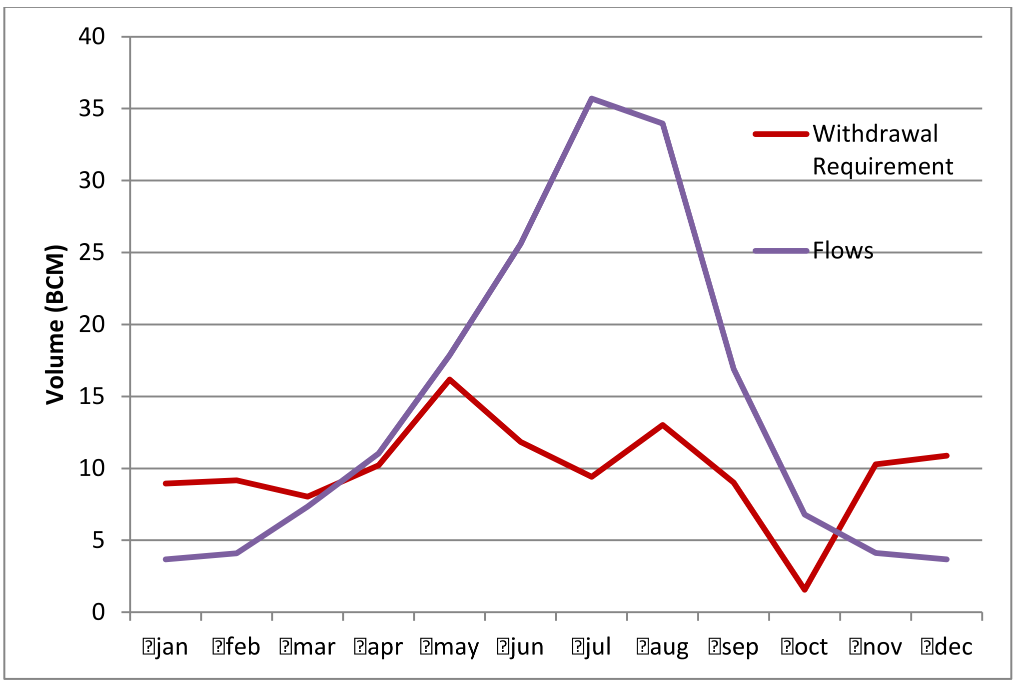


Figure 18: Monthly water demand against the unmanaged flows of all the rivers in the Indus river system (Indus, Jehlum, Chenab, Ravi, Sutlej, Swat and Kabul). Water demand exists throughout the year with farming done in every season. But water supply from rivers is highly seasonal, leading to the need for water management.

2.1.3 Model Operation and Constraints

The objective function (OBJ) of the model reads:

$$OBJ = \sum^{t,\, prov} \text{water stress}(t, prov)$$

where t stands for time in months and prov stands for province. In the absence of management, the winter months would be the highest stressed due to high demand for wheat irrigation and low river flows. The summer months have inflows far in excess of demand. The model meets the objective by limiting summer reservoir releases to mitigate winter stress to some degree.

However, in reality, water managers in Pakistan are far more concerned with food security than with cash crops. Winter wheat is the crucial crop. I depict this prioritization by weighing winter ('*rabi*') stress twice as much as summer ('*kharif*') stress, thus penalizing high winter stress.

$$OBJ = 1.33*(\sum \text{water stress}(t_r, prov)) + 0.67*(\sum \text{water stress}(t_k, prov))$$

where t_r stands for *rabi* or winter months (ONDJFM), t_k stands for *kharif* or summer months (AMJJAS), and prov stands for provinces.

In addition, the monthly water allocations are governed by the Interprovincial Water Accord (IWA) signed in 1990. The Accord determines the water allocation to each province for each season – *rabi* and *kharif*.

Province	**Kharif**	**Rabi**
Punjab	47.9%	51.0%
Sindh	43.9%	40.0%
KPK	4.5%	6.2%
Balochistan	3.7%	2.8%

Table 5: Pakistan's interprovincial water accord of 1990 allocates these fractions of surface water to each province, assuming a minimum amount of flow each year. Excess water is distributed according to a different rubric.

The model computes flow downstream from Tarbela and Mangla dams through a simple mass balance formulation of the Indus and the Jehlum river volumes, respectively:

Tarbela mass balance:

TarbelaStorage(t+1) = TarbelaStorage(t) + IndusFlow(t) – TarbelaRelease(t)

Mangla mass balance:

ManglaStorage(t+1) = ManglaStorage(t) + JehlumFlow(t) – ManglaRelease(t)

The monthly releases from the two reservoirs, together with the (unmanaged) flows of the Kabul, Swat and Chenab rivers, make up the pool of available water to be apportioned every month among the provinces according to the IWA. However, Punjab's water supply via the Accord is augmented by two eastern rivers, Ravi and Sutlej, which contribute small seasonal flows to eastern Punjab.

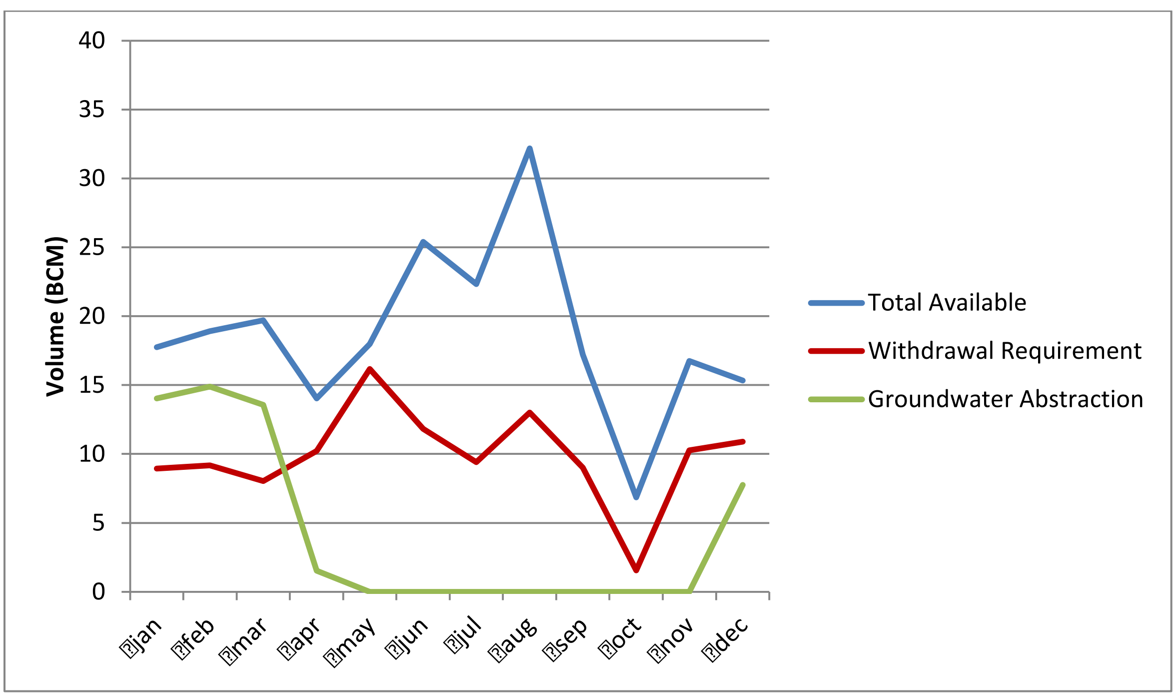
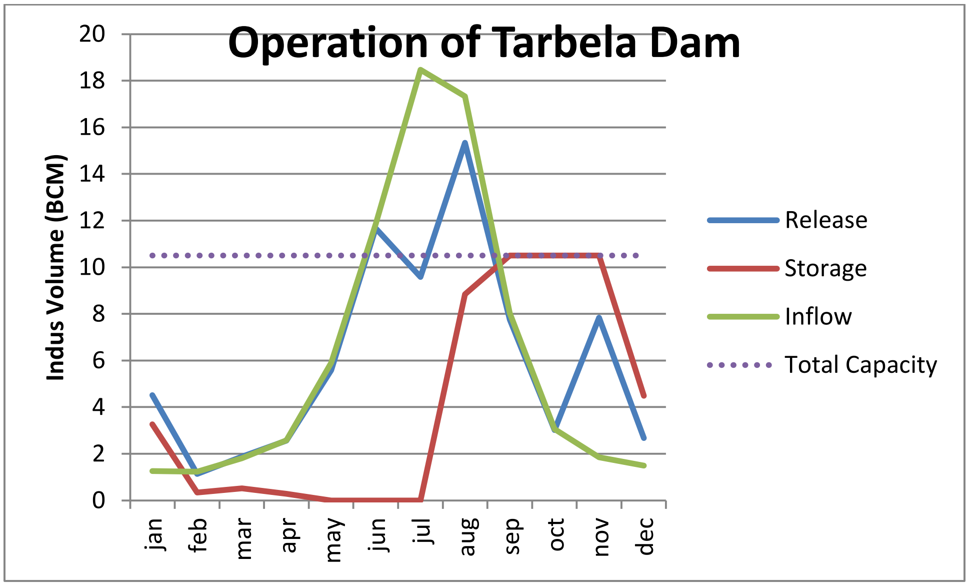


Figure 19: Monthly water withdrawals against the water made available after dam operation in the model. Available water includes releases from Tarbela and Mangla dams as well as Chenab, Kabul, Swat, Ravi and Sutlej flows. It includes groundwater, which in the model is pumped in December-March to make up for low river flows. Notice how, in contrast to the unmanaged Figure 18, this management scheme tends to 'distribute' the peak July flows throughout the off-peak winter season.



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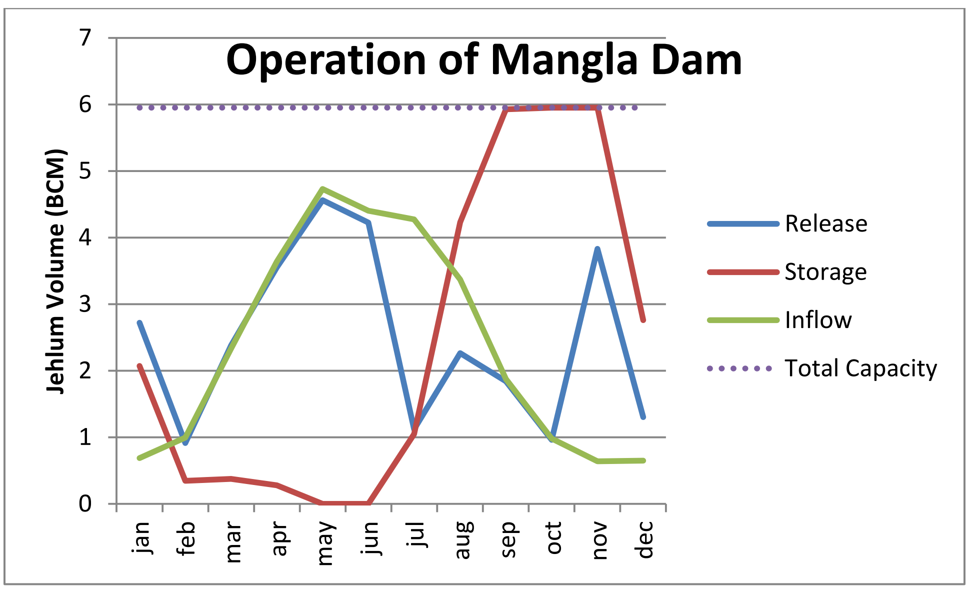


(b)

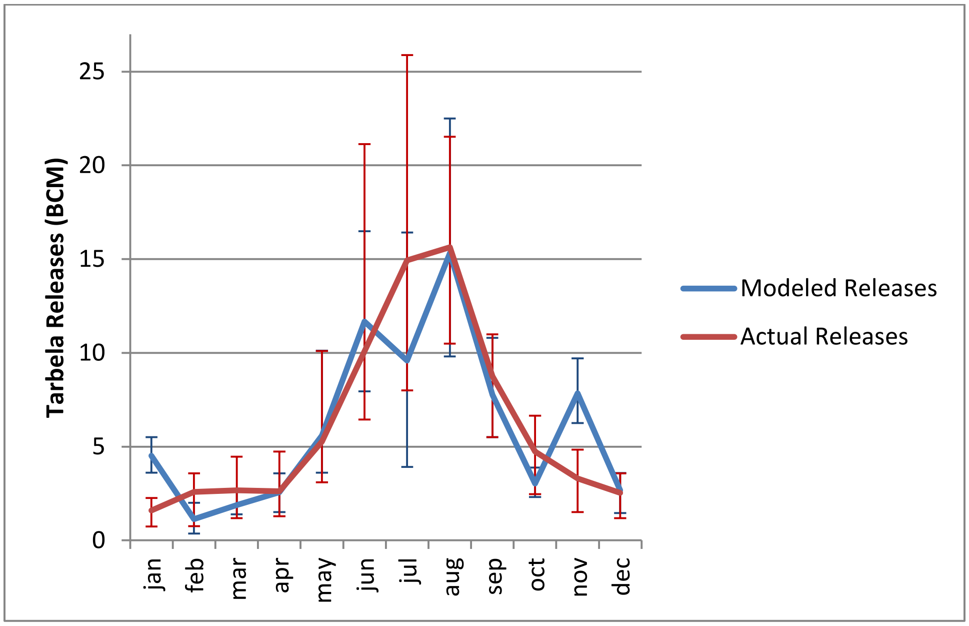
Figure 20: The model's operations of (a) Tarbela and (b) Mangla dams against the incoming flows of the Indus and Jehlum rivers, respectively. All quantities shown are mean values over 30 years.

Figure 20 shows the model's operation of the Tarbela and Mangla dams in a typical year to manage the Indus' and Jehlum's water. Note that this reflects how the dams would be operated if the only purpose of the dams were water management and not hydropower.

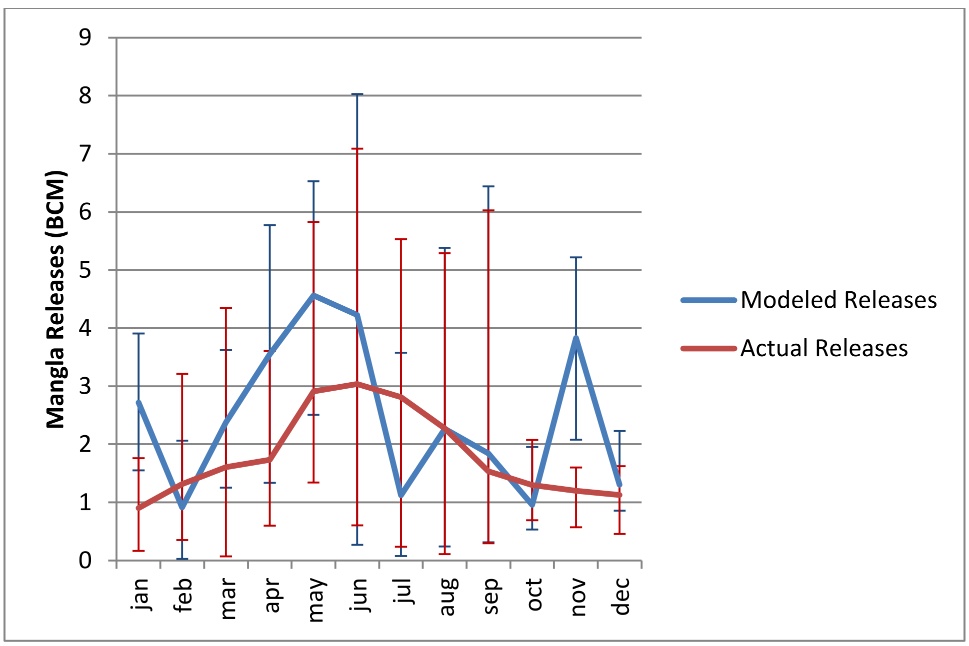
Compare these model outputs with actual mean dam releases by the Indus River System Authority (IRSA) in figure 21. Further note that storage is shown for the beginning of each month, meaning it 'lags' the residual of flow minus release by a month. The model releases most of the incoming water in the months of January-June. In July of a typical year, the dams store the high volumes of inflow and fill to more than 80% capacity. In August, the inflows are almost as high as July, but the dams have little capacity left to store the incoming water. So as the dams fill to the brim in August, most of the August inflows are simply released. This is what is meant by the Indus only being able to store a month's worth of flows. August releases are far in excess of August demand and, absent any downstream storage, go unused to the Arabian Sea.

The model accurately depicts Pakistan's tough balancing act between storing high summer inflows and buffering against a flood. If the dams are filled up in July, it ceases to act as a flood mitigation mechanism. As mentioned before, in July 2010, Pakistan's water managers filled up the dams to more than half capacity, fearing a dry monsoon. In the last week of July, unusually heavy rains flooded Tarbela dam which could not store them. The high inflows had to be released to flood farmland. Additional storage capacity could have mitigated the flood.

In November of a typical year, the dams release most of their stored capacity to irrigate wheat planting. By December, which is wheat growing season, the dams are mostly depleted. For the rest of winter and spring, until the next monsoon, the dams are empty and Pakistan is at the mercy of natural river flows and groundwater.



(a)



(b)

Figure 21: A comparison of modeled monthly releases from (a) Tarbela and (b) Mangla dams with actual dam release data from 1974-2000, where the error bars show the range (maximum and minimum values) of releases over this period. Source: Government of Pakistan, 2001.

A comparison with actual data on dam releases from the Government of Pakistan (2001, figure 21) allows me to validate my model. For Tarbela dam, the model predicts releases in the same range as actual releases for nine months of the year. The model's releases miss the range of actual releases in the months of July, November and January. In

July, more water is released from Tarbela than the model predicts. This is because Tarbela is actually used to fulfill hydropower as well as irrigation needs, with the former peaking in the summer, whereas the model optimizes only for water stress. This can be seen in the case of Mangla dam as well. In November and in January, the model tends to over-predict both Tarbela and Mangla releases. This may either indicate a miscalculation of water demands in these months, or be attributable simply to a difference in the timing of groundwater pumping. In the model, groundwater is extracted in December-March, and not in November. It may well be that in reality, groundwater is extracted in November, in which case dam releases need not be as high. I do not possess data on monthly groundwater extraction and have placed no constraints on the timing of pumping. Similarly, the model over-predicts Mangla releases in April and May, which may point to inaccuracies in monthly water demands. The reader is advised to note these caveats for the rest of the analysis.

2.2 Mean Annual Cycle of Water Stress in Major Indus Provinces

In the most populous province of Punjab, the agricultural heartland of Pakistan, the model manages to keep water stress at or below 0.7 for most of the year (figure 22). This includes the winter growing season of wheat and the summer growing season of cash crops like sugarcane and cotton. However, in April and May, water stress approaches 1 in Punjab. This indicates that irrigation demands are being met by exceeding the sustainable groundwater yield, and groundwater is being mined in late spring, especially in dry years. Water tables, however, are falling in most of Punjab, unable to keep up with the rapid increase in the number of tubewells in recent years (Briscoe and Qamar, 2007). As the groundwater reserves get depleted, dry years will become more stressed and the sowing season of important cash crops like sugarcane, cotton and maize will be increasingly affected.

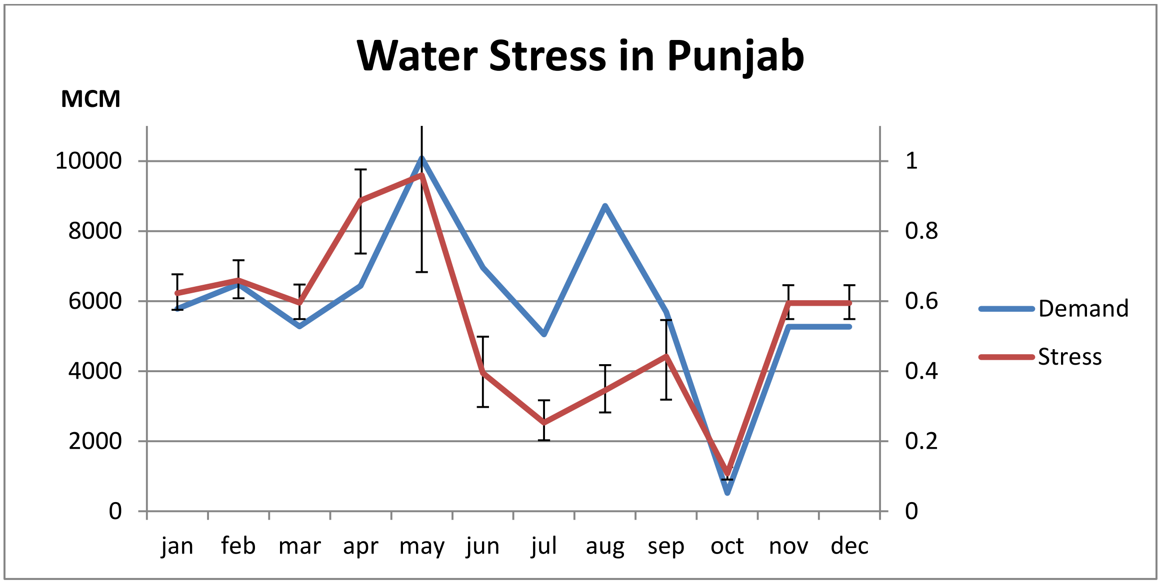


Figure 22: Water demand and average monthly water stress in Punjab over 1974-2003. The error bars show the range of monthly water stress during this period. Stress is plotted against the total water demand from irrigation, municipal and industrial sectors in Punjab in 2002.

The Sindh province enjoys low water stress according to my model (figure 23). At worst, the stress goes up to 0.53 in the wheat sowing season. However, it is important to note that my regime does not account for the ecosystem needs of the delta mangroves, which Sindh claims are about 10 MAF (12.3 BCM) annually, and which do not reach the sea in drought years. Counting this environmental water requirement should scale up the water stress in Sindh. However, I have not included that demand in my analysis because the timing of the demand is uncertain.

In the KPK province, the stress is similarly low but may be even lower in reality. This is due to the fact that my model does not include the Warsak dam on the Kabul river for simplicity. This dam (with a live storage capacity of 300 MCM) irrigates the agricultural plains of the Peshawar valley.

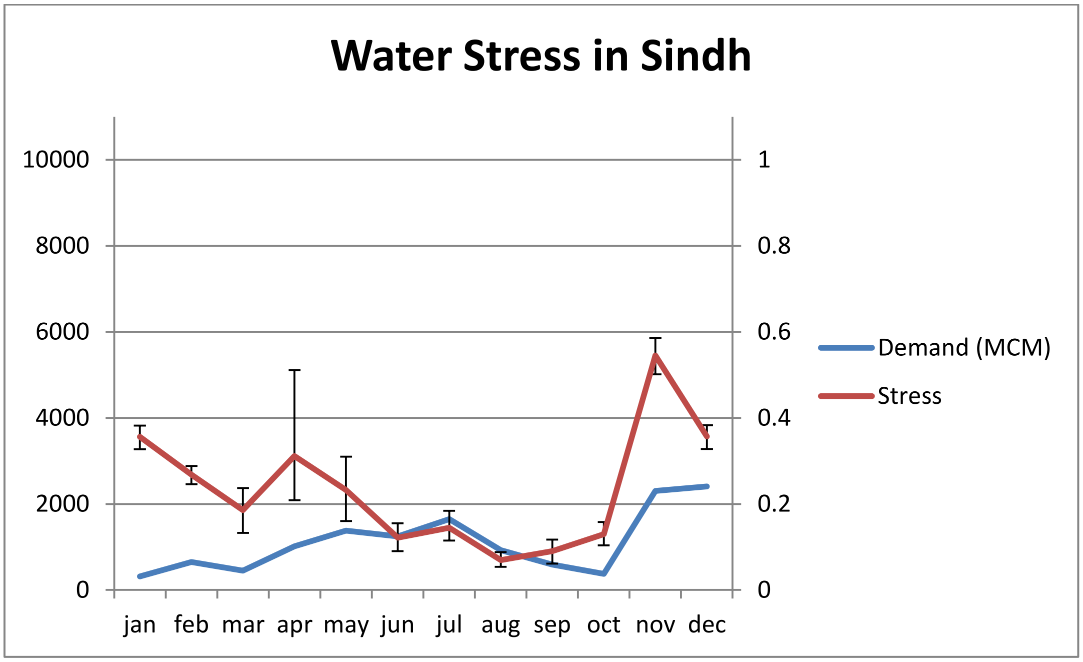


Figure 23: Average monthly water stress in Sindh over 1974-2003. The error bars show the range of monthly water stress during this period. Stress is plotted against the total water demand from irrigation, municipal and industrial sectors in Sindh in 2002.

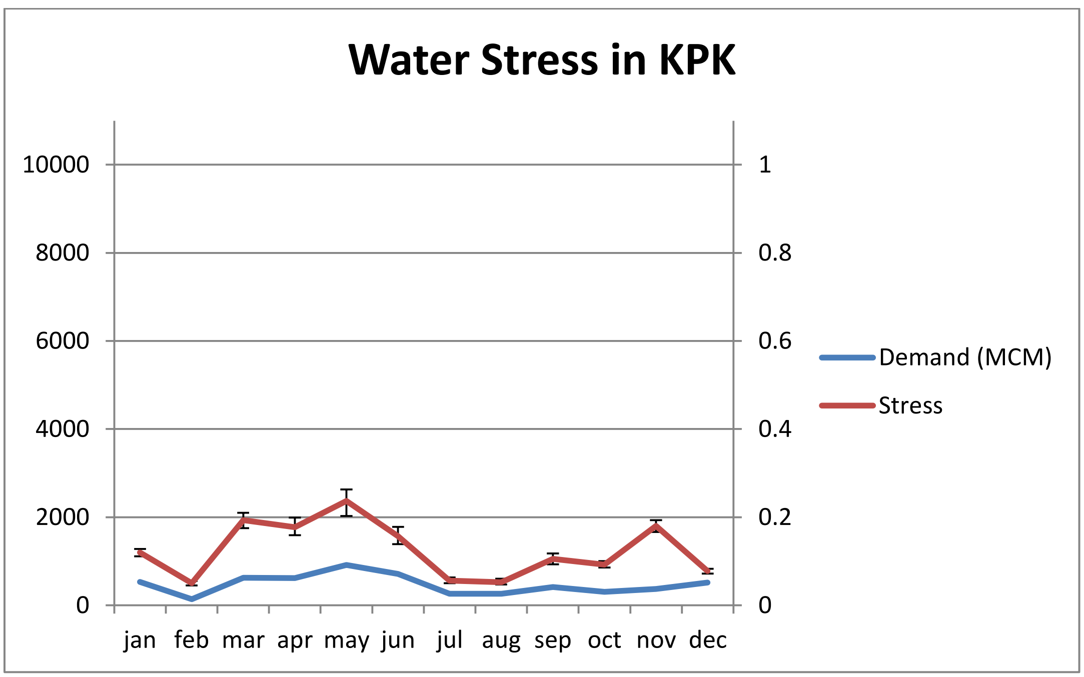


Figure 24: Average monthly water stress in KPK over 1974-2003. The error bars show the range of monthly water stress during this period. Stress is plotted against the total water demand from irrigation, municipal and industrial sectors in KPK in 2002.

2.3 Augmenting Storage Capacity on the Indus

Pakistan is planning to build another dam upstream of Tarbela, called the Diamer-Bhasha (or Bhasha) dam. Located near Gilgit, the live storage capacity of this dam will be roughly 7900 MCM (WAPDA's brochure on Bhasha Dam). Adding Bhasha to the system will add to the security of the winter months by retaining more of the excess releases during the peak flows of July and August than Tarbela and Mangla are currently able to achieve (see figures 25 and 26). In the next section, I show that during the months of November-March, Bhasha dam will uniformly lower stress in Punjab in all years by 5% (table 6).

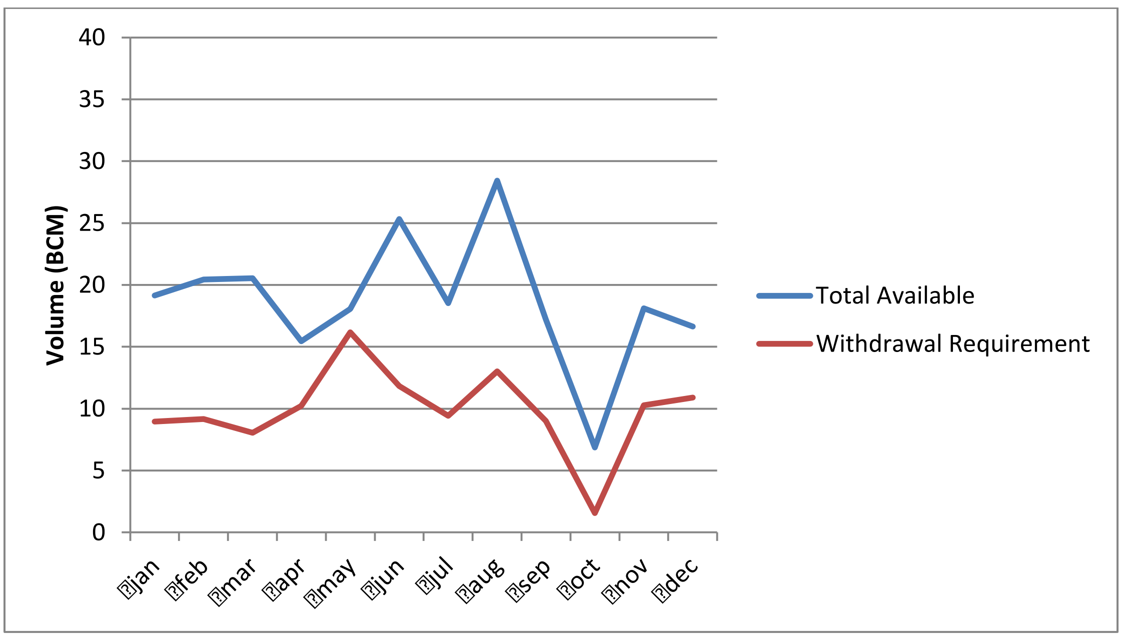


Figure 25: Monthly water withdrawals against the water made available after the addition of Bhasha dam to the system. Available water includes releases from Tarbela, Bhasha and Mangla dams as well as Chenab, Kabul, Swat, Ravi and Sutlej flows. It includes groundwater, which in the model is pumped in December-March to make up for low river flows. Compare this with figure 19.

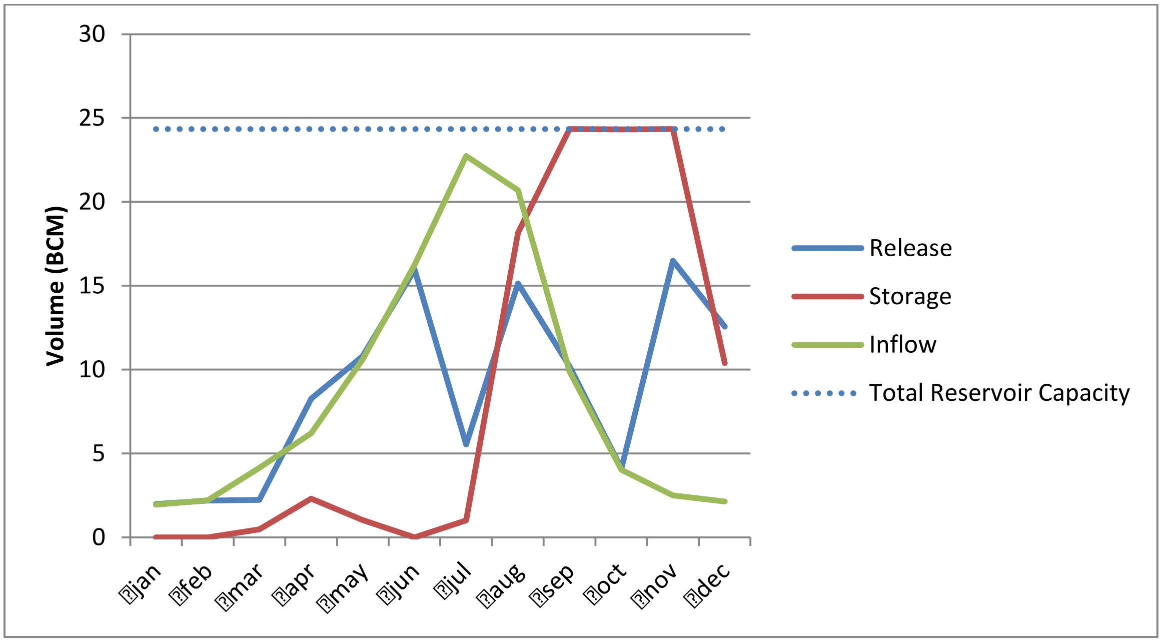


Figure 26: The model's operations of the Tarbela, Bhasha and Mangla Dams, here shown jointly, against the incoming flows of the Indus and Jehlum rivers, also shown jointly. All quantities shown are mean values over 30 years. Compare this with figure 20.

2.4 Monthly Water Stress

Figure 27(a)-(l) shows the detailed output of the model. It details the monthly stress in three provinces of Pakistan against historical fluctuations in river flows in that month. The figure also shows the effect of adding another storage dam to the system – here taken to be the 7900 MCM storage capacity of Bhasha Dam. Generally, high flows correspond to low stresses, as expected. However, the water stress in the winter months is reduced preferentially, at the expense of spring and summer, in agreement with Pakistan's emphasis on food security. So, in years of low flow, the dams direct the drought disproportionately to the spring and summer months.

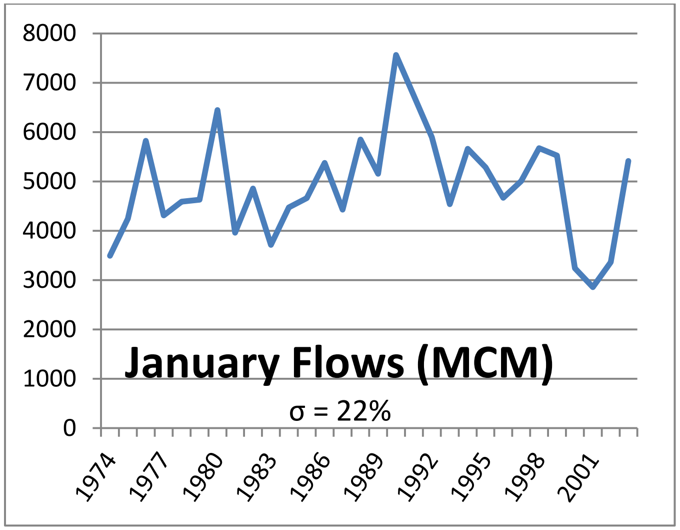
A survey of the flow data shows that flows are most erratic in the months of February-April, when they have diverged up to 65% from the mean value over 30 years.

The effect of these fluctuations is most apparent in months like April when demands are high. Stress in April in Punjab ranges goes up to almost 1 in dry years (figure 27(d)).

The addition of Bhasha dam is particularly effective in reducing water stress during the drought years. In figure 27(d), the stress during April in Punjab with current storage capacity peaks in the years 1974, 1984, 2000 and 2001 when the flows are at their lowest. Conversely, the stress dips in 1991 and 1998 when the flows are the highest. With Bhasha in place, the high April stress during the low-flow years of 1974, 1984, 2000 and 2001 is reduced, whereas the low stress during the wet years of 1991 and 1998 is left unchanged.

Even though the model favors winter months, Bhasha dam successfully targets stress in May and June as well when stress can be high. It slashes off the peaks in stress during the driest May's of 1974, 1977, 1984 and 1997. Chapter 4 explores the issue of Bhasha dam in greater detail.

Figure 27(a): Water stress in January as estimated by the model from 1974-2003. Total river flows are also provided.



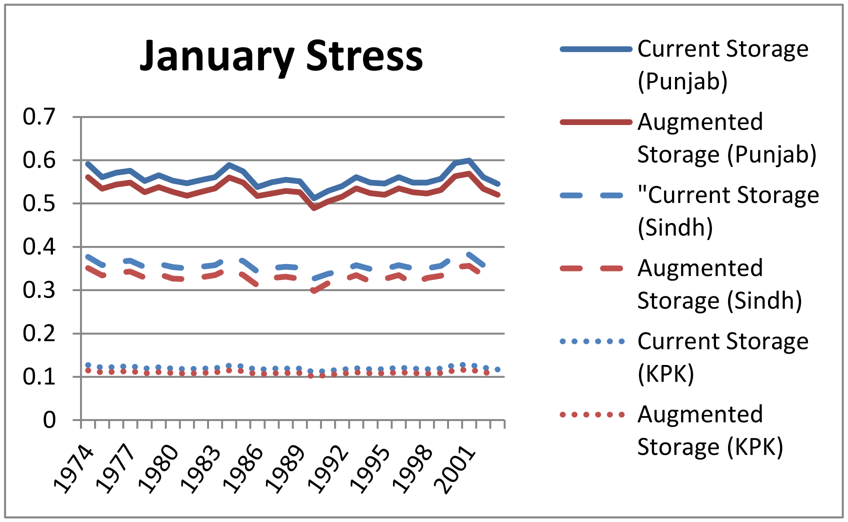
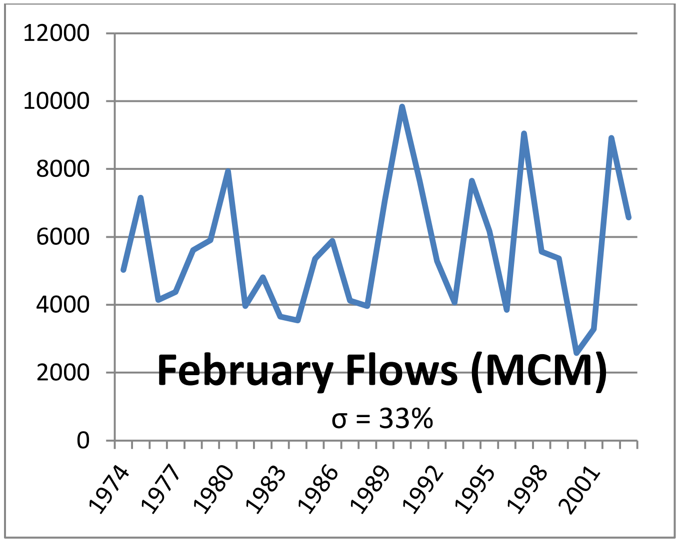


Figure 27(b): Water stress in February as estimated by the model from 1974-2003. Total river flows are also provided.



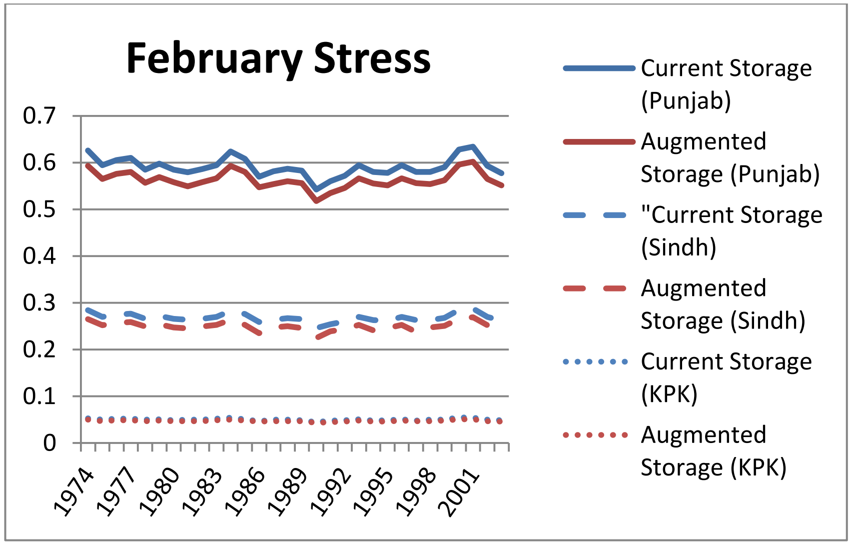
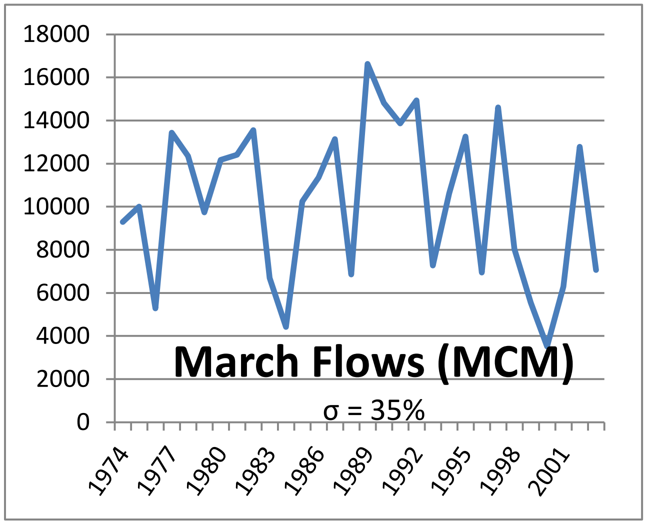


Figure 27(c): Water stress in March as estimated by the model from 1974-2003. Total river flows are also provided.



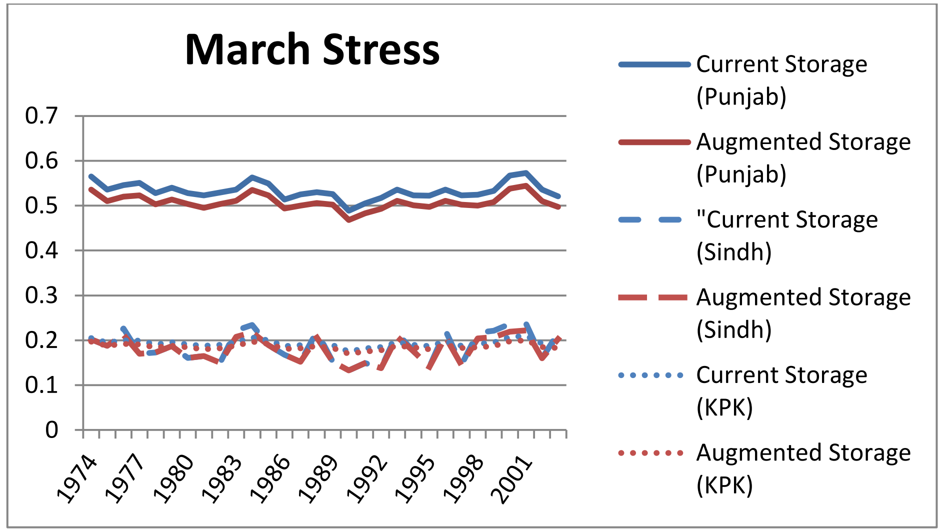
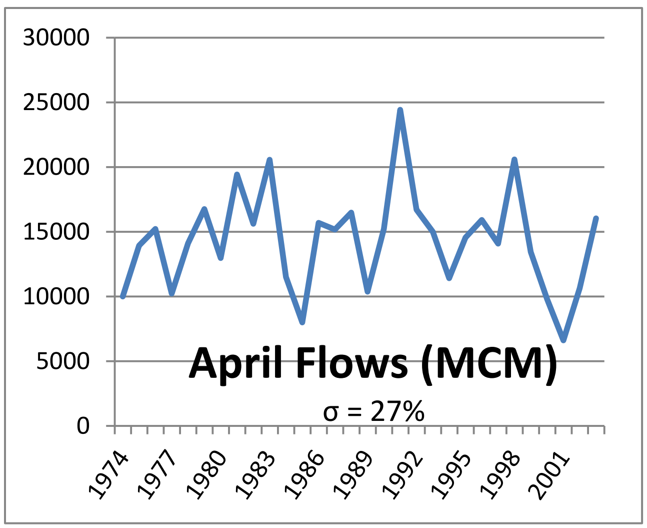


Figure 27(d): Water stress in April as estimated by the model from 1974-2003. Total river flows are also provided.



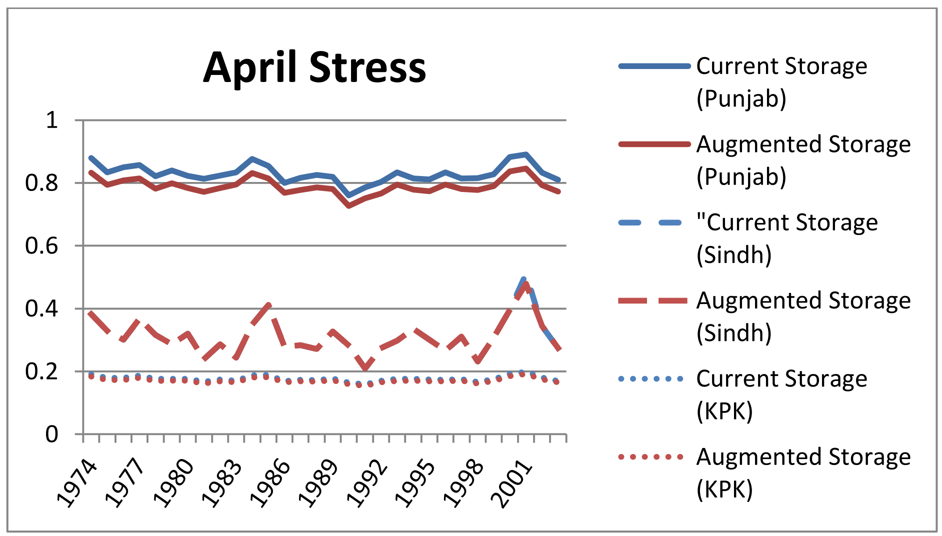
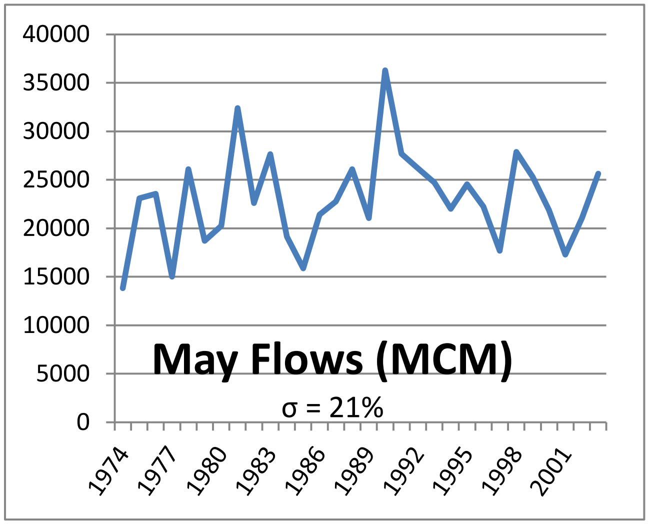


Figure 27(e): Water stress in May as estimated by the model from 1974-2003. Total river flows are also provided.



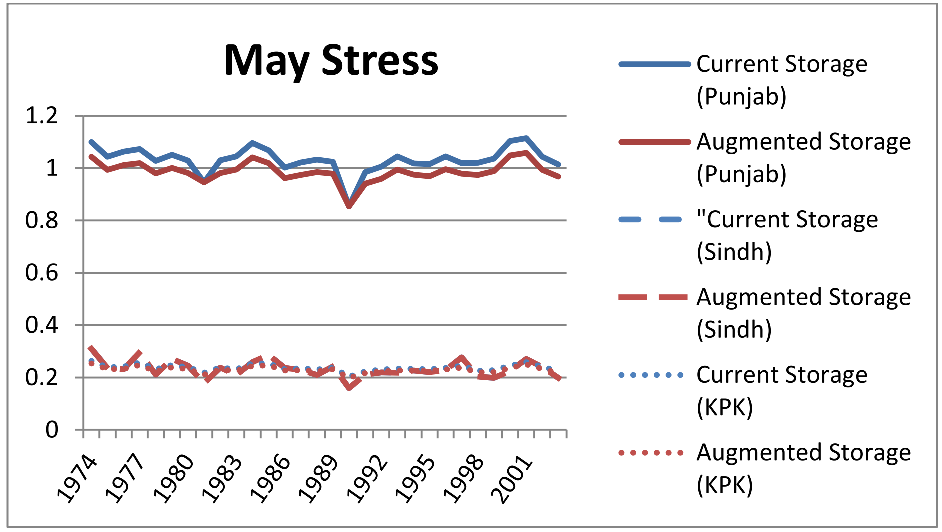
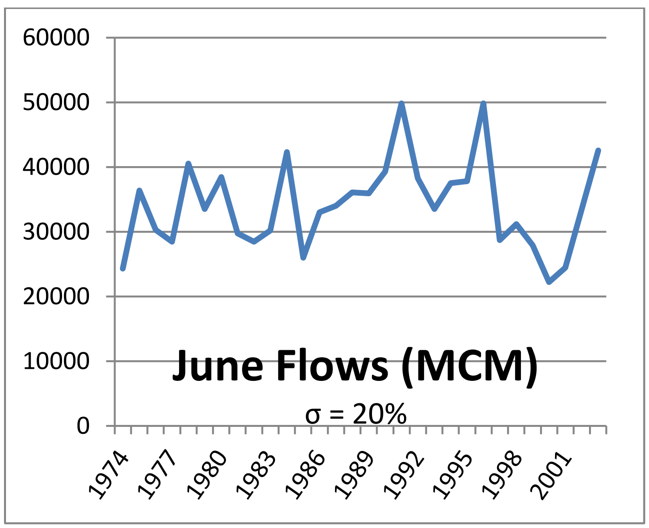


Figure 27(f): Water stress in June as estimated by the model from 1974-2003. Total river flows are also provided.



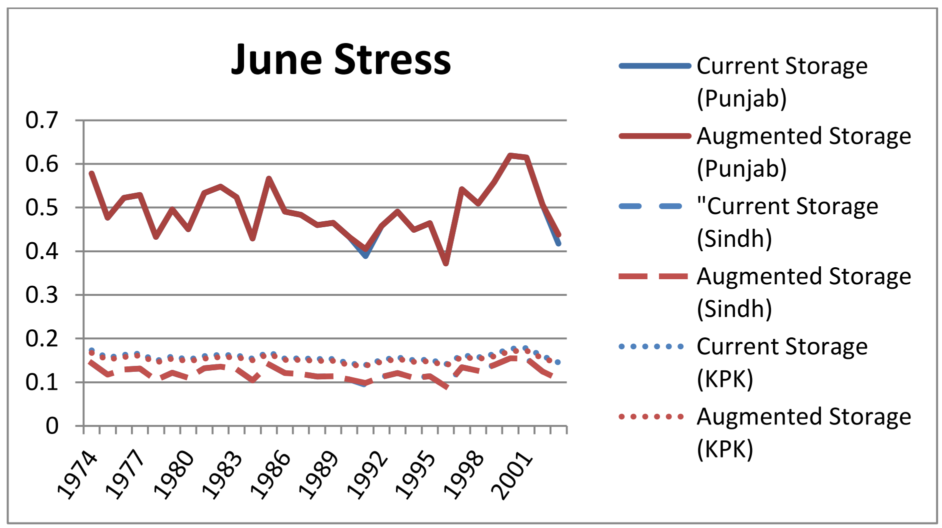


Figure 27(g): Water stress in July as estimated by the model from 1974-2003. Total river flows are also provided.

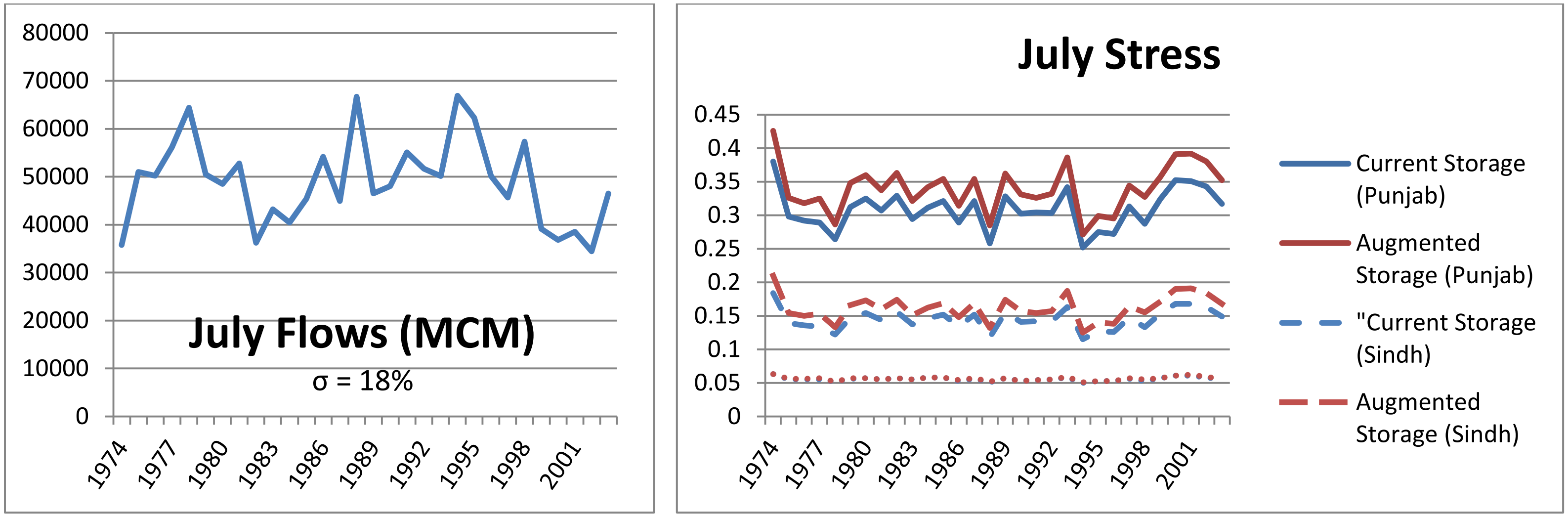


Figure 27(h): Water stress in August as estimated by the model from 1974-2003. Total river flows are also provided.

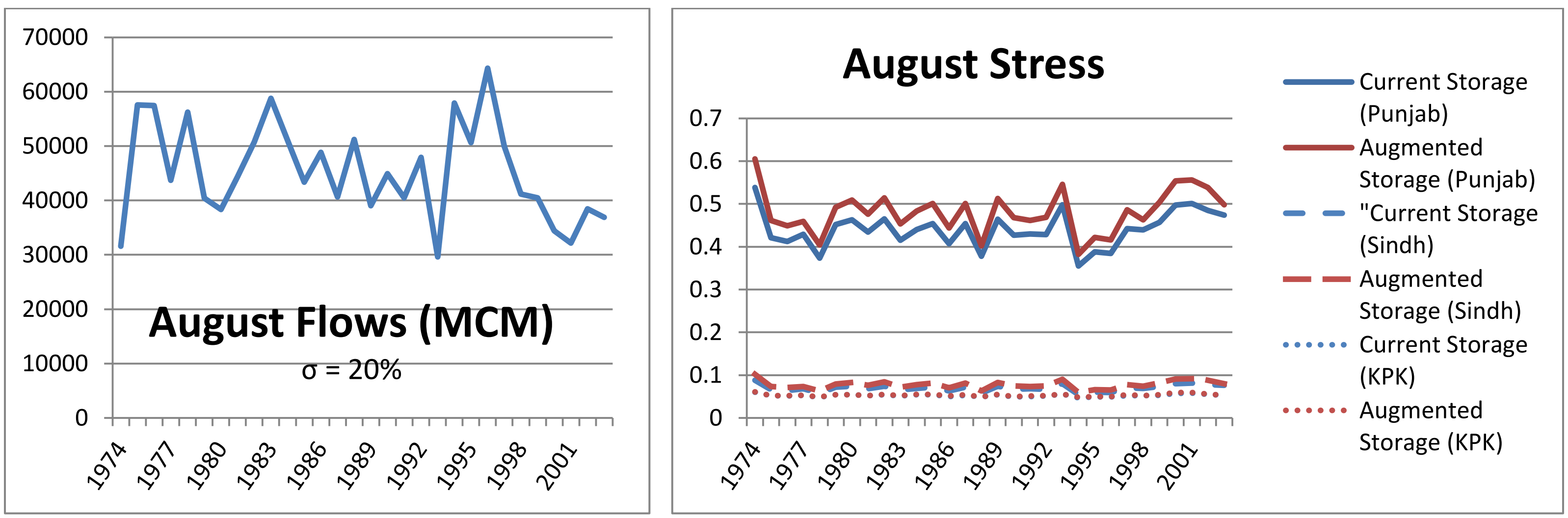


Figure 27(i): Water stress in September as estimated by the model from 1974-2003. Total river flows are also provided.

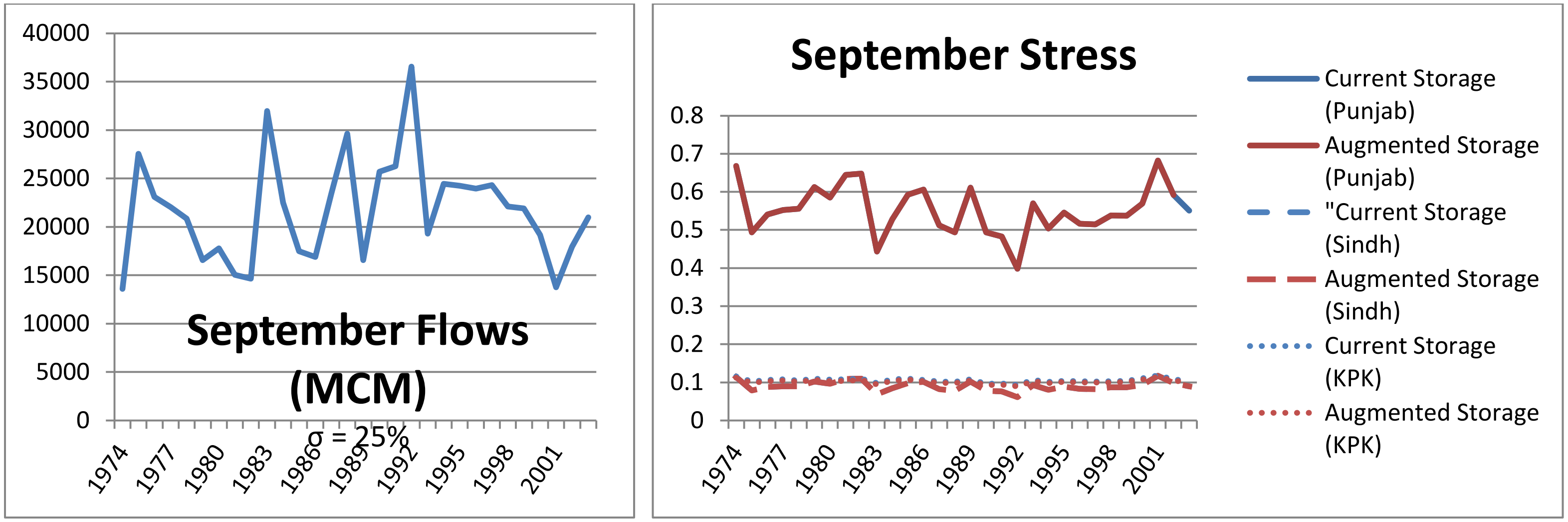


Figure 27(j): Water stress in October as estimated by the model from 1974-2003. Total river flows are also provided.

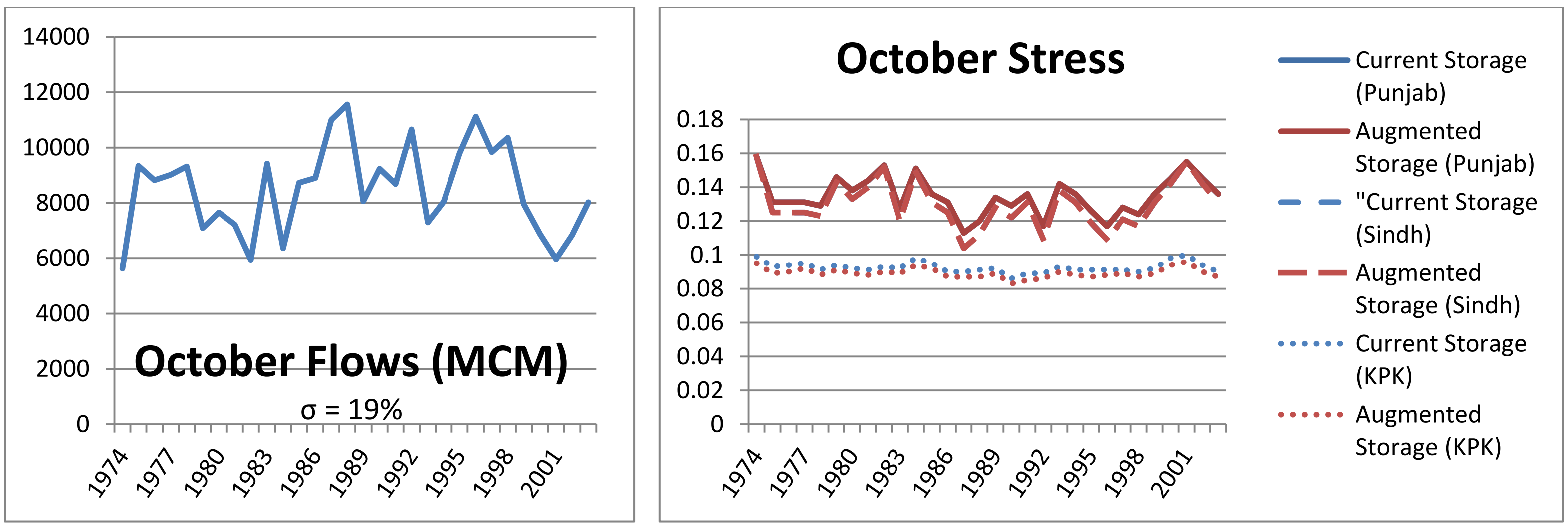


Figure 27(k): Water stress in November as estimated by the model from 1974-2003. Total river flows are also provided.

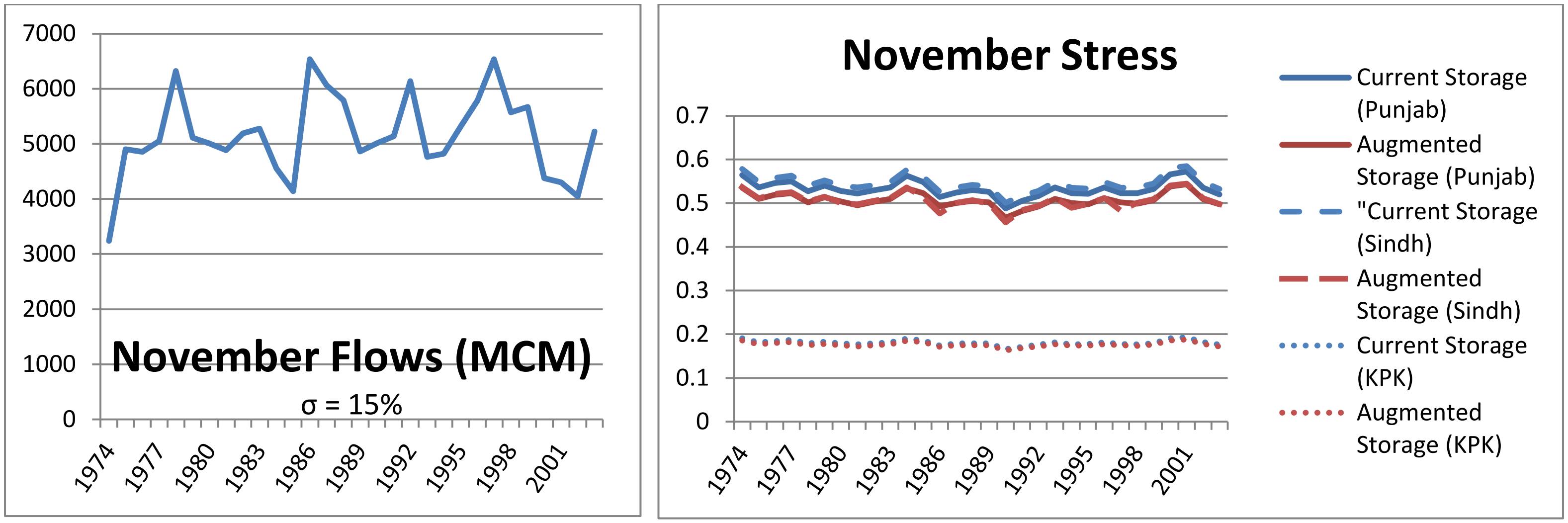
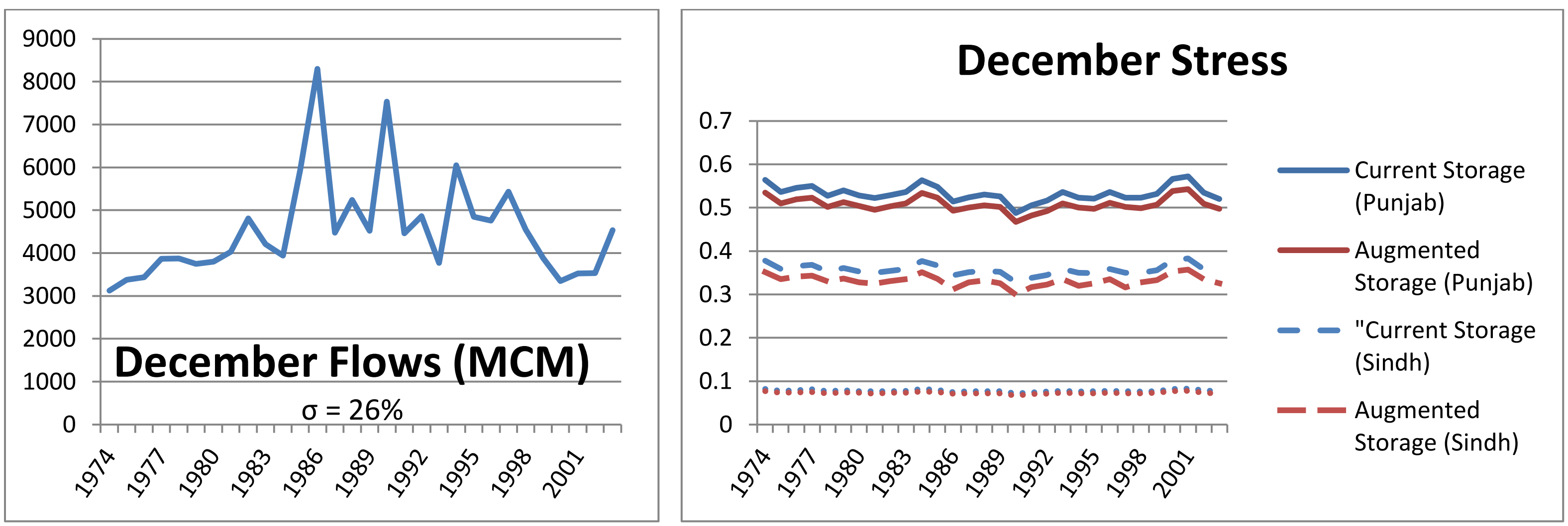


Figure 27(l): Water stress in December as estimated by the model from 1974-2003. Total river flows are also provided.



	Punjab			Sindh			KPK		
	Stress with Augmented Storage	Stress with Current Storage	Decrease in Stress	Stress with Augmented Storage	Stress with Current Storage	Decrease in Stress	Stress with Augmented Storage	Stress with Current Storage	Decrease in Stress
January	0.53	0.56	5%	0.33	0.36	7%	0.11	0.12	9%
February	0.56	0.59	5%	0.25	0.27	7%	0.05	0.05	6%
March	0.51	0.53	5%	0.18	0.19	3%	0.19	0.19	4%
April	0.79	0.83	5%	0.31	0.31	0%	0.17	0.18	3%
May	0.99	1.03	4%	0.23	0.23	0%	0.23	0.24	3%
June	0.49	0.49	0%	0.12	0.12	0%	0.15	0.16	3%
July	0.34	0.31	-10%	0.16	0.14	-12%	0.06	0.06	-1%
August	0.48	0.44	-9%	0.08	0.07	-11%	0.05	0.05	-1%
September	0.55	0.55	0%	0.09	0.09	0%	0.10	0.11	3%
October	0.13	0.13	0%	0.13	0.13	0%	0.09	0.09	4%
November	0.51	0.53	5%	0.51	0.55	7%	0.18	0.18	2%
December	0.51	0.53	5%	0.33	0.36	7%	0.07	0.08	6%

Table 6: The effect on province-wise monthly water stress of adding Bhasha Dam to the Indus infrastructure. Bhasha dam cuts water stress in the winter months by 5-9% in all provinces. The rises in stress in the monsoon season are owing to a greater retention of peak river flows.

3 CLIMATE CHANGE ANALYSIS

What is the likely impact of climate change on water stress in the Indus basin? In this chapter, I answer this question by:

a) Analyzing historical trends in temperature, precipitation and glacier cover in the upper Indus basin;
b) Investigating GCM predictions for the same parameters to 2050;
c) Using both, construct plausible climate change scenarios;
d) Translating changes in temperature, precipitation and glacier cover to changes in river runoffs;
e) Projecting irrigation, household and industrial water demands in the Indus basin to 2050, assuming GDP growth under (i) no climate policy and (ii) stabilization of global greenhouse gas emissions;
f) Running WRS-Indus in 2050 under each scenario.

3.1 Climate Change: Trends and Projections

The Global Change Impact Study Center analyzed Climate Research Unit (CRU) data for the country as a whole to announce an overall pattern of warming of +0.6C over 1900-2000. This trend is significant at 99 percent level (Sheikh et al. 2009). The upper Indus Basin has been warming disproportionately with respect to the rest of Pakistan from 1960-2000, according to Immerzeel et al. (2009). However, two significant points deserve mention: (i) Winters have been warming more rapidly than summers. (ii) The warming has slowed down in the twenty-first century.

Most of the world's mountain glaciers have been shrinking for the last 50 years (World Glacier Monitoring Service 2002), including the neighboring Greater Himalaya (Hasnain 1999; Mastny 2000; Shrestha and Shrestha 2004). The global land ice measurements from space (GLIMS) project report a long-term decrease of glacier extent in the upper Indus basin (Kargel et al., 2005). However, Hewitt (2005) and Gardelle et al. (2012) report a slight mass gain and document individual surges of the highest–altitude Karakoram glaciers in the 1990's.

3.2 Scenario A: Stable Climate

I use temperature data for the years 2001-08 and 2009-10, obtained directly from Pakistan's Water and Power Development Authority for the Kachura weather station in the upper Indus basin (elevation: ~2500 m). Regression shows that summer temperatures are weakly decreasing and winter temperatures are weakly increasing.

These trends agree with Fowler and Archer's (2006) temperature trends for the Astore and Skardu weather stations (elevations: 2394 and 2210 m, respectively) obtained from the Indian and Pakistani Meteorological departments for 1961-1999. The trends in mean monthly temperature suggest a significant winter warming of 0.38°C in Skardu, but an insignificant winter cooling of 0.07°C in Astore. Summers in Skardu and Astore cooled by 0.05°C (insigificant) and 0.3°C (significant), respectively.

All of these weather stations (Kachura, Astore and Skardu) are in the snow-fed zone, well below the glacier elevation (which is above 4000m). There are conflicting accounts of the behavior of the upper Indus glaciers. For the purpose of this scenario, we consider the reports by Hewitt (2005) and Gardelle et al. (2012) that the Karakoram glaciers have been either stable or advancing since the 1990's. For the first scenario, then, I assume that no appreciable change occurs in either temperature, precipitation or glacier melt in the next 50 years. Thus, this scenario only considers rises in water demand and its subsequent effect on estimated water stress. An additional plausible scenario may be an expansion of glacier area and/or a decrease in summer temperatures. I have not considered that scenario for brevity and for inconsistency with both long term historical record and trends in neighboring mountain ranges. Future work may well consider that scenario.

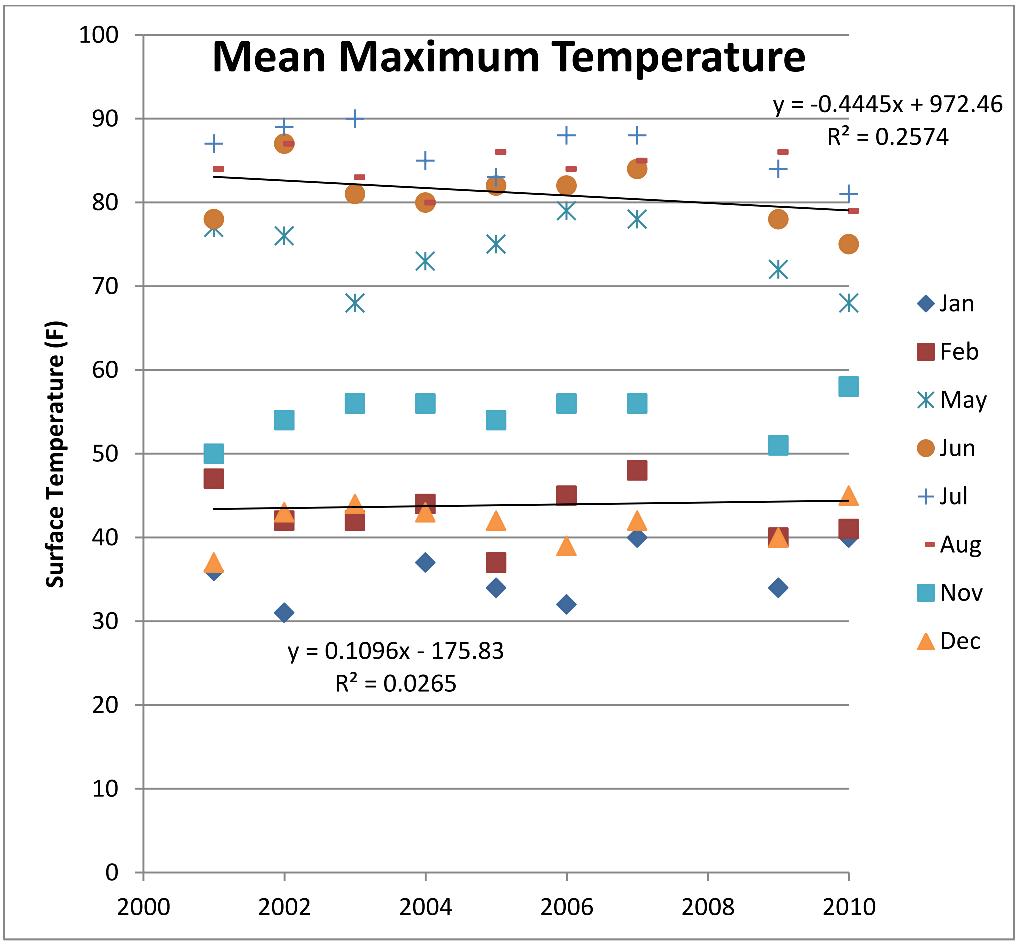


Figure 28: Plot shows monthly mean values of daily maximum temperatures at the Kachura weather station from 2001-10, excepting the year 2008 for which data is not available. Only the winter months (Nov-Feb) and the summer months (May-Aug) are plotted. Trendlines show weakly increasing winter maximum temperatures, and decreasing summer maximum temperatures.

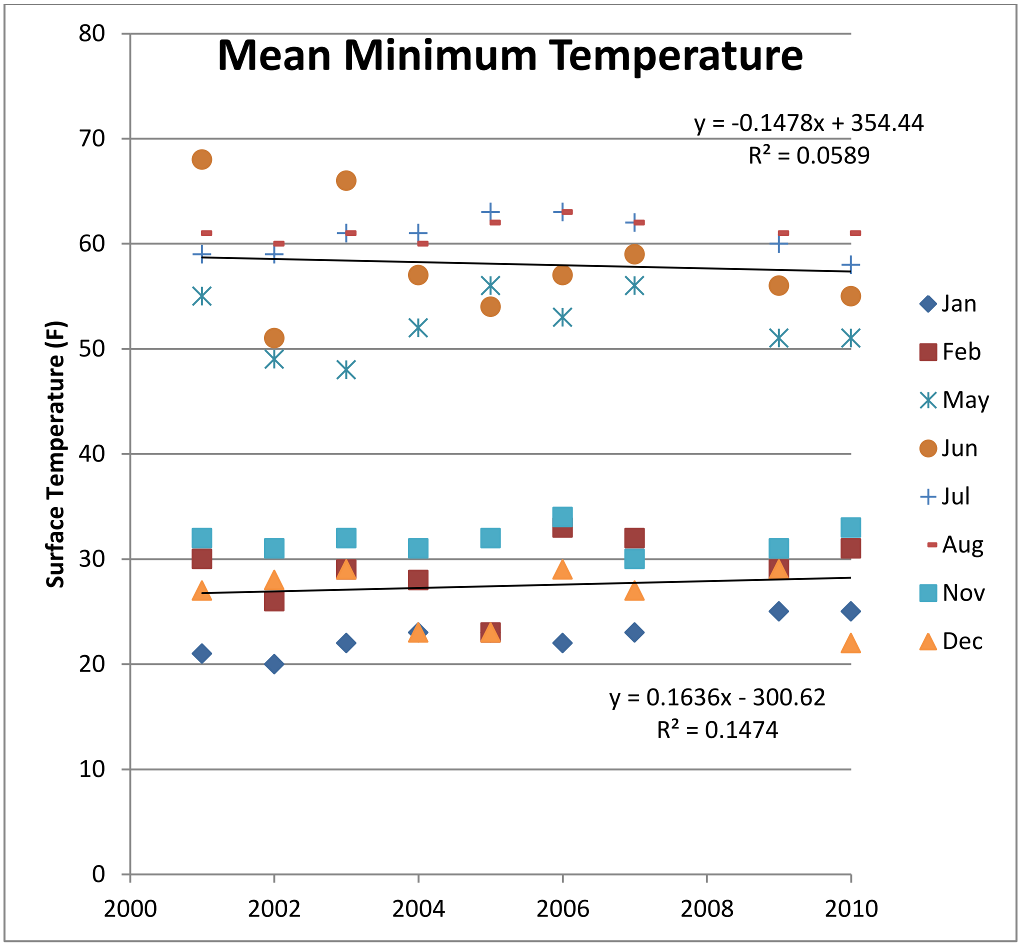


Figure 29: Plot shows monthly mean values of daily minimum temperatures at the Kachura weather station from 2001-10, excepting the year 2008 for which data is not available. Only the winter months (Nov-Feb) and the summer months (May-Aug) are plotted. Trendlines show increase in winter minimum temperatures and decrease in summer minimum temperatures. Individual winter months show stronger warming trends: January warmed at $y = 0.49x - 950$, $R^2 = 0.81$, and February at $y = 0.34x - 661$, $R^2 = 0.12$.

3.3 Scenario B: Temperature Rise with a Stable Glacier Cover

Immerzeel et al. (2009) derive long term temperature patterns in the upper Indus basin using the CRU dataset version TS 2.1. The CRU TS 2.1 is a set of monthly climate grids which are constructed for nine climate variables and interpolated onto a 0.5° grid, and provide best estimates of month-by month variations. In contrast with Fowler and Archer (2005), Immerzeel et al. (2009)

provide high elevation (>5000m) data for temperature. Table 1 shows the average temperature and precipitation trends for three elevation zones in the Upper Indus Basin for the period 1972-2002.

		T (°C)	ΔT (°C y^{-1})	P (mm)	ΔP (mm y^{-1})
Entire domain	Spring	10.5	0.023	108	0.0
	Summer	18.2	0.023	359	−1.0
	Autumn	9.9	0.027	125	−0.4
	Winter	−0.6	0.046	39	−0.1
	Annual	9.5	0.029	635	−1.5
Upper Indus basin	Spring	−1.6	0.031	109	−1.0
	Summer	9.8	0.027	115	−0.7
	Autumn	0.4	0.041	45	−0.6
	Winter	−11.6	0.053	84	−0.2
	Annual	−0.7	0.038	343	−2.6
Upper Indus basin zone 1 (2000 m)	Spring	3.8	0.024	172	−1.5
	Summer	14.0	0.012	174	−0.1
	Autumn	5.8	0.026	66	0.0
	Winter	−5.8	0.049	123	−0.9
	Annual	4.4	0.028	514	−2.7
Upper Indus basin zone 2 (4700 m)	Spring	−1.3	0.030	111	−1.2
	Summer	10.1	0.026	107	−0.5
	Autumn	0.8	0.040	43	−0.5
	Winter	−10.9	0.052	84	−0.3
	Annual	−0.3	0.037	336	−2.5
Upper Indus basin zone 3 (5000 m)	Spring	−4.3	0.034	78	−0.7
	Summer	7.6	0.035	96	−1.2
	Autumn	−2.3	0.048	37	−1.0
	Winter	−13.8	0.055	66	0.2
	Annual	−3.2	0.043	275	−2.7

Table 7: Average Seasonal Climatology and Trends from 1972-2002 based on CRU TS 2.1 dataset for the entire Himalayas, the upper Indus basin, and three elevation zones in the upper Indus basin, respectively. Source: Immerzeel et al. 2009.

In all areas there is a clear warming trend in all seasons, with the strongest trend in winter and the weakest in summer. The warming trends are stronger than the global and northern hemisphere warming rates. An interesting observation is that there are clear differences between the entire domain and the upper Indus basin, and among the elevation zones of the basin. Both the warming rate and the precipitation trends are stronger in the upper Indus basin when compared with the entire domain. Within the upper Indus basin there is a clear relation between elevation and warming rate. On an annual basis it increases from 0.028°C yr^{-1} at 2000 m to 0.043°C yr^{-1} at 5000 m.

If we take the trends in this study for the upper Indus basin – 0.027°C yr^{-1} warming in the summer and 0.053C yr^{-1} warming in the winter – and project them from 2002 to 2050, it translates to a warming of 1.3°C in the summer and 2.5°C in the winter from 2002-2050.

The Joint Program for Global Change chose two GCM's to project global climate change for water stress analysis (Schlosser et al. 2013). The climate patterns were derived from the climate simulation results from the Coupled Model Intercomparison Project Phase 3 (CMIP3, Meehl et al., 2007). The climate patterns chosen reflect the two climate models (among the CMIP3 pool of models) that project, the most "dry" (CSIRO) and the most "wet" (NCAR) pattern changes over land as determined by the climate-moisture index analyses of Strzepek and Schlosser (2010). These climate patterns were run assuming both a "no climate policy" scenario and an emissions stabilization scenario. The "Level 1 stabilization" scenario is formulated applying the growth that is projected under a global policy to restrain global emissions to the Level 1 scenario (**L1S**) developed for the US Climate Change Science Program (Clarke et al., 2007). The L1S scenario imposes a target of 560 ppm CO_2-equivalent concentrations by 2100, and it limits economic growth in some parts of the developing world: primarily Africa, Middle East, and Central and South America. The temperature rise predictions under the two scenarios are hardly different, at least to 2050. The CSIRO model predicts a summer warming over the upper Indus basin of 0.97°C to 2050, and a winter warming of 2.55°C. The NCAR model predicts a summer warming over the upper Indus basin of 0.94°C and a winter warming of 2.15°C.

Considering both historical trends and GCM predictions of temperature, I assume in scenario B that temperature in the upper Indus basin will rise by 1C in the summer and 2.5C in the winter between 2000 and 2050. However, the rate of warming in the lower troposphere increases with altitude, i.e. temperatures will increase more in high mountains than at low altitudes (Bradley et al., 2006). Immerzeel et al. (2009) have found that high altitudes have been warming a lot faster than low altitudes since 1972. Warming rate has been 0.028 °C yr^{-1} at 2000 m and 0.043 °C yr^{-1} at 5000 m according to CRU dataset. Immerzeel et al. (2009) have identified 3 climatic zones in the upper Indus basin (see figures 30 and 31):

- High altitude (>4000m) catchments where runoff depends on summer heat input
- Mid-altitude (2000-4000m) where winter precip dominates spring runoff
- Low foothills where both winter and monsoon rainfall occurs.

The upper Indus basin includes the Hunza, Gilgit, Shigar and Shyok sub-basins. The altitude of the basins ranges from 335 m to 8238 m and, as a result, the climate within the basin varies greatly. The largest part of the basin (90%) is in the rain shadow of the Himalayas and not affected by the summer monsoon (Immerzeel et al., 2009). Low intensity winter and spring precipitation originating from western low pressure systems are the primary source of water. A small part of the basin (10%) directly upstream of the Tarbela dam is unprotected by mountain ranges and subject to summer monsoon rainfall. Average annual precipitation is around 340 mm with a peak in February and in July.

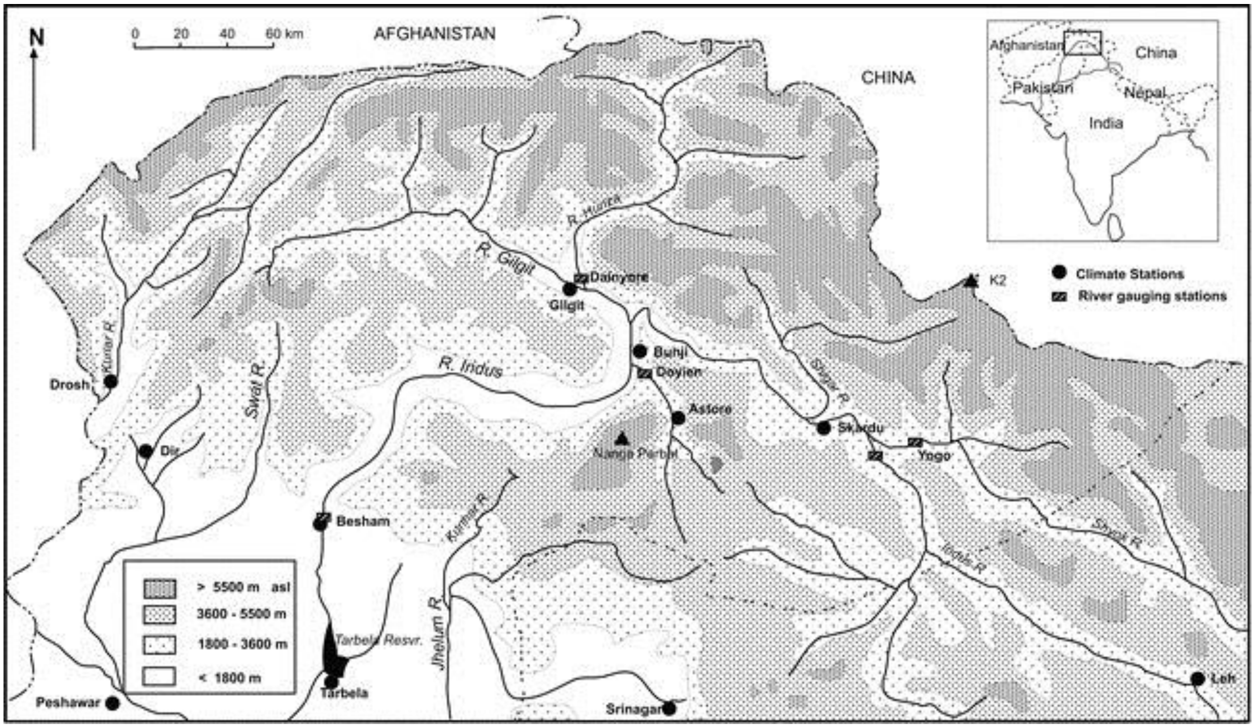


Figure 30: The upper Indus basin showing relief, rivers and stations used in my analysis. Inset shows location of the basin. Source: Fowler and Archer, 2003.

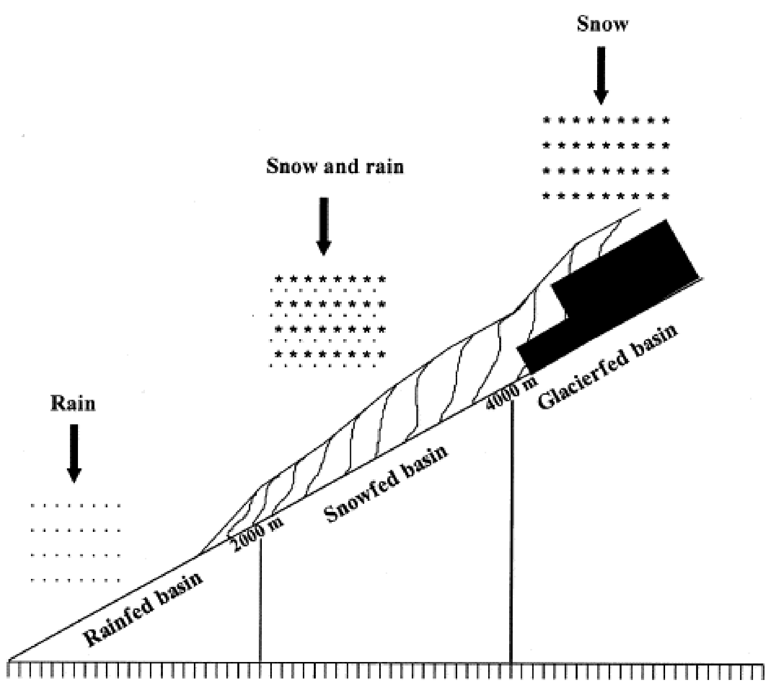


Figure 31: A schematic presentation of glacier-, rain-, and snow-fed basins. Source: Singh and Bengtsson, 2006.

Singh and Bengtsson (2004) have simulated the impacts of warming on runoff from snow- and glacier-fed basins via a conceptual snowmelt model (SNOWMOD, Singh and Jain, 2003). They use weather station data for temperature and precipitation, and remote sensing data for snow-covered area, snow-free area, and glacier-covered area, respectively. The model computes the different components of runoff by treating each elevation zone as a separate watershed with its own characteristics (figure 31). They apply the model to the Sutlej[1] river basin in the western Himalayas. 60% of the annual flows in Sutlej result from snow and glacier melt. A large portion of annual precipitation falls in the winter from westerly winds, rather than the summer monsoon. The simulated streamflow was calibrated and validated against runoff data from 1985-91. The overall efficiency of the model, explained variance, R^2 over the study period of 6 years was about 0.90. The difference in total volume of computed and observed streamflow was about 2.0% and root mean square error (RMSE) was about 0.33 min.

The model calculates snowmelt and rainfall runoff by performing the following three operations at each time step: (a) available meteorological data are extrapolated to the different elevation zones, (b) rates of snowmelt and/or rainfall are calculated at different points, and (c) snowmelt runoff from snow-covered area and rainfall runoff from snow-covered area are integrated, and these components are routed separately with proper accounting of baseflow to the outlet of the basin. Surface temperature determines the form of precipitation. If temperature is above 2°C, precipitation falls as rain; and if it is below 0°C, it falls as snow. Between 0 and 2°C, precipitation is

[1] Sutlej originates in the vicinity of the Indus river in Indian territory and historically irrigated the Indus basin (Punjab and Sindh). However, the Indus Water Treaty (1960) awarded the Sutlej to India. Residual flows reach Pakistan seasonally.

a mixture of snow and rain. The depth of snowmelt per unit area M is calculated by multiplying the surface temperature (in degrees Celsius) with the degree factor D in mm/°C/day.

They found linear but opposite responses (figure 32) of snow- and glacier-fed basins to temperature rise. With higher temperature, more snow falls as rain as the 0°C line shifts upward. In effect, with temperature rise, the rainfed zone expands upwards, the snowfed zone shifts up the mountain, and the glacierfed zone shrinks. Note that the modelers applied uniform temperature changes throughout the year to obtain the runoff relationships in figure 32.

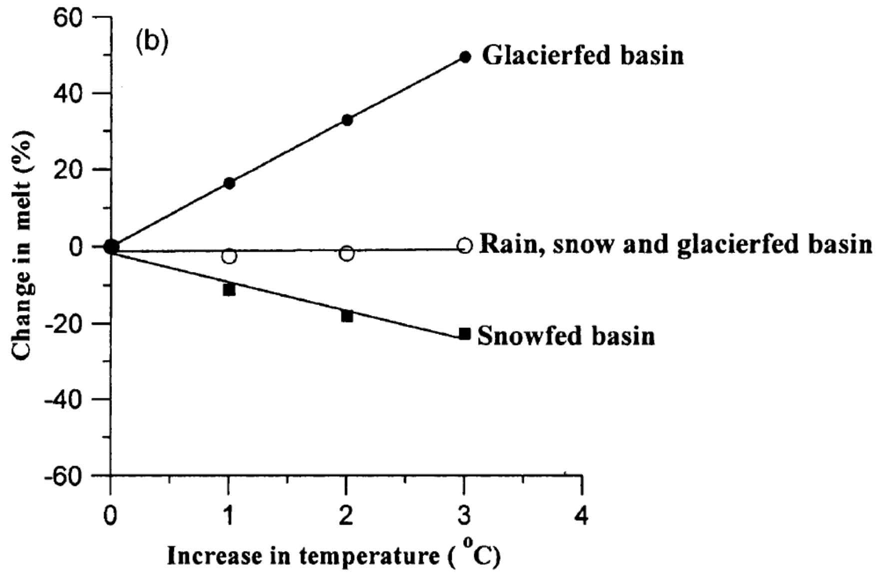


Figure 32: Modeled results for changes in annual melt with increase in temperature for different types of basins. Source: Singh and Bengtsson, 2004.

A summer temperature rise of 1°C should, then, increase glacial melt by 18%. This increase in glacial melt may or may not cause a depletion or a retreat of the glacier cover. If precipitation above 5000m (in the glacial zone) increases in tandem with the melt loss due to temperature rise, the glacier cover may remain stable from a mass-balance point of view. Immerzeel et al. (2009, table 7) show that precipitation trends in the glacial zone have been rising in the winter but falling in the rest of the year. However, if precipitation does not rise in the glacial zone, then the glacier cover will shrink and the snowfed zone will move upward.

Temperature rise may also cause increasing amount of snow to fall as rain, thus decreasing runoff from the snowfed zone. In contrast with glacier melt, which is exclusively a summer phenomenon (figure 33), snow melt is distributed over the spring and summer. Our approach then is to decrease the snow melt in the winter months (October-March) by 20% (corresponding to a 2.5°C temperature rise) and in the summer months (April-September) by 8% (corresponding to a 1°C temperature rise). These cuts in snow melt now fall as rain and are distributed over the year according to the rain probability mass function (PMF, figure 33), which runs off quickly. The assumption here is that this PMF will not change 2050 even as temperature rises.

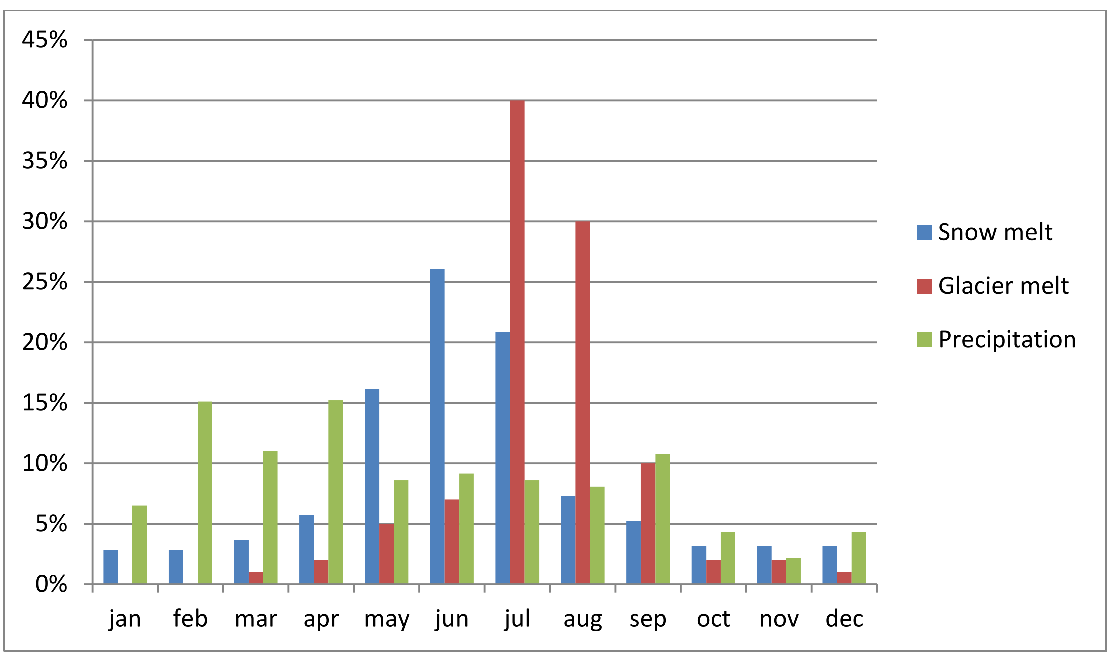


Figure 33: The year-round probability mass function (PMF) of snow- and glacier-melt in the rivers originating from the Karakoram/western Himalayas, as modeled by Immerzeel et al. (2009). Each monthly value of snow

melt is expressed as fraction of total annual snow melt, and likewise for glacier melt. While glacier melt is a summer phenomenon, snow melt is distributed over the spring and summer, and rain is distributed throughout the year. I use these PMFs to arrive at a distribution of the estimated snow- and glacier-melt components of observed annual runoff.

The missing piece of information now is the composition of the Indus river system in terms of its glacier melt, snow melt and rain components. Yu et al. (2013) and Bookhagen and Burbank (2010) provide breakdown of the flows of the Indus tributaries (table 8). According to Yu et al. (2013), the Indus runoff derives on average 55% from snow-melt and 32% from glacier melt. The Chenab river derives 90% from snow melt and 10% from glacier melt. The Jehlum river is composed 100% of snow melt, claim Yu et al. (2013).

		Area, (km^2)	**Glacier, (km^2)**	**q (mm)**	**Q (MAF)**	**Ice melt (MAF)**	**Snow-melt (MAF)**
(a)	Hunza	13,734	4,339	0.76	8.5	4.0	4.5
(b)	Astore	3,988	450	1.29	4.2	0.8	3.4
(c)	Shigar	6,922	2,885	0.98	5.5	2.9	2.7
(d)	Shyok	33,350	6,221	0.32	8.7	4.9	3.8
(e)	Gilgit	12,682	994	0.62	6.4	1.5	4.8
(f)	Kachura (estimated)	75,000	n.a.	0.21	12.9	n.a.	12.9
(g)	**Beshama**	**166,096**	**14,889**	**0.44**	**58.0**	**14.1**	**32.0**
(h)	Chitral	11,396	2,718	0.71	6.6	3.2	3.4
(i)	**Chenab**	**22,503**	**2,708**	**1.22**	**22.2**	**2.3**	**19.9**
(j)	**Jhelum**	**27,122**	**0**	**1.08**	**23.6**	**0**	**23.6**
	Total	***199,995***	***20,315***		***110.4***	***19.6***	***79.0***

Table 8: Estimated contributions of glacier and snow melt to the Indus tributaries, as well as the Jehlum and Chenab rivers. In bold are the three major rivers of Pakistan represented explicitly in my model. (g) Beshama represents the Indus river as it flows into the Tarbela reservoir after the Hunza, Gilgit, Shigar and Shyok rivers have joined it. Source: Yu et al., 2013.

Yu et al.'s (2013) estimates of the contribution of melt to river runoffs are consistently higher than those reported by Bookhagen and Burbank (2010). The latter report only melt contribution, which lumps together both snow- and glacier-melt. Their reported snow melt contributions are 65.7% to the Indus, 43.4% to Chenab, and 24.9% to Jehlum. A likely reason for the difference between Yu et al. (2013) and Bookhagen and Burbank (2010) is that the former use runoff data upstream at high elevations, whereas the latter use downstream flow. Yu et al. (2013) report no rain contribution to the Jehlum and Chenab rivers, which indicates that they report the fraction of melt water in the upstream Indus tributaries. When these tributaries pass the Himalayan foothills and enter the plains, their runoffs include rainfed runoff. In other words, Yu et al.'s (2013) estimate of rainfed contribution to runoff is not applicable to this analysis. I am concerned with this latter definition of runoff which reaches the plains. But the ratio between snowmelt and glacial melt that Yu et al. (2013) is useful.

So, my approach is to use Bookhagen and Burbank's (2010) estimates to determine how much of the 'downstream' river runoff is melt water. On this melt water contribution to river runoffs, I impose Yu et al.'s (2013) ratio between snow melt and glacial melt. The resulting breakdown of the annual Indus, Jehlum and Chenab runoffs into their rain, snow and glacier melt components is shown in Figure 34. The runoffs used are averaged over 1998-2002. Glacial melt contributes 20% to the Indus runoff, 4% to the Chenab runoff, and 0% to the Jehlum runoff. Snow melt contributes 46% to the Indus runoff, 39% to the Chenab runoff, and 25% to the Jehlum runoff.

Using the PMF of snow melt and glacier melt established in Figure 33 (Immerzeel et al., 2009), I distributed the aggregate annual snow melt and glacier melt over the twelve months (Figures 35-37).

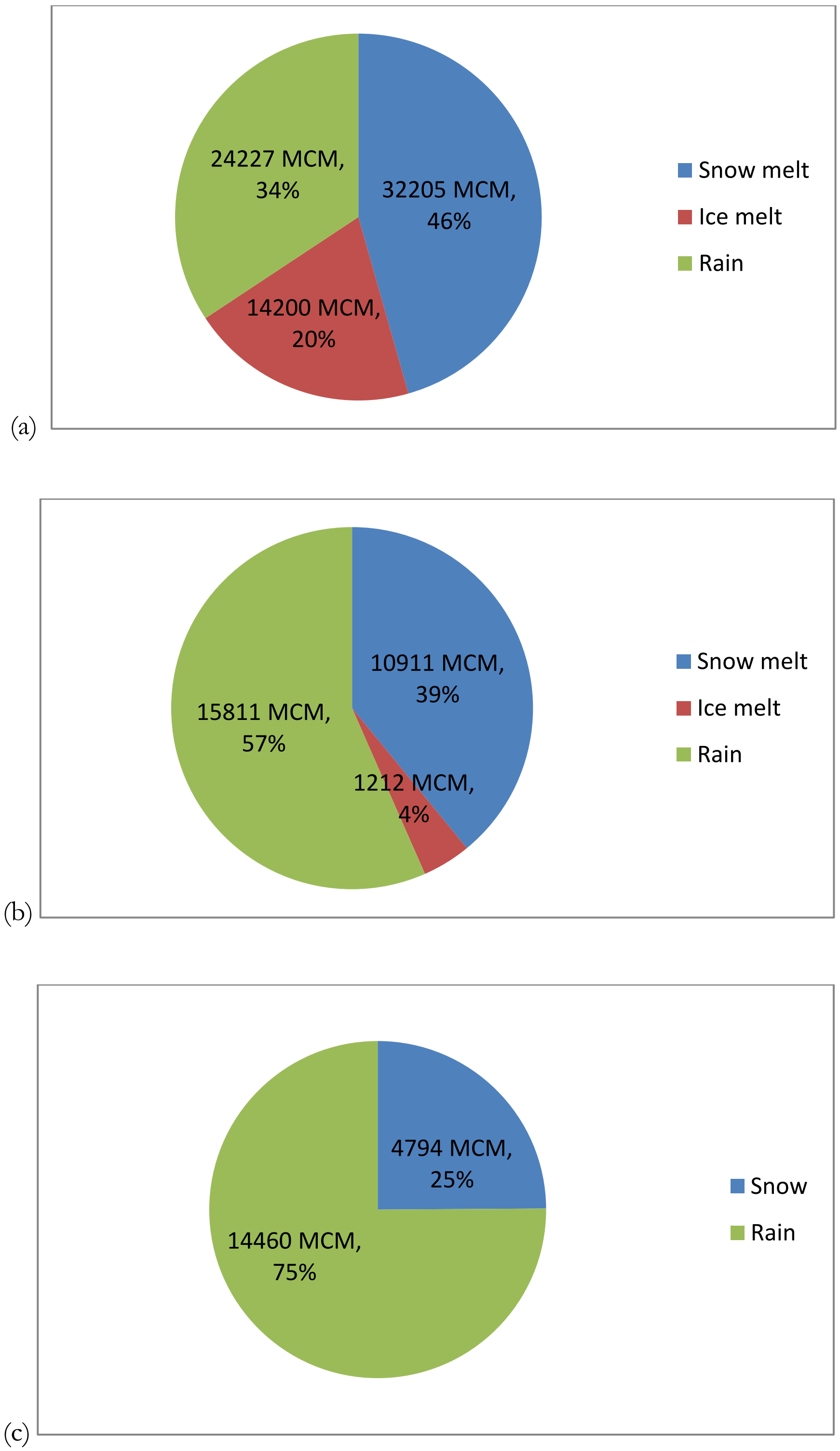


Figure 34: A breakdown of the snow melt, glacier melt and rain-fed components of the mean annual runoff in MCM from 1998-2002 in (a) the Indus river, (b) the Chenab river and (c) the Jehlum river.

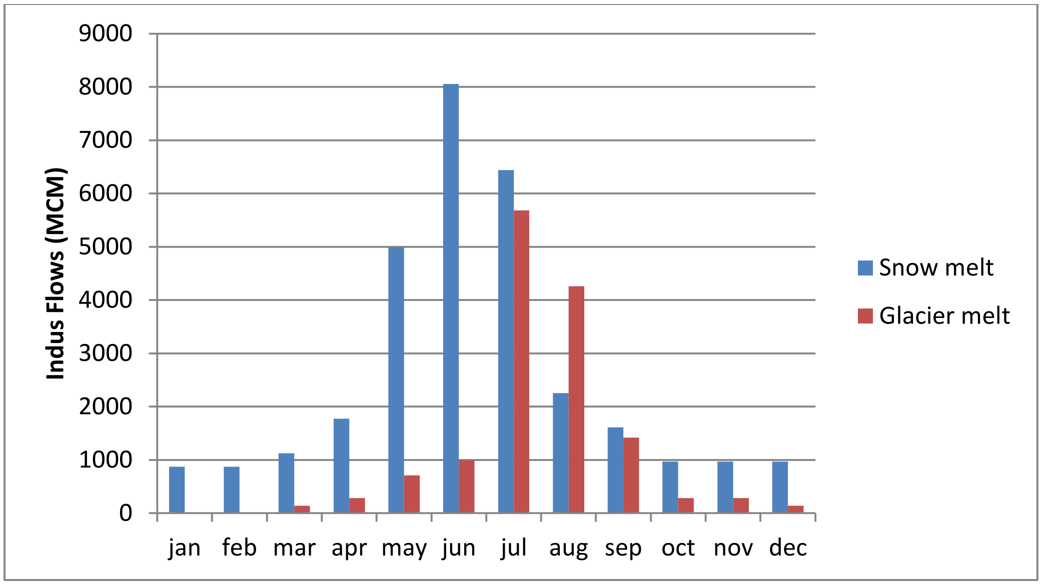


Figure 35: Estimated distribution of snow- and glacier-melt in the Indus river on a mean annual basis. Data shows the breakdown of mean annual runoff from 1998-2002.

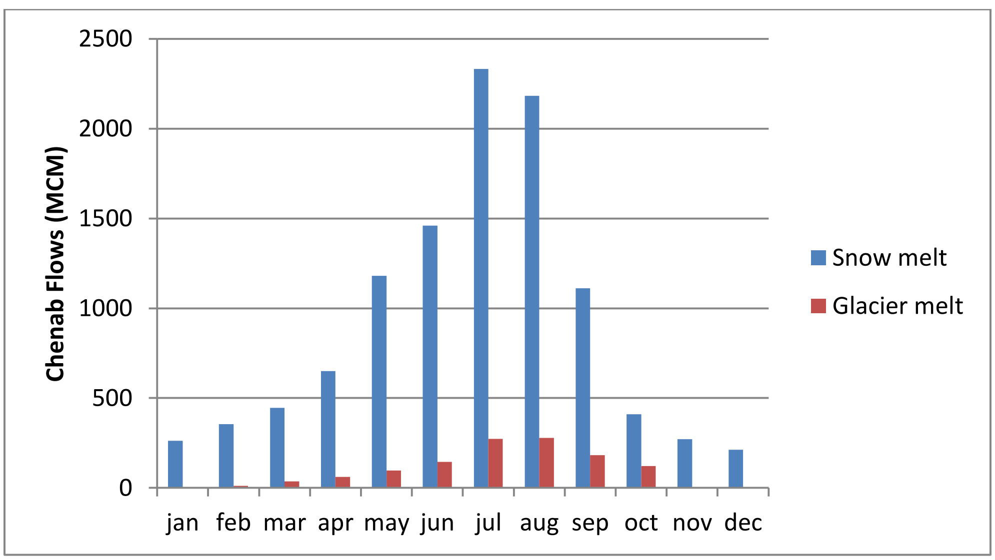


Figure 36: Estimated distribution of snow- and glacier-melt in the Chenab river on a mean annual basis. Data shows the breakdown of mean annual runoff from 1998-2002.

Figures 38-40 show the simulated snow- and glacier melt components of the Indus, Chenab and Jehlum, respectively, in 2050 in Scenario B. To recap, the simulated 2050 runoffs in Scenario B assume an 18% increase in glacier melt. They also assume a 20% decrease in snowmelt in the winter and an 8% decrease in snow melt in the summer. These cuts in snowmelt are distributed throughout the year according to the rain PMF.

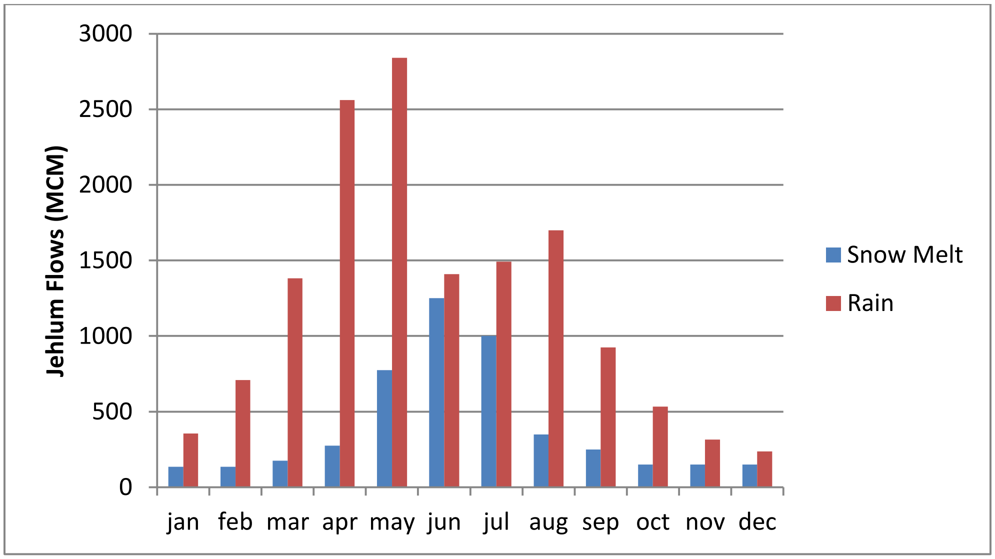


Figure 37: Estimated distribution of snowmelt and rain in the Jehlum river on a mean annual basis. Data shows the breakdown of mean annual runoff from 1998-2002.

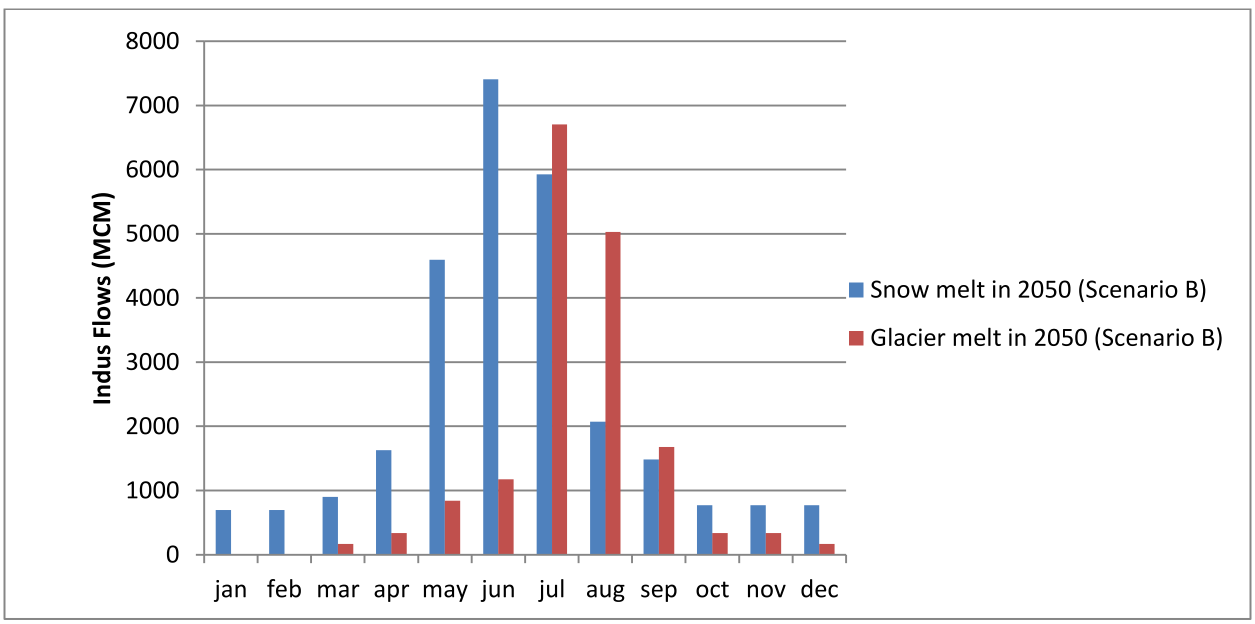


Figure 38: Estimated monthly snow and glacier melt components of the Indus runoff in 2050 under climate change scenario B.

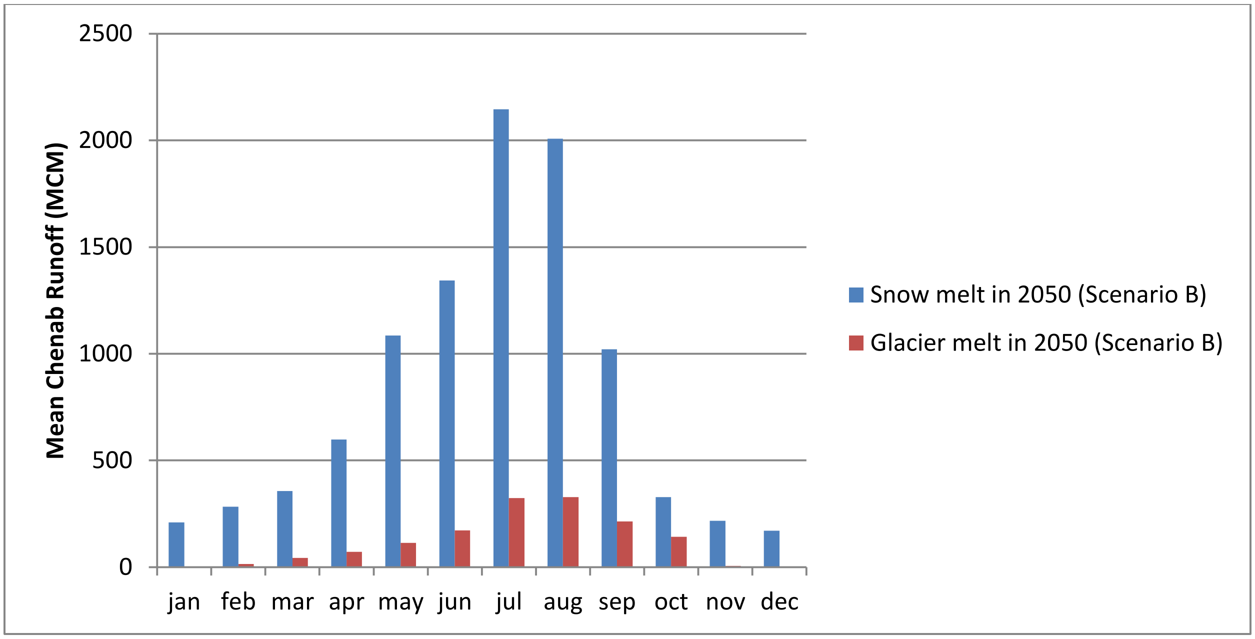


Figure 39: Estimated monthly snow and glacier melt components of the Chenab runoff in 2050 under climate change scenario B.

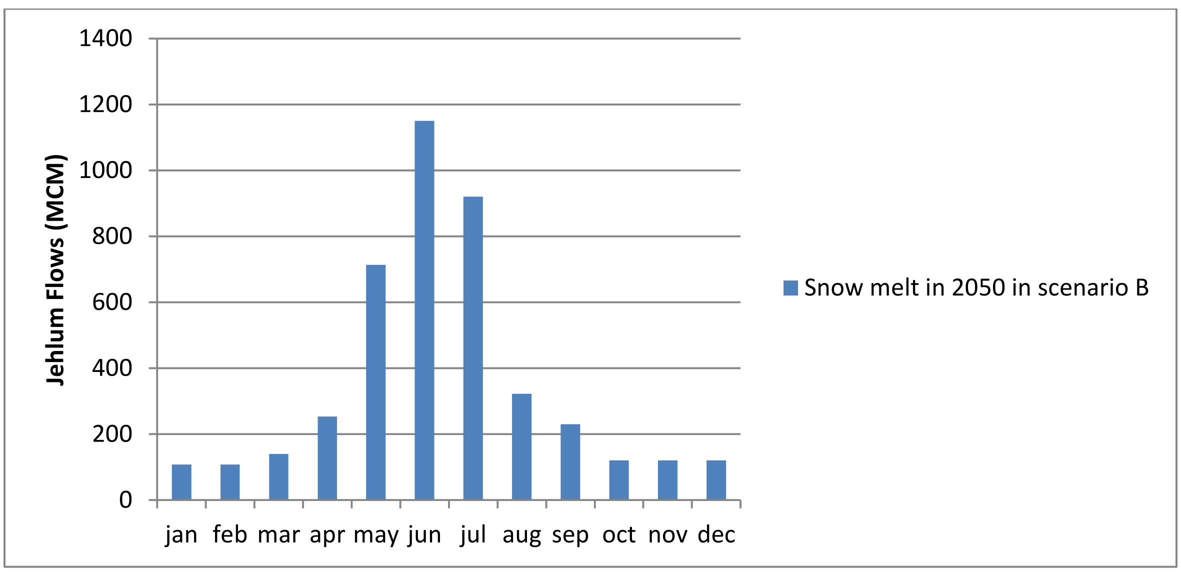
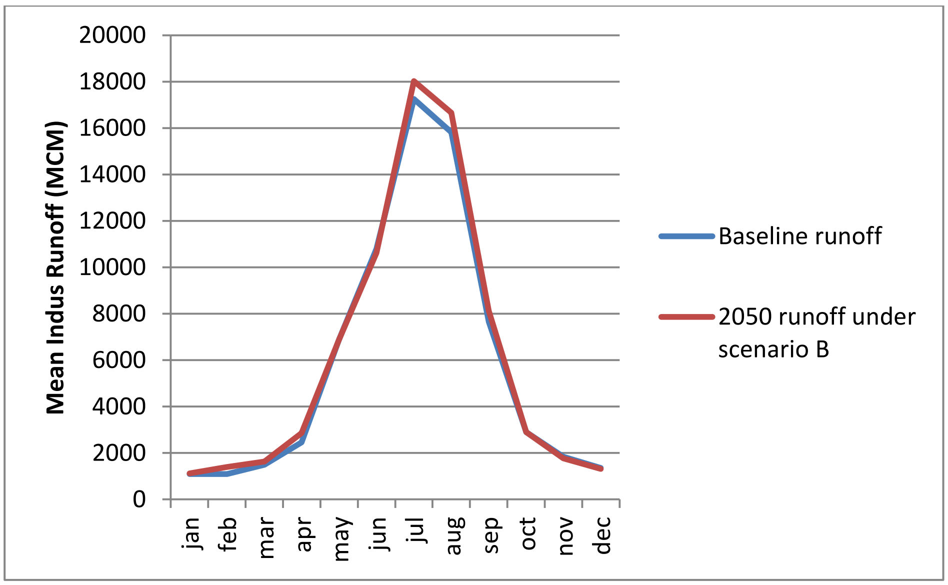
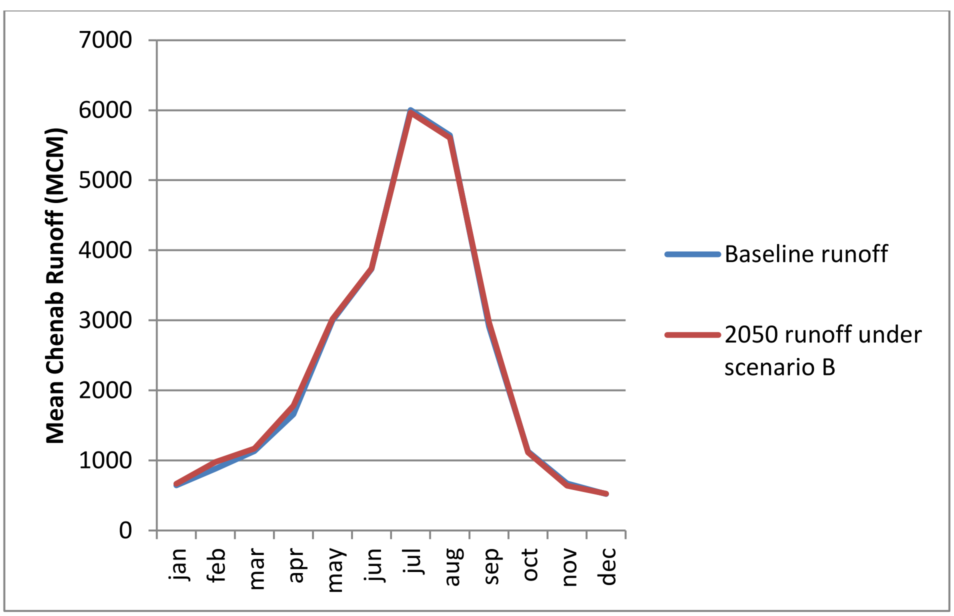


Figure 40: Simulated monthly snow melt component of the Jehlum runoff in 2050 under the climate change scenario B.

In this way we obtain the simulated total runoff in the Indus, Chenab and Jehlum rivers in 2050 under climate change scenario B. The runoffs are shown in figure 41(a-c). The most noticeable feature of these projected runoffs are that they do not forecast any major change in runoffs to 2050, except for the Indus in the summer. The changes are well within historical variability. This is only expected given that glacial melt and snow melt change in opposite directions due to rising temperatures. Also noticeable is the redistributive effect of temperature on runoff. Less snow melts in the summer and more rain falls in the winter as a result of warming, somewhat damping the seasonality of river flows.



(a)



(b)

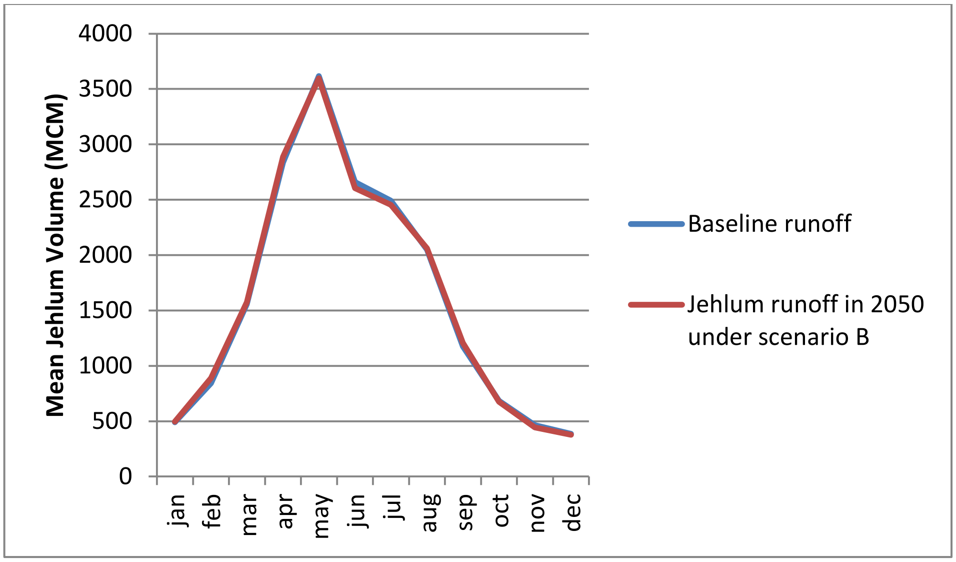
(c)


Figure 41: Simulated runoffs in the Indus, Chenab and Jehlum in 2050 under the climate change scenario B.

3.4 Scenario C: Shrinkage of Glacier Cover

The global land ice measurements from space (GLIMS) project report a long-term decrease of glacier extent in the upper Indus basin (Kargel et al., 2005). Immerzeel et al. (2009) support this result. They find that the runoff records of the Indus at Besham consistently exceed the total precipitation on the upper Indus basin, as measured by the Tropical Rainfall Measuring Mission (TRMM, a satellite). The total TRMM precipitation for the entire basin based equals 311mm/yr, while the total modeled streamflow at Besham equals 360mm/yr. The modeled discharges match the observed discharge and it is concluded that there must be an additional source of water to explain the reported stream flow, especially considering that actual evapotranspiration is not accounted for. The possibility of TRMM underestimating precipitation is remote, since a recent study of TRMM actually found the opposite – that TRMM consistently overestimates precipitation. The authors attribute this undercatch to the summer warming trend they measure (table 5). This summer warming would contribute to glacier melt, which could be the missing source of runoff.

This hypothesis is in line with reports from the IPCC (2007) and GLIMS (Kargel et al., 2005) about the shrinkage of the greater Himalayas.

If glacial melt is contributing to the Indus runoff in excess of precipitation, how does this apparent loss of mass compare with the total ice reserves? A previous study revealed that the glacier coverage in the entire upper Indus basin is approximately 10% (Kulkarni et al., 2007). The average glacier thickness is reported to be around 100 m (Kulkarni et al., 2007) and therefore the total ice reserve in the upper Indus basin is estimated to be 1982 km^3. If we assume that at least 100 mm is required to make up the deficit, this equals 1% of the total ice reserve per year and is plausible.

In this context, scenario C assumes a 1% decrease per year in the glacial ice reserves in the upper Indus basin from 2007 (the year of publication of the glacial mass estimate) to 2050. We need a few simplifying assumptions: that the glacial ice has a uniform depth of 100 m (e.g. Kulkarni et al., 2007) and uniform density, such that a 1% loss in mass results in a 1% loss in area $A(t)$ in every year t.

$$dA(t)/dt = -\ 0.01A(t)$$

for $t = 2007$ to 2050. Solving, we get:

$$dA(t)/A(t) = -\ 0.01dt$$

$$\ln A(t) = -\ 0.01t + \text{constant}$$

$$A(t) = A_0 \exp(-0.01t)$$

where A_0 is the glacier-covered area in 2007, which we take to be 19820 m^2. Then, in 2050, $A(t)$ will be 12893 m^2, or 65% of the area in 2007.

Assuming (as do Immerzeel et al., 2009) that half of the melted volume results in downstream runoff, we arrive at the area and flow curves of figure 42. According to the Immerzeel et al. (2009), current contribution of glacial melt to the Indus runoff is about 13% of total runoff. This is less than the estimate of 20% I assumed earlier (figure 34(a)). This probably indicates that Immerzeel et al. (2009) consider the net annual loss in glacial ice reserves, whereas my estimate of ice melt includes melt that is replenished by precipitation in the short term.

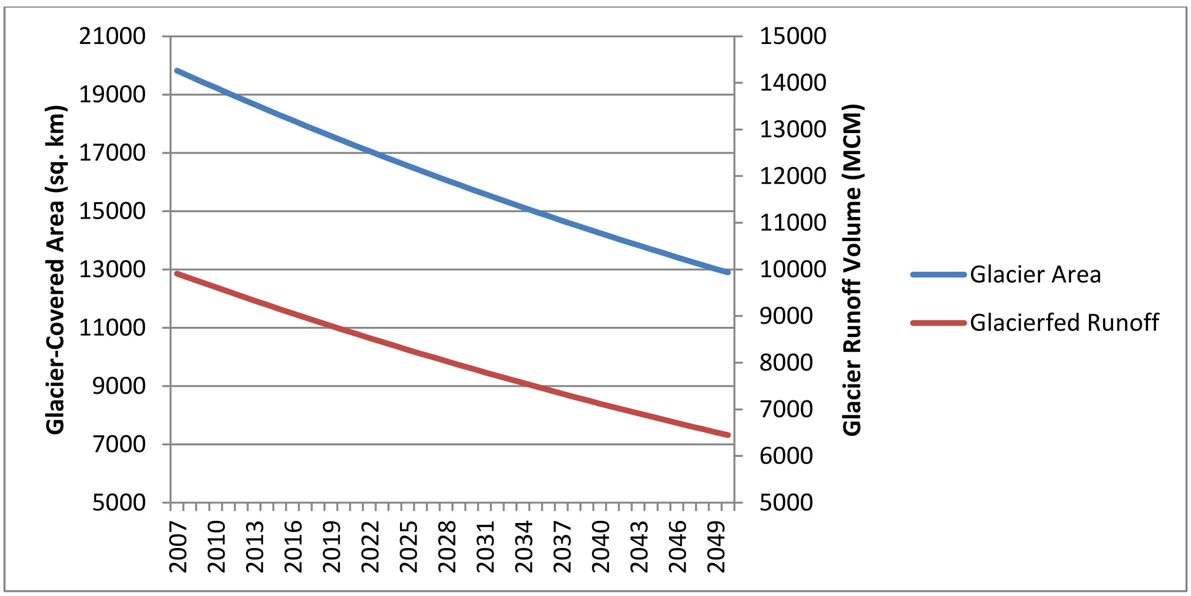


Figure 42: Glacier area declining by 1% every year to 2050. The resulting yearly glacial-fed runoff is also shown, assuming half of glacial melt results in river runoff.

Since glacier melt decreases over the years, total volume in the Indus river ends up being lower in 2050 than in 2007. The cuts in glacier-melt are distributed according to the PMF of glacier melt specified by Immerzeel et al. (2009, figure 33 in this chapter). The resulting Indus runoff is shown in figure 43.

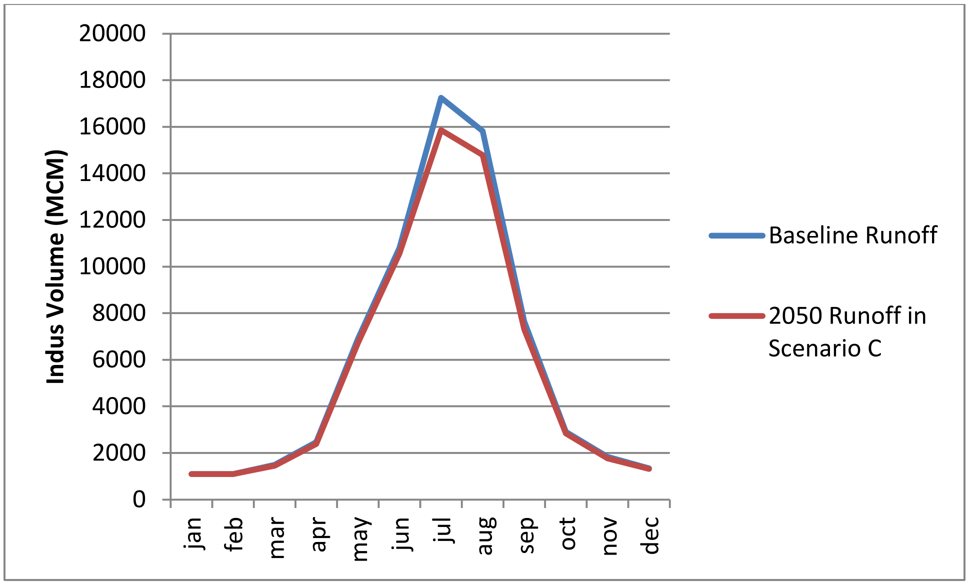


Figure 43: Indus runoff in 2050 under the climate change scenario C, which assumes 1% shrinkage of glacier volume every year (so that glacial-covered area in 2050 is 65% of 2007).

3.5 Projection of Water Demand

Water demand from the municipal and industrial sectors is driven by MIT Emissions Prediction and Policy Analysis (EPPA) model for the globe (Paltsev et al., 2005). EPPA assumes that household and industrial water demands are independent of climate, while irrigation requirements are driven by monthly temperature and precipitation. These demands were also used in the Joint Program's assessment of global water stress (Strzepek et al., 2013). That assessment considers four global change scenarios: unconstrained greenhouse gas emissions, stabilization of greenhouse gas emissions to "Level 1", and two selected climate patterns. The climate patterns were derived from the climate simulation results from the Coupled Model Intercomparison Project Phase 3 (CMIP3, Meehl et al., 2007). The climate patterns chosen reflect the two climate models (among the CMIP3 pool of models) that project, the most "dry" (DRY) and the most "wet" (WET) pattern changes over land as determined by the climate-moisture index analyses of Strzepek and Schlosser

(2010). The “Level 1 stabilization” scenario is formulated applying the growth that is projected under a global policy to restrain global emissions to the Level 1 scenario (**L1S**) developed for the US Climate Change Science Program (Clarke et al., 2007). The L1S scenario imposes a target of 560 ppm CO_2-equivalent concentrations by 2100, and it limits economic growth in some parts of the developing world: primarily Africa, Middle East, and Central and South America. The increases in water demands under each scenario are given in table 9.

The rise in irrigation demand to 2050 assumes no changes in cropping patterns. It assumes that either more area will be brought under cultivation with the same irrigation requirement as existing area, or that more water will applied to existing cultivated area to increase yields. In reality, fallow land, if brought under cultivation, will probably have higher irrigation requirements than those of existing cultivated area.

To arrive at water demands in 2050, I simply add the changes listed in table 9 to the baseline water demands listed in tables 1-3. According to my analysis, the total annual water demand in the Indus basin in the base period of 2000 was about 95 BCM, whereas WRS determines it to be 56 BCM. This difference is attributable to the fact that the CliCrop model only estimates the biophysical demand for water at the root of the plant, and does not consider inefficiencies in water conveyance and application at the field. In projecting water demand to 2050, it is sufficient to only consider the increase in the biophysical demand for irrigation, and changes in efficiencies are assumed to be zero.

Municipal requirements include domestic use (urban and rural), public use, and commercial use connected to a municipal water system. The annual growth rate of municipal water demand, ϕ_{MUN}, in year t is such that:

Water demand in year t = water demand in year $(t-1)*(1+ \phi_{MUN})$

ϕ_{MUN} is based on projections of growth rates of population and per-capita income, ϕ_{POP} and ϕ_{PCI} for the relevant region in EPPA. EPPA also estimates the income elasticity of demand for municipal water to GDP (η) for the economic region.

$$\phi_{MUN} = \phi_{POP} + \eta*\phi_{PCI}$$

Similarly, increases in requirements for each industrial water use sector are based on estimates of the elasticity of water use to per-capita GDP

	Change in Domestic Demand (BCM)	Change in Industrial Demand (BCM)	Change in Irrigation Demand (BCM)	Total Change in Demand (BCM)
No Policy - CSIRO	3.81	1.09	2.2	7.1
No Policy - NCAR	3.81	1.09	1.7	6.6
Level 1 Stabilization - CSIRO	3.84	1.02	1.4	6.26
Level 1 Stabilization - NCAR	3.84	1.02	0.9	5.76

Table 9: Increases in water demand in BCM from various economic sectors under four global change scenarios: the presence or absence of a mitigation policy, and a wet or dry course of global climate.

3.6 Scenario Ensemble

We set up a scenario ensemble consisting of both policy alternatives (which impact water demands) and the various climate outcomes (which impact water supplies). The resulting ensemble contains of 12 scenarios presented below

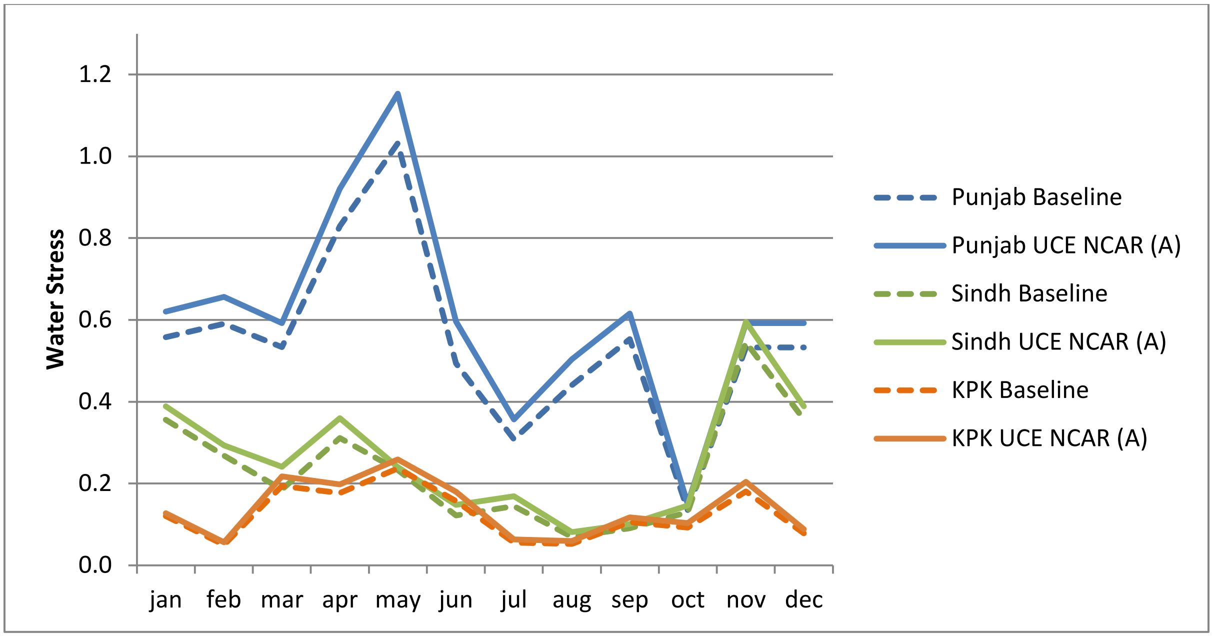
← **Policy** →

← **Climate Change** →

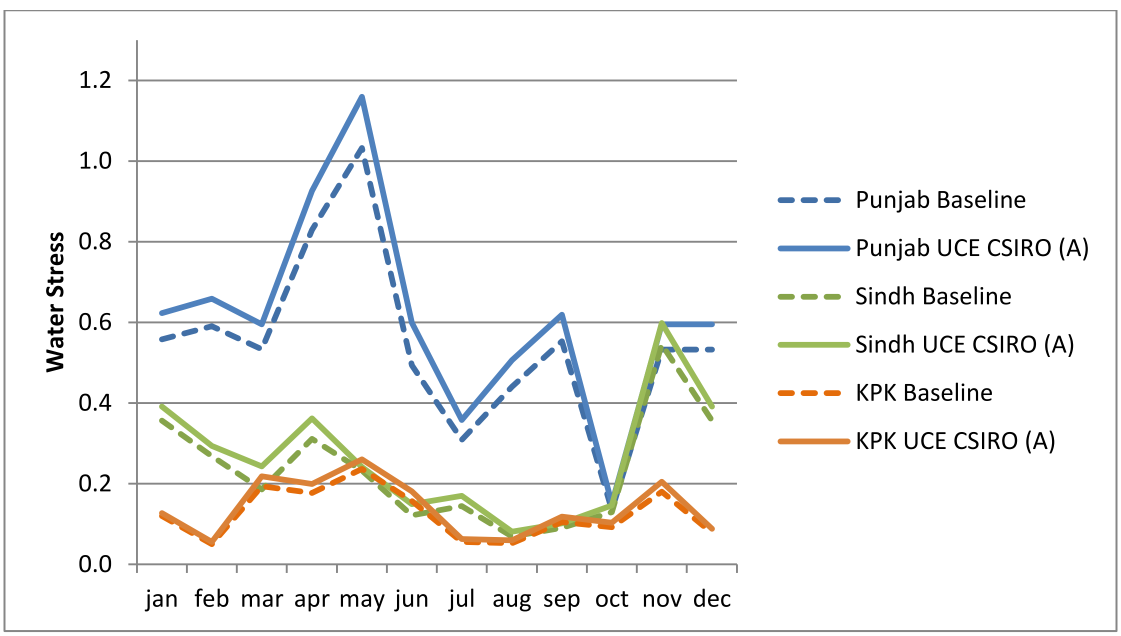
No Policy-NCAR (A): Water demands are determined by unconstrained carbon emissions, assuming a globally "wet" climate. Water supplies are determined by no climate change.	**Stabilization-NCAR (A):** Water demands are determined by stabilized carbon emissions to Level 1, assuming a globally "wet" climate. Water supplies are determined by no climate change.
No Policy-CSIRO (A): Water demands are determined by unconstrained carbon emissions, assuming a globally "dry" climate. Water supplies are determined by no climate change.	**Stabilization-CSIRO (A):** Water demands are determined by stabilized carbon emissions to Level 1, assuming a globally "dry" climate. Water supplies are determined by no climate change.
No Policy-NCAR (B): Water demands are determined by unconstrained carbon emissions, assuming a globally "wet" climate. Water supplies are determined by temperature rises over the upper Indus basin of 1C in the summer and 2.5 C in the winter.	Stabilization-NCAR (B): Water demands are determined by stabilized carbon emissions to Level 1, assuming a globally "wet" climate. Water supplies are determined by temperature rises over the upper Indus basin of 1C in the summer and 2.5 C in the winter.
No Policy-CSIRO (B): Water demands are determined by unconstrained carbon emissions, assuming a globally "dry" climate. Water supplies are determined by temperature rises over the upper Indus basin of 1C in the summer and 2.5 C in the winter.	**Stabilization-CSIRO (B):** Water demands are determined by stabilized carbon emissions to Level 1, assuming a globally "dry" climate. Water supplies are determined by temperature rises over the upper Indus basin of 1C in the summer and 2.5 C in the winter.
No Policy-NCAR (C): Water demands are determined by unconstrained carbon emissions, assuming a globally "wet" climate. Water supplies are determined by a 1% decline in glacial area/yr.	**Stabilization-NCAR (C):** Water demands are determined by stabilized carbon emissions to Level 1, assuming a globally "wet" climate. Water supplies are determined by a 1% decline in glacial area/yr.
No Policy-CSIRO (C): Water demands are determined by unconstrained carbon emissions, assuming a globally "dry" climate. Water supplies are determined by a 1% decline in glacial area/yr.	**Stabilization-CSIRO (C):** Water demands are determined by stabilized carbon emissions to Level 1, assuming a globally "dry" climate. Water supplies are determined by a 1% decline in glacial area/yr.

3.7 Results: Water Stress in 2050

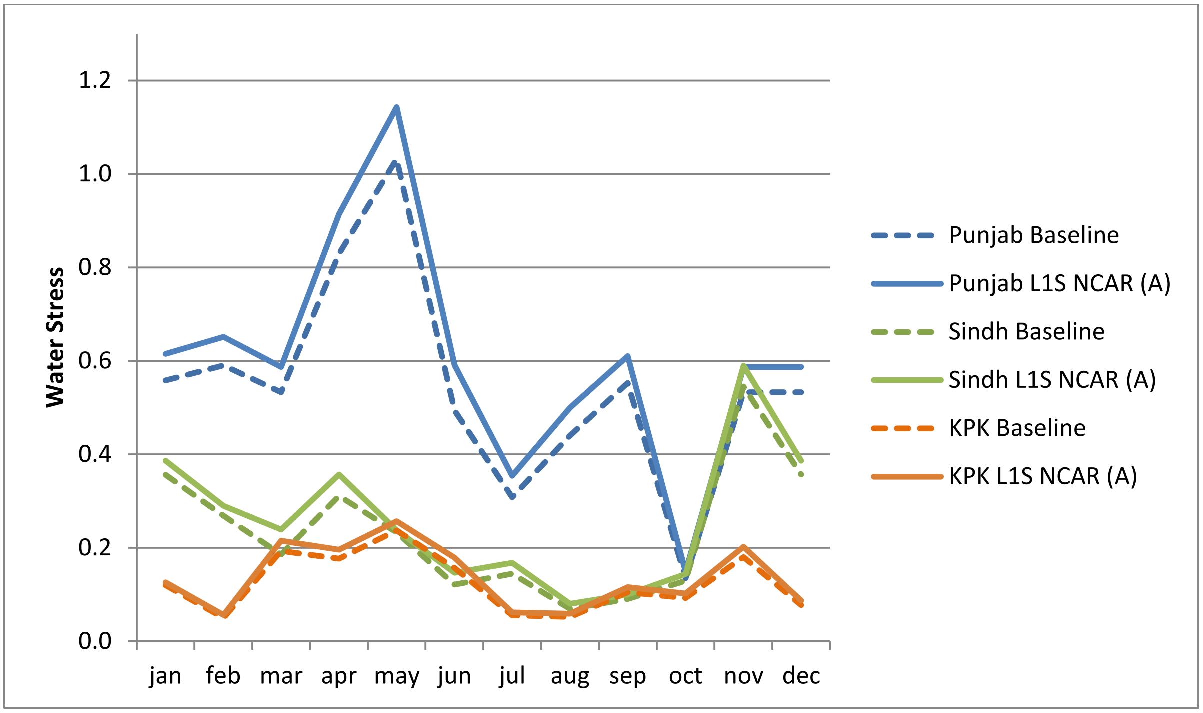
UCE NCAR (A)



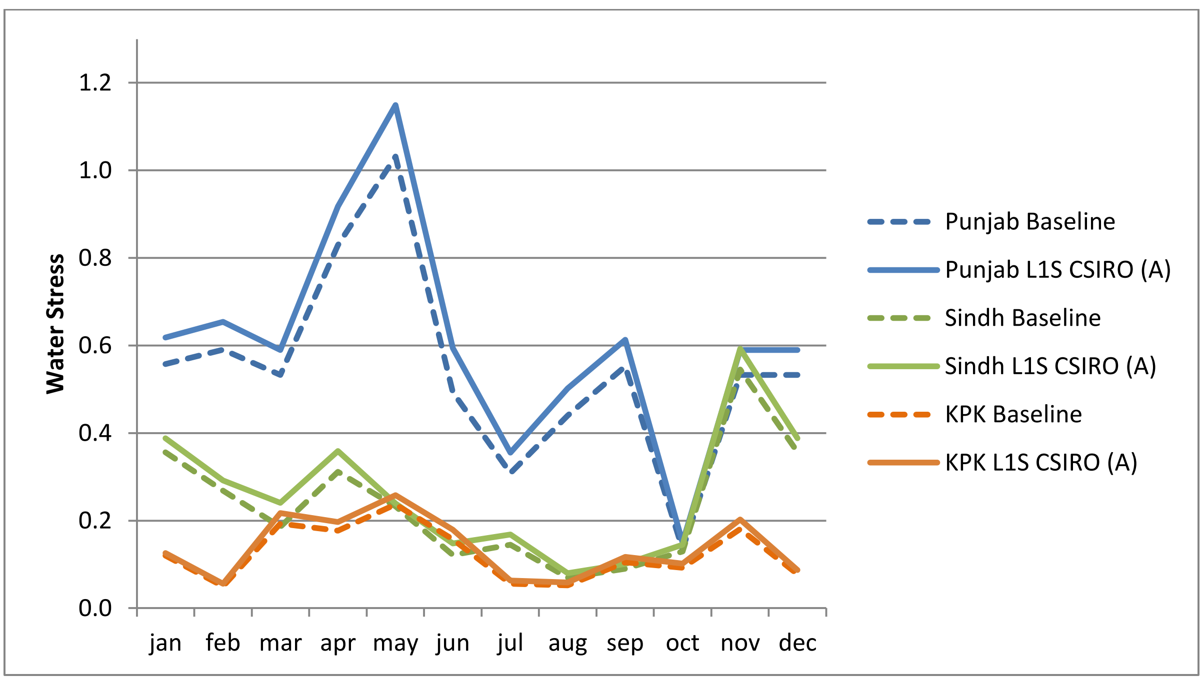
UCE CSIRO (A)



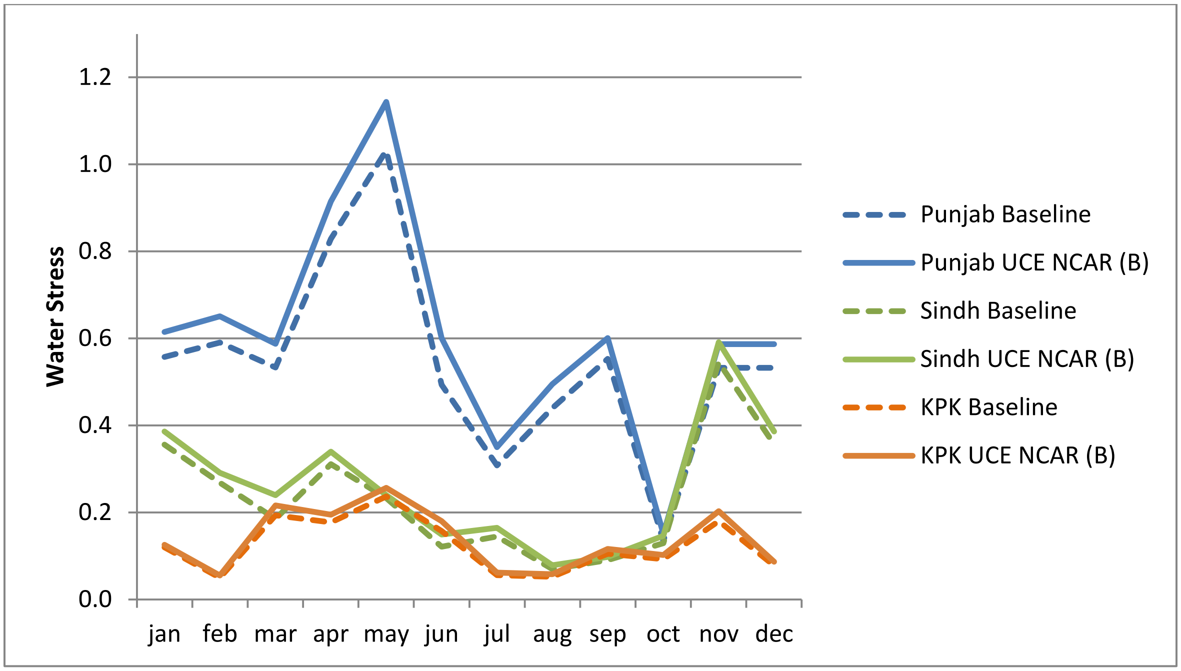
L1S NCAR (A)



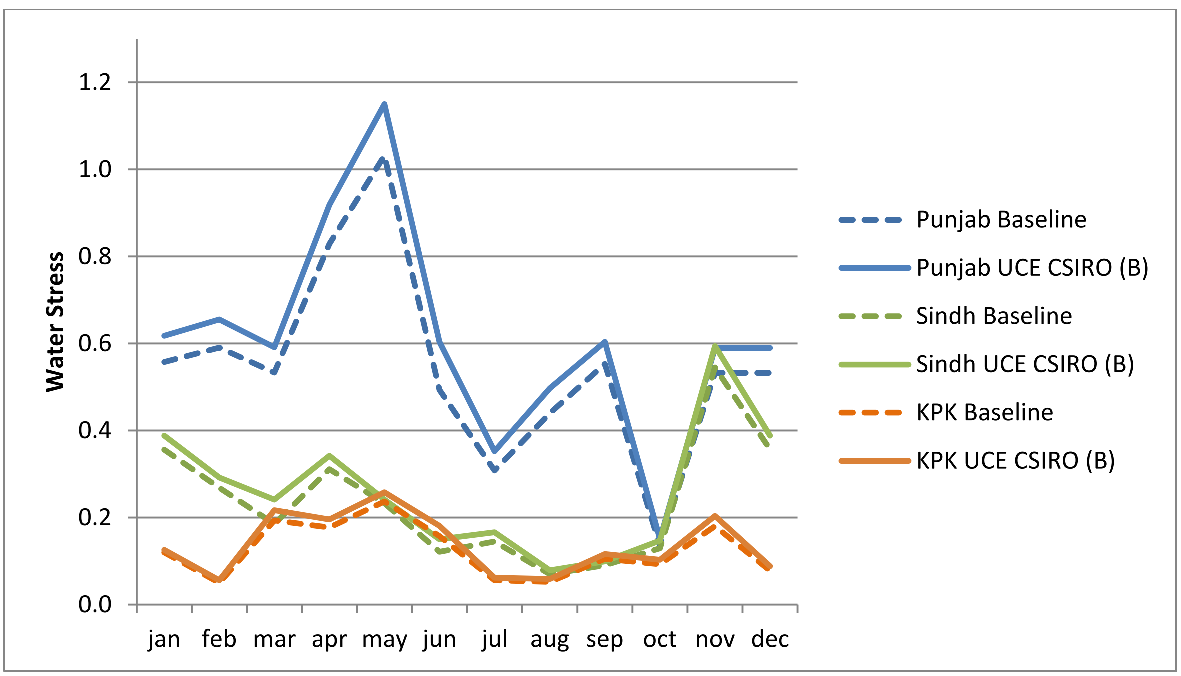
L1S CSIRO (A)



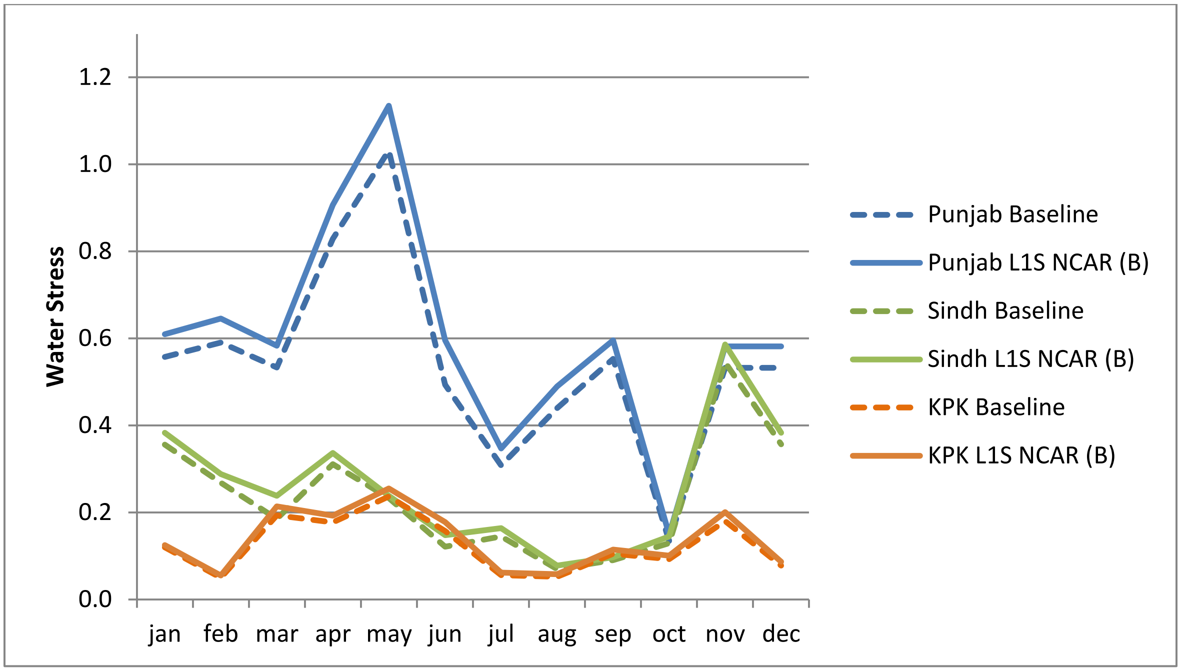
UCE NCAR (B)



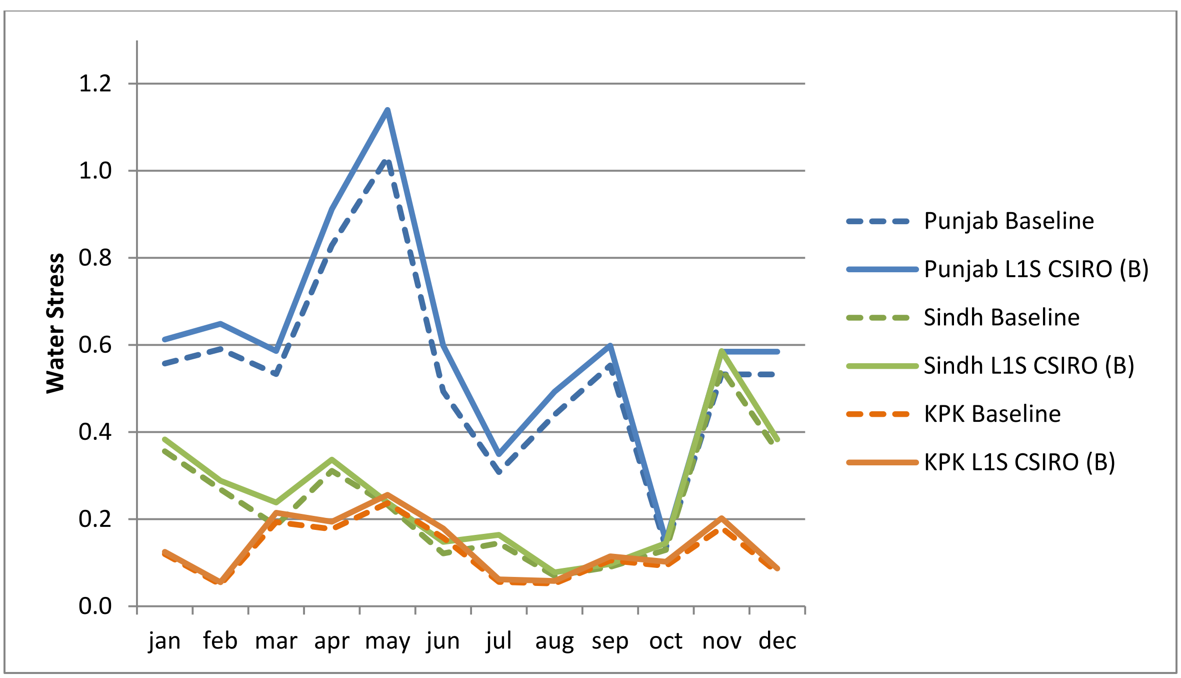
UCE CSIRO (B)



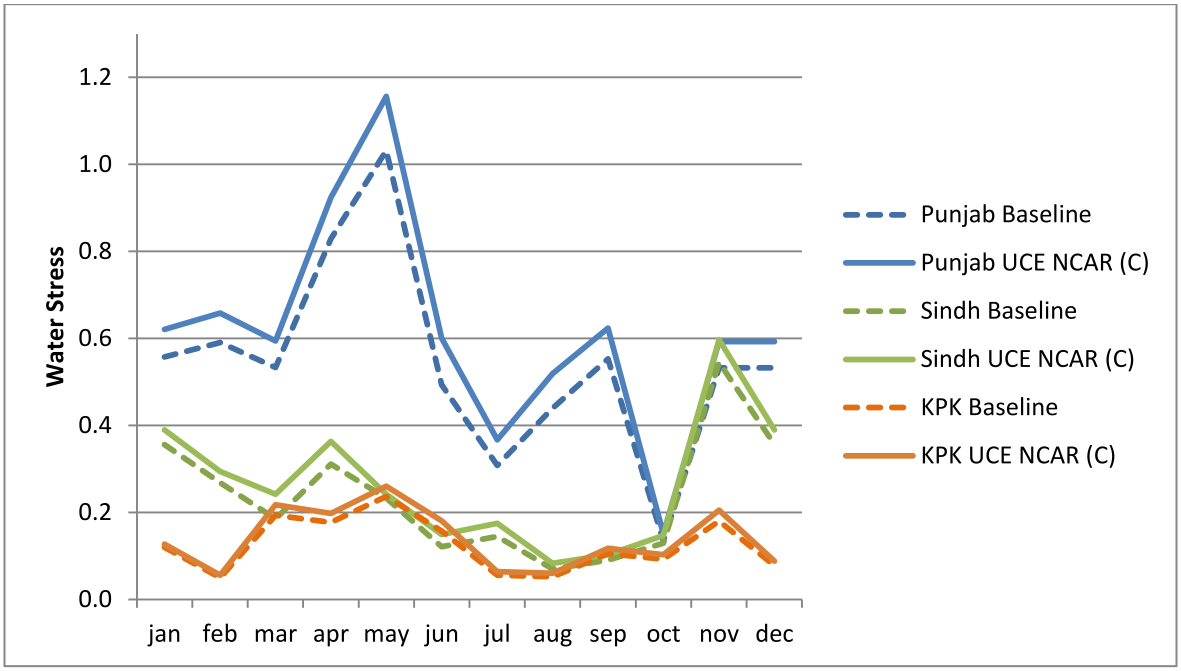
L1S NCAR (B)



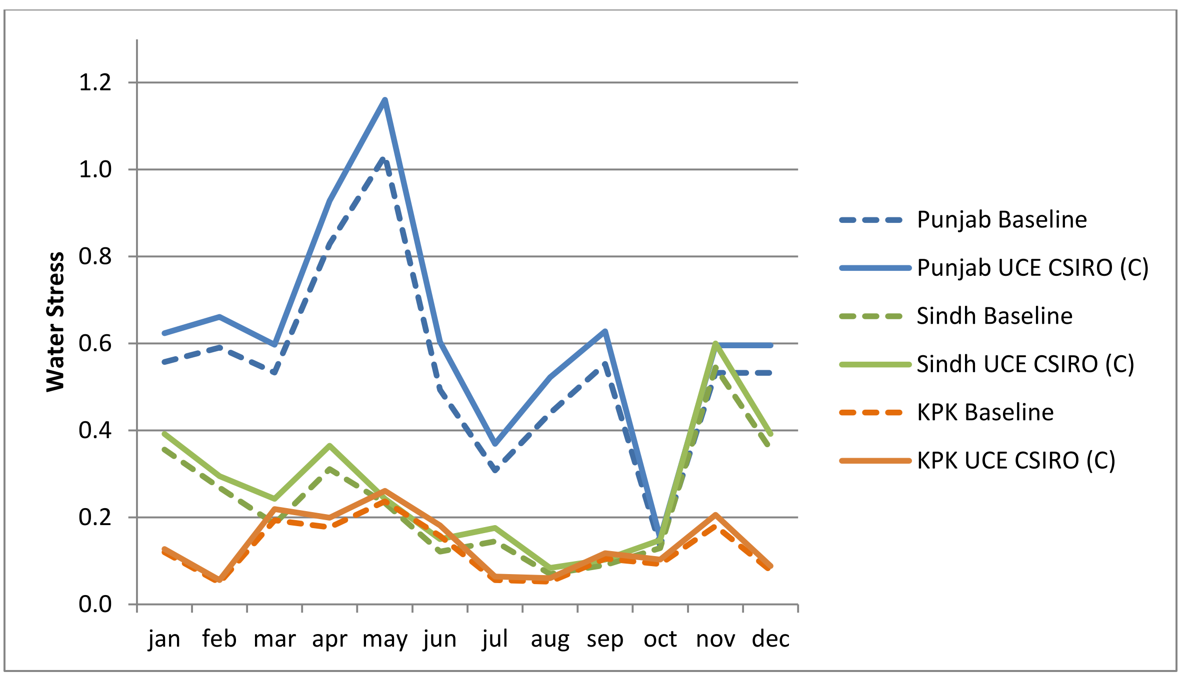
L1S CSIRO (B)



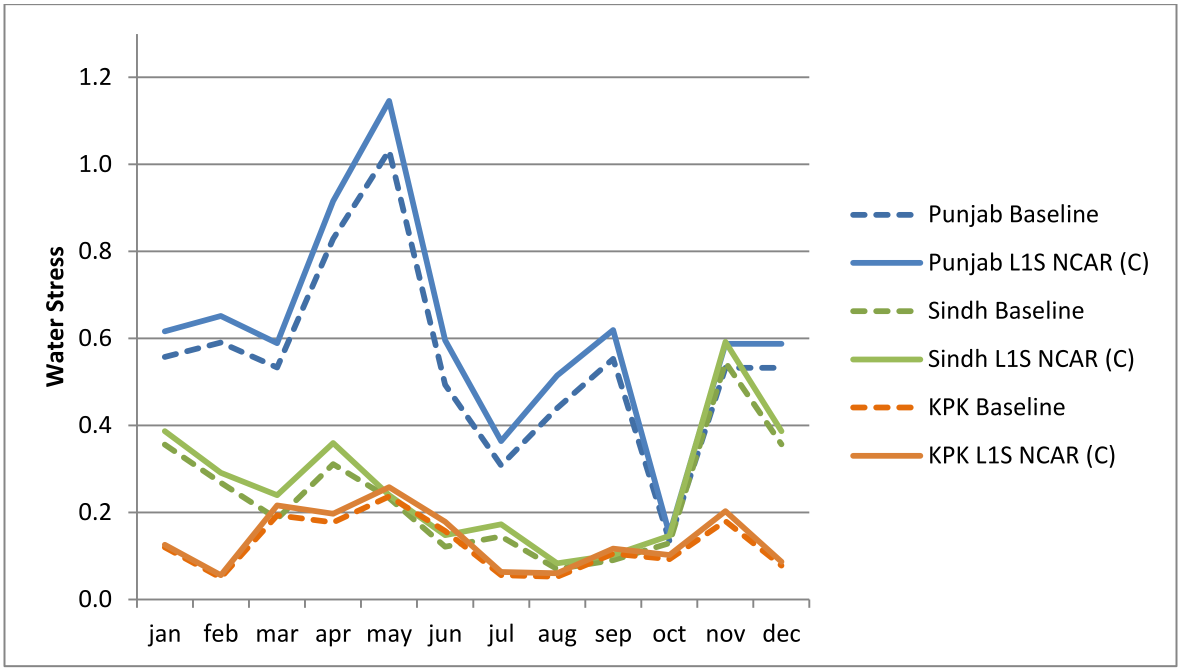
UCE NCAR (C)



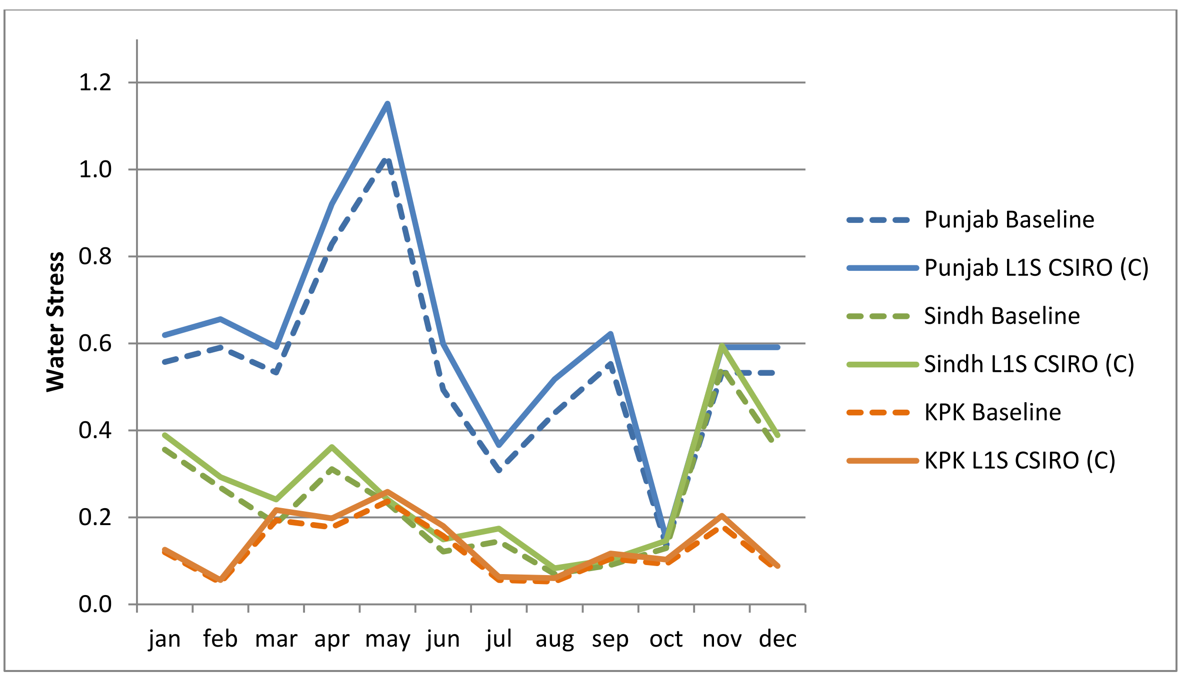
UCE CSIRO (C)



L1S NCAR (C)



L1S CSIRO (C)



3.8 Summary of Results

This analysis, summarized in the tables below, leads to some interesting observations. Recall that the alternative greenhouse gas emission policies ("unconstrained emissions" and "Level 1 stabilization") did not give rise to appreciably different climate scenarios. But these policy alternatives predicted quite different rates of demand growth. In my analysis, the scenario which gives rise the lowest water stress in 2050 is 'L1S (B)', in which demands are checked by appropriate global policies, the temperature rises as predicted, but the glaciers do not retreat. A close second is 'L1S (A)', where demand is checked but climate does not change. These results suggest that checking the rise in demand – whether through aggressive climate policy or by other means – leads to the most favorable water stress outcomes. On the other hand, the worst water stress outcome, 'UCE (C)', in which the demand grows unchecked and the glaciers retreat, is only a little worse than 'UCE (A)', in which the demand grows unchecked but the climate does not change at all. With or without climate change, allowing water demand to grow unchecked leads to the worst outcomes.

That said, climate change scenario (B) represents a 'sweet spot' in which water supplies rise enough to counter the rise in demand. However, we do not know if scenario (B) is any more or less likely than the other climate scenarios.

All this suggests that Pakistan should constrain its irrigation water demands, which are 91% of total water demands, from growing in tandem with the country's economic growth imperatives. The next chapter discusses a few ways of doing that. Climate change can alter Pakistan's water supply in either direction, and it is best simply to invest in water management structures that are resilient to all possible outcomes.

PUNJAB

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline (2000)	**0.56**	**0.59**	**0.53**	**0.83**	**1.03**	**0.49**	**0.31**	**0.44**	**0.55**	**0.13**	**0.53**	**0.53**
UCE NCAR (A)	0.62	0.66	0.59	0.92	1.15	0.60	0.36	0.50	0.62	0.15	0.59	0.59
UCE CSIRO (A)	0.62	0.66	0.60	0.93	1.16	0.60	0.36	0.51	0.62	0.15	0.60	0.60
L1S NCAR (A)	0.62	0.65	0.59	0.91	1.14	0.59	0.35	0.50	0.61	0.15	0.59	0.59
L1S CSIRO (A)	0.62	0.65	0.59	0.92	1.15	0.59	0.36	0.50	0.61	0.15	0.59	0.59
Mean A	**0.62**	**0.66**	**0.59**	**0.92**	**1.15**	**0.60**	**0.36**	**0.50**	**0.61**	**0.15**	**0.59**	**0.59**
UCE NCAR (B)	0.62	0.65	0.59	0.92	1.14	0.60	0.35	0.50	0.60	0.15	0.59	0.59
UCE CSIRO (B)	0.62	0.66	0.59	0.92	1.15	0.60	0.35	0.50	0.60	0.15	0.59	0.59
L1S NCAR (B)	0.61	0.65	0.58	0.91	1.14	0.60	0.35	0.49	0.60	0.15	0.58	0.58
L1S CSIRO (B)	0.61	0.65	0.59	0.91	1.14	0.60	0.35	0.49	0.60	0.15	0.59	0.59
Mean B	**0.61**	**0.65**	**0.59**	**0.91**	**1.14**	**0.60**	**0.35**	**0.49**	**0.60**	**0.15**	**0.59**	**0.59**
UCE NCAR (C)	0.62	0.66	0.59	0.92	1.16	0.60	0.37	0.52	0.62	0.15	0.59	0.59
UCE CSIRO (C)	0.62	0.66	0.60	0.93	1.16	0.60	0.37	0.52	0.63	0.15	0.60	0.60
L1S NCAR (C)	0.62	0.65	0.59	0.92	1.15	0.60	0.36	0.52	0.62	0.15	0.59	0.59
L1S CSIRO (C)	0.62	0.66	0.59	0.92	1.15	0.60	0.37	0.52	0.62	0.15	0.59	0.59
Mean C	**0.62**	**0.66**	**0.59**	**0.92**	**1.15**	**0.60**	**0.37**	**0.52**	**0.62**	**0.15**	**0.59**	**0.59**
Mean L1S	**0.62**	**0.65**	**0.59**	**0.91**	**1.14**	**0.60**	**0.36**	**0.50**	**0.61**	**0.15**	**0.59**	**0.59**
Mean UCE	**0.62**	**0.66**	**0.59**	**0.92**	**1.15**	**0.60**	**0.36**	**0.51**	**0.62**	**0.15**	**0.59**	**0.59**

SINDH

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline (2000)	**0.356**	**0.268**	**0.186**	**0.311**	**0.233**	**0.122**	**0.145**	**0.070**	**0.090**	**0.130**	**0.545**	**0.357**
UCE NCAR (A)	0.389	0.293	0.241	0.360	0.240	0.148	0.169	0.081	0.101	0.146	0.595	0.389
UCE CSIRO (A)	0.391	0.294	0.243	0.362	0.241	0.149	0.17	0.081	0.102	0.146	0.598	0.391
L1S NCAR (A)	0.386	0.29	0.239	0.357	0.238	0.147	0.168	0.08	0.1	0.144	0.59	0.386
L1S CSIRO (A)	0.388	0.292	0.241	0.359	0.239	0.148	0.168	0.08	0.101	0.145	0.593	0.388
Mean A	**0.389**	**0.292**	**0.241**	**0.360**	**0.240**	**0.148**	**0.169**	**0.081**	**0.101**	**0.145**	**0.594**	**0.389**
UCE NCAR (B)	0.386	0.291	0.24	0.34	0.24	0.149	0.165	0.079	0.098	0.146	0.591	0.386
UCE CSIRO (B)	0.388	0.292	0.241	0.342	0.241	0.15	0.166	0.079	0.099	0.147	0.594	0.388
L1S NCAR (B)	0.383	0.288	0.238	0.337	0.238	0.148	0.164	0.078	0.097	0.145	0.586	0.383
L1S CSIRO (B)	0.385	0.29	0.239	0.339	0.239	0.149	0.165	0.079	0.098	0.146	0.589	0.385
Mean B	**0.386**	**0.290**	**0.240**	**0.340**	**0.240**	**0.149**	**0.165**	**0.079**	**0.098**	**0.146**	**0.590**	**0.386**
UCE NCAR (C)	0.39	0.294	0.242	0.363	0.242	0.149	0.175	0.083	0.103	0.147	0.597	0.39
UCE CSIRO (C)	0.392	0.295	0.243	0.365	0.243	0.15	0.176	0.084	0.103	0.148	0.6	0.392
L1S NCAR (C)	0.387	0.291	0.24	0.36	0.24	0.148	0.173	0.083	0.102	0.146	0.592	0.387
L1S CSIRO (C)	0.389	0.293	0.241	0.362	0.241	0.149	0.174	0.083	0.103	0.146	0.595	0.389
Mean C	**0.390**	**0.293**	**0.242**	**0.363**	**0.242**	**0.149**	**0.175**	**0.083**	**0.103**	**0.147**	**0.596**	**0.390**
Mean L1S	0.042	0.084	0.066	0.231	0.191	0.119	0.139	0.063	0.080	0.117	0.328	0.337
Mean UCE	0.042	0.084	0.067	0.233	0.193	0.120	0.141	0.063	0.081	0.117	0.330	0.339

KPK

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Baseline (2000)	**0.120**	**0.050**	**0.194**	**0.177**	**0.237**	**0.157**	**0.056**	**0.052**	**0.105**	**0.093**	**0.180**	**0.078**
UCE NCAR (A)	0.127	0.056	0.217	0.198	0.259	0.18	0.063	0.059	0.117	0.103	0.204	0.088
UCE CSIRO (A)	0.127	0.056	0.218	0.199	0.26	0.181	0.063	0.06	0.118	0.103	0.205	0.088
L1S NCAR (A)	0.126	0.056	0.215	0.196	0.257	0.179	0.062	0.059	0.116	0.102	0.202	0.087
L1S CSIRO (A)	0.126	0.056	0.217	0.197	0.258	0.179	0.063	0.059	0.117	0.102	0.203	0.087
Mean A	**0.13**	**0.06**	**0.22**	**0.20**	**0.26**	**0.18**	**0.06**	**0.06**	**0.12**	**0.10**	**0.20**	**0.09**
UCE NCAR (B)	0.126	0.055	0.216	0.195	0.257	0.18	0.062	0.058	0.116	0.102	0.203	0.087
UCE CSIRO (B)	0.126	0.056	0.217	0.196	0.258	0.181	0.062	0.059	0.116	0.103	0.204	0.088
L1S NCAR (B)	0.125	0.055	0.214	0.193	0.255	0.178	0.062	0.058	0.115	0.101	0.201	0.087
L1S CSIRO (B)	0.125	0.055	0.215	0.194	0.256	0.179	0.062	0.058	0.115	0.102	0.202	0.087
Mean B	**0.13**	**0.06**	**0.22**	**0.19**	**0.26**	**0.18**	**0.06**	**0.06**	**0.12**	**0.10**	**0.20**	**0.09**
UCE NCAR (C)	0.127	0.056	0.218	0.198	0.26	0.181	0.064	0.06	0.118	0.103	0.205	0.088
UCE CSIRO (C)	0.127	0.056	0.219	0.199	0.261	0.182	0.064	0.06	0.118	0.103	0.206	0.088
L1S NCAR (C)	0.126	0.056	0.216	0.197	0.258	0.179	0.063	0.06	0.117	0.102	0.203	0.087
L1S CSIRO (C)	0.126	0.056	0.217	0.198	0.259	0.18	0.063	0.06	0.117	0.103	0.204	0.088
Mean C	**0.13**	**0.06**	**0.22**	**0.20**	**0.26**	**0.18**	**0.06**	**0.06**	**0.12**	**0.10**	**0.20**	**0.09**
Mean L1S	**0.13**	**0.06**	**0.22**	**0.20**	**0.26**	**0.18**	**0.06**	**0.06**	**0.12**	**0.10**	**0.20**	**0.09**
Mean UCE	**0.13**	**0.06**	**0.22**	**0.20**	**0.26**	**0.18**	**0.06**	**0.06**	**0.12**	**0.10**	**0.20**	**0.09**

4 OPTIONS FOR LOWERING WATER STRESS

To confront impending water stress, a few options are offered in this chapter. They include both supply and demand management options. Water supply can be managed by augmenting built storage on the Indus river and operating it flexibly for a historically unprecedented ensemble of river flows. Many analyses have emphasized the necessity of more reservoirs on the Indus and the stakeholders need little convincing. A more important question is *which* dam to build, and it is a more controversial question than one would like. Chapter 5 addresses it. On the other hand, adopting national and international policies to limit the emissions of greenhouse gases, as well as those of black carbon and other snow cover-depleting aerosols, can also limit drastic changes to Pakistan's water supply.

Demand management can be done in many ways, the most obvious being irrigation efficiency gains and the use of drought-resistant crops. Both are important and have been discussed at length (e.g., Ali et al., 1990, Kahlown et al., 2007). This chapter, however, discusses two less-explored options: (a) the introduction of inter-provincial water trading, and (b) a shift in Pakistan's cropping calendars away from the spring and towards the summer.

4.1 Interprovincial Water Trading

One way to relieve Punjab's water stress, especially in the high-stress months of April and May, would be to relax the Interprovincial Water Accord. The Accord itself represents a rare instance of consensus among the provinces and should not be tempered with. However, Punjab should consider negotiating with the other provinces the terms of an agreement to purchase their water for appropriate compensation. Given that KPK and Balochistan hardly use their Accord allocations in most of the year (as is evident from the low stress levels in KPK), it should present a win-win opportunity.

4.2 Adapting Cropping Patterns

Instead of transferring agriculture wholesale to Punjab, we can take the competitive advantage approach and let each province grow the crop it grows best. We are talking not in terms of yield but water requirements: looking at the table 10 of irrigation requirements per unit area of major crops in each province, we notice that they vary. For example, KPK (presumably because it receives more precipitation than the rest of Pakistan) requires less water to grow rice per unit area than Punjab and Sindh. Similarly, Punjab has a competitive advantage in other crops.

	Punjab	**Sindh**	**KPK**
wheat	400*	450	420
maize	375*	400	400
chickpea	280*	300	280*
potato	600	600	600
rice	1000	1100	900*
cotton	650*	650*	650*
sugarcane	1200	1200	1000*
mango	1100*	1100*	1100*
vegetable	600	650	550*

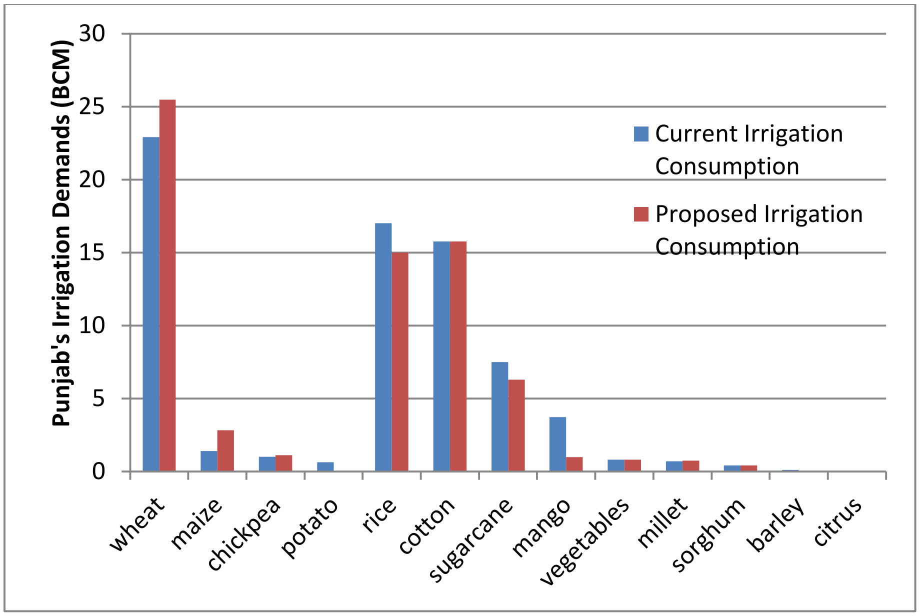
millet	320*	350	350
sorghum	370*	400	400
barley	370	300*	300*
citrus	1100*	1100*	1100*

Table 10: Water requirements in mm for major crops. Source: NARD

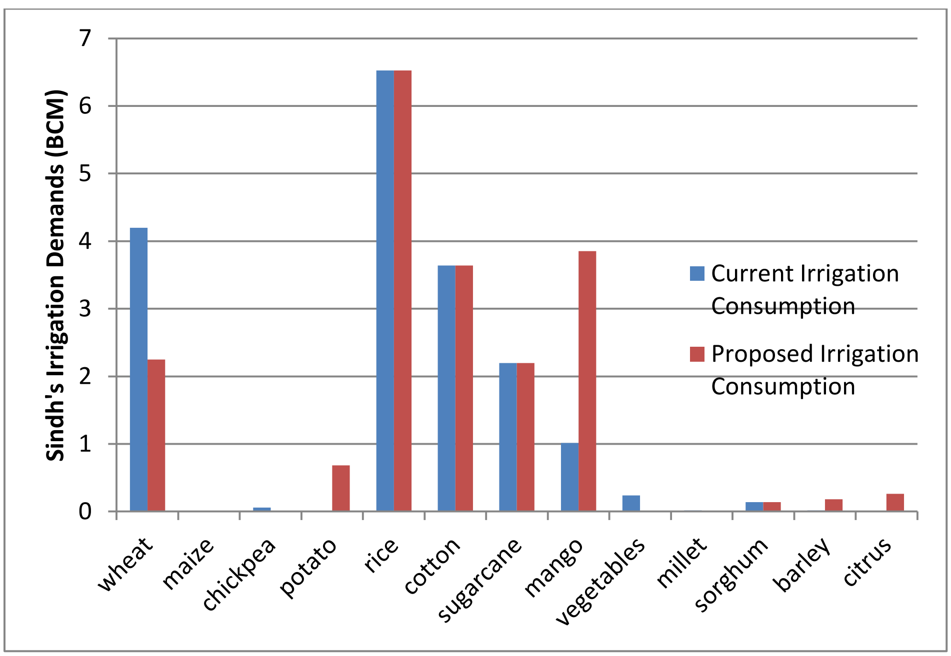
If we set aside economic returns and yields for a moment and focus only on the irrigation water requirements, as summarized in table 10, we can draw some simple observations:

a) Punjab has a competitive advantage in wheat, maize, chickpea, cotton, millet, and sorghum. It has a competitive disadvantage in rice, sugarcane, vegetables, barley and even mangoes.
b) Sindh has a competitive advantage in citrus, mangoes, barley, potatoes and some sugarcane. It has a competitive disadvantage in wheat, rice, maize, chickpea, vegetables, millet and sorghum.
c) KPK has a competitive advantage in grow rice, sugarcane and vegetables. It has a competitive disadvantage in cereals like wheat, maize, millet and sorghum.

Based on these observations, we can propose making gains in water economy by redistributing cultivated areas geographically among provinces. Figure 44 shows the current and proposed irrigation requirements of each crop in each province, keeping total area cultivated of each crop constant. Future work should investigate this opportunity more rigorously.

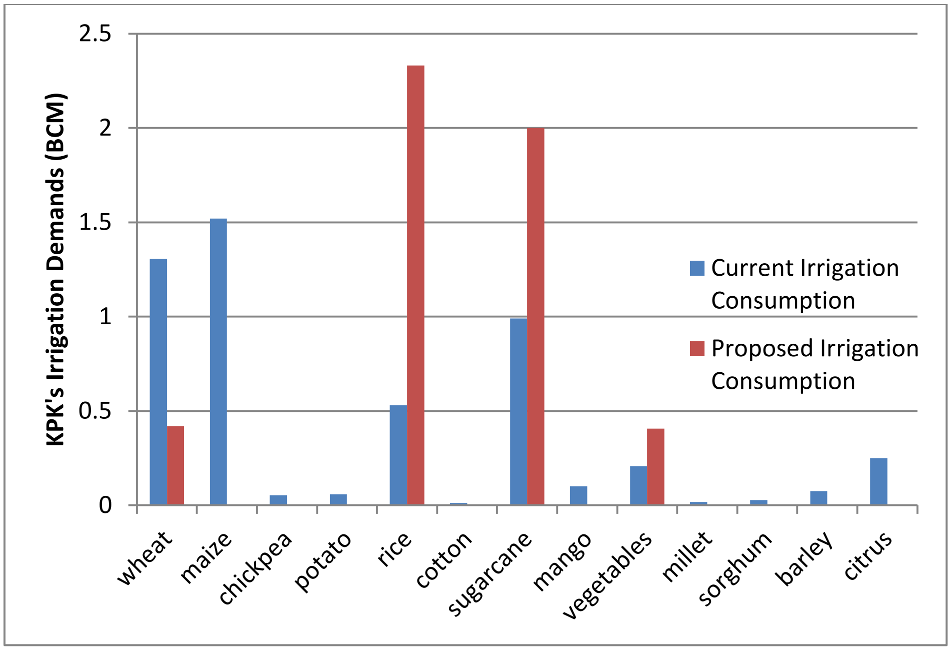

Punjab's Irrigation Demands (BCM)
30
25
20
15
10
5
0
Current Irrigation Consumption
Proposed Irrigation Consumption
wheat
maize
chickpea
potato
rice
cotton
sugarcane
mango
vegetables
millet
sorghum
barley
citrus

(a)


Sindh's Irrigation Demands (BCM)
7
6
5
4
3
2
1
0
Current Irrigation Consumption
Proposed Irrigation Consumption
wheat
maize
chickpea
potato
rice
cotton
sugarcane
mango
vegetables
millet
sorghum
barley
citrus

(b)

(c)



(d)

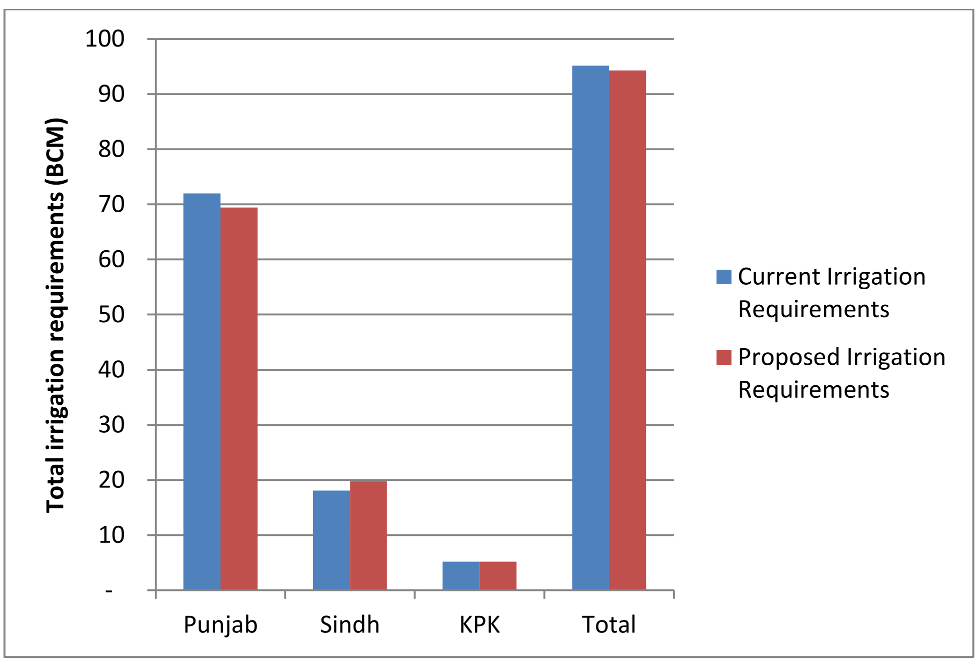


Figure 44: Current and proposed irrigation requirements of each crop in (a) Punjab, (b) Sindh and (c) KPK. (d) shows that redistribution decreases total irrigation requirement in the Indus basin by nearly 1 BCM. In particular, it relieves Punjab of some of its water stress.

Pakistan should consider a temporal, as well as a spatial, rearrangement of its cropping calendar (figure 16). Too many crops have their crucial planting and growing seasons coincide with the risky late winter-early spring months. Curiously, the months of plenty – July-September – do not see as much agricultural activity as later winter and spring.

Punjab and Sindh should attempt to grow some of their wheat in the summer when water is plentiful. It will be a step towards greater food security. Sugarcane, another water-intensive crop, should be grown later in the year alongside cotton and rice in the monsoon season. Vegetables should also be grown in mid-year rather than in spring. Sindh grows most of its vegetables, fruit, cotton and rice in the summer which is a good idea. However, maize and sorghum should also be grown in the summer.

4.3 Building the Next Dam

Chapter 1 introduced the concept that Pakistan will improve its water management by augmenting its current built storage on the Indus river system. Chapter 2 supported this claim by providing quantitative estimates of the decrease in water stress associated with the construction of a large storage dam. Experts and decision-makers alike have long known the salutary effects of additional storage on water availability in Pakistan. See, for example, the World Bank's yield curve with storage capacity for the Indus basin (figure 45). In 1975, WAPDA had planned to build one major dam every decade.

However, Pakistan has not been able to achieve a favorable political environment to build a major dam since 1970. Relatively smaller projects like Mangla-raising have not mitigated the impacts of silting Tarbela and Mangla and rising water demands. The reason for this long stalemate is the Kalabagh dam, which has caused a bitter controversy among the provinces which refuses to die down.

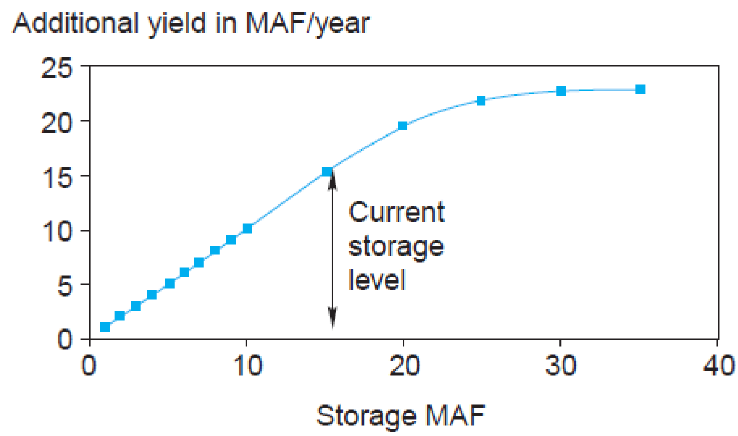


Figure 45: The World Bank's estimate of the yield curve in the Indus basin, based on additional arable land more storage will bring under irrigation. (Briscoe and Qamar, 2007)

Last month, the Punjab High Court "stirred up a hornet's nest" (Mehmood, 2012) by issuing a verdict that the Federal Government had undermined the national interest by delaying the construction of the Kalabagh Dam. The verdict was based on hearings from technical experts, mostly from Pakistan's Water and Power Development Authority (WAPDA). A storm of outrage poured in from the provinces of Sindh and KPK, where politicians fought for television airtime in accusing the Punjab High Court of 'anti-federation crimes' (Abro, 2012).

The Kalabagh Dam, a 3600 MW, 6 MAF hydropower reservoir, was conceived in the 1960's during the tenure of General Ayub Khan, then chief martial law administrator. Its feasibility studies were commissioned in the 1980's by General Zia Ul Haq, another martial law administrator. In the democratic 1970's and 1990's, dissenting voices from Sindh and KPK stalled progress on the dam. In 2008, when the Sindh-based Pakistan People's Party (PPP) assumed power at the center, it did exactly as expected by shelving the Kalabagh dam project for good.

When asked to testify in the Lahore High Court, Pakistan's Water and Power Development Authority (WAPDA) submitted a report that said, "The objections of three provinces of Pakistan against… Kalabagh Dam are… based on a lack of knowledge". It further stated:

"Legislators do not understand this highly complex technical project. An awareness campaign should have been launched to inform them about the importance of the venture… They also needed to be informed about the economic loss and the hardships people would suffer due to food and water shortages and load-shedding[2] if the reservoir was not built. The apprehensions raised by KPK and Sindh have been critically examined with the help of proper technical studies. These studies have revealed that most of these are based either on lack of information or hearsay." (The Nation, 2012)

This 'deficit model' (Gregory and Miller, 2000) of public understanding assumes that opposition to the dam stems from ignorance; if only the critics could learn the facts, agreement would follow. A recent conference on riparian disputes, held by IUCN-Pakistan, came to a similar conclusion: "Neutral fact and science-based studies can be very useful in solving the regional water issues" (IUCN, 2011).

However, there exists a coherent narrative of opposition. Sindhis point out that Zia Ul Haq, who ordered the feasibility studies for the Kalabagh dam in the 1980's, is otherwise notorious for having the iconic Sindhi prime minister Zulfiqar Bhutto hanged. It does not help that the Punjab High Court issued the verdict for Bhutto's hanging. The objectivity of the Punjab High Court is suspect, and WAPDA is seen to be Punjab-led as well.

[2] 'Load-shedding' is euphemism in Pakistan for power blackouts. Today the electricity shortfall in Pakistan stands at about 8000 MW.

In the following pages, I describe the versions of truth upheld in Punjab, Sindh and KPK, and investigate why they have been unable to convince one another. Having diagnosed the underlying issues of credibility and legitimacy, I propose lessons learned for water policy in a diverse democracy.

4.3.1 Interprovincial Water Accord

Although the Water Accord of 1991 should be seen as a triumph, there are several competing interpretations of the distribution formula, exacerbated by growing scarcity. The Accord allocated nearly 12 MAF of additional supplies around the year. To meet these allocations, the peak flows will need to be stored in at least 3.6 MAF of additional storage, says the World Bank (Briscoe and Qamar, 2007). Twenty years after the Accord was signed, there is still not a neutral organization equipped with the right instruments that would give all parties confidence that the Accord is being implemented transparently. The paradox is that the Water Accord, designed to apply to a scenario with additional storage and higher availability, is being stretched to suit the prevailing status quo of scarcity and deadlock. Insufficient storage capacity leads to year-around low flows, reducing everyone's share. Sindh interprets the low flows as evidence of Punjab helping itself to more water than its due share. This distrust prevents Sindh from supporting new storage, completing the vicious cycle.

4.3.2 Objections by KPK

Khyber-Pakhtunkhwa has three major concerns regarding the Kalabagh dam:

- The cities of Nowshehra and Mardan may be inundated by the reservoir in flood years. Both cities are important economic hubs and electoral constituencies.

- Affectees may not be adequately compensated and resettled. The fact that the Mangla dam affectees are still awaiting compensation to this date (The Nation, 2011) adds to the doubts. According to official figures from 1999 (as WAPDA cited in its report to the Punjab High Court), the number of people to be relocated by Kalabagh dam is 120,320, of which 78,170 are from Punjab and 42,150 from KPK.

- KPK claims that the reservoir for Kalabagh will be located in KPK but the hydropower generation plant in Punjab. The Constitution of Pakistan awards royalties to the province in which the power plant is located.

4.3.3 Objections by Sindh

Sindh's existential worry is that the Kalabagh dam will render Sindh into a desert, destroying agricultural livelihoods and urban industry. Sindh alleges that instead of fostering mutual trust, the Water Accord of 1991 handed Punjab a tool for fudging the total available flow in the Indus in a given year. With a history of injustice, Punjab cannot be trusted to operate the Kalabagh dam.

In addition, Sindh worries about the environmental health of the Indus delta ecosystem and the livelihoods of the communities living on the delta. In low-flow years, very little water reaches the sea. Consequently, environmental organizations have noted seawater intrusion as a serious problem. If delta flows are further reduced, seawater intrusion will lend more arable land barren, destroy more fisheries and cause the already shrinking mangrove forests on the delta to disappear. (See Table 11.)

Component	Observed impact
Mangrove forests	• Reduction in size of forests. • Decrease in biodiversity (loss of five species in the last 20 years). • Desertification due to loss of forests.
Fisheries	• Decrease in reproductive success of fish and shrimp due to loss of mangrove habitat, change in seasonal water availability and modified water quality.
Water quality	• Reduction in water quality following the use of pesticides and fertilisers from the irrigation plots. Effects are exacerbated as flows are reduced, since the concentration of pollutants increases. Chemicals found in the water include nitrates, phosphates, mercury, iron, manganese, hydrogen sulphide, lindate and DDT. • Accumulation of agricultural chemicals in the soil. • Growth of filamentous algae on the mudflats as a result of increased nutrient and organic enrichment. Saline-tolerant algae restrict the growth of mangrove seedlings. • Increased salinisation of the Lower Indus has resulted in a decline of fish species sensitive to changes in temperature and salinity.
Sea encroachment	• The reduction in freshwater inflow has led to severe encroachment of the sea into the Delta area. Saline water has intruded 64 km inland and 1.2 million acres of farmland have thus far been lost.

Table 11: A summary of the environmental impacts of reduced releases into the Indus delta in southern Sindh.

4.3.4 Response to Sindh's Concerns

The World Bank has historical ties with Pakistan's WAPDA, with continual exchange of expertise since the inception of the Indus Water Treaty and the Indus Basin Replacement Works. Both organizations share a rather technocratic view of the management of Pakistan's water, one that implements technically 'correct' solutions from above. However, in the democratic periods of Pakistan's history, WAPDA has made efforts to address stakeholder objections explicitly, both in open forums and through user-friendly material on their website. Until the shelving of the Kalabagh dam in 2008, the WAPDA website carried a point-by-point rebuttal of what it deemed the most common objections that Sindh posed to the Kalabagh dam. The following is an extract from the website (http://www.infopak.gov.pk/public/Kalabagh_Dam.htm):

1. **The Kalabagh Dam will desertify Sindh:** "Dams do not consume any water. Instead they store water during flood season and then make it available on crop demand basis for the remaining dry periods of the year. The real demonstration of this came after full commissioning of Tarbela Dam in 1976. During pre-storage era of 1960–67, average annual canal withdrawals of Sindh were 35.6 MAF. After Tarbela the corresponding figure rose to 44.5 MAF. It is estimated that after Kalabagh, canal withdrawals of Sindh would further increase."

2. **Outlets will be built to divert water away from the reservoir:** "Initial studies have indicated that construction of high level outlets at Kalabagh is economically unviable. Notwithstanding this, if any province wants to build [sic], then its share of water would be strictly governed by the Water Accord, 1991."

3. **Seawater intrusion into Sindh will increase:** "This fear is not substantiated by factual data… sea water intrusion, which seems to be at its maximum even now, is unlikely to be aggravated further by Kalabagh Dam."

4. **The mangrove forest will shrink further:** Studies show that mangrove forests are declining not because of lack of freshwater but varying tidal patterns, population pressures from Karachi, and overgrazing by cattle.

5. **Fish production in freshwater lakes in the delta will decline:** "Statistical data indicates that fish production has been on the rise in the delta. The Kalabagh dam is unlikely to have any adverse effect on fishing."

This narrative overlooks Sindh's more existential complaint – that putting Punjab in 'control' of another large dam will reinforce the historical imbalance of power between the dominant Punjab and the 'underdog' Sindh. To address this concern, the World Bank report posits the claim summarized in Figure 46. The plan enshrined in the 1991 Accord for the allocation of additional water has a strong redistributional component. Punjab and Sindh get equal shares of any additional water. KPK and Baluchistan, Pakistan's poorest provinces, get disproportionately large shares, with Punjab being the "biggest loser".

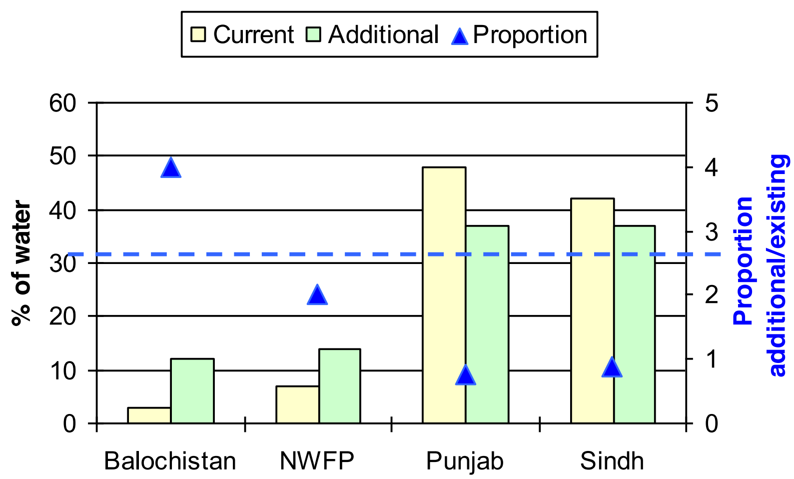


Figure 46: The allocation of additional water made available through the Kalabagh Dam, as agreed in the Water Accord of 1991. This figure is meant to debunk the 'pro-Punjab' image of the Kalabagh Dam and emphasize its redistributional component. (Briscoe and Qamar, 2007)

There is a long-standing debate about the flows that are needed to maintain environmental and ecosystem health in the delta. In his definitive history of the Indus Waters Treaty, Gulhati (1973) records that "for salinity repulsion at the mouth of the Indus and for purposes of navigation between Kotri and the sea, Pakistan wanted to reserve 17 MAF as an "existing use". This was taken up again in 1991 in the discussions of the Water Accord. The need for certain minimum escapage to sea, below Kotri, to check sea intrusion, was recognized. Sindh held the view that the optimum level was 10 MAF, which was discussed at length, while other studies indicated higher/lower figures. It was, therefore, decided that further studies would be undertaken to establish the minimal escapage needs down-stream Kotri." (Indus River System Authority, undated) According to the World Bank report, after many years of discussion, the Ministry of Water and Power has commissioned major studies by international consultants to examine the issue of the decline of the delta, the various contributing factors, and the role of diminished flows. Their recommendations about the quantity and timing of managed flows for the delta are expected soon.

4.3.5 Response to KPK's Concerns

The Indus delineates the historical border of Punjab with KPK (figure 1). The World Bank points out that practically any project built upstream on the Indus will have to be at the Punjab-KPK border. Ownership disputes are, therefore, inevitable. Similarly, it is unavoidable that the Kalabagh Dam will be located in both provinces.

WAPDA points out that Kalabagh will displace more Punjabis than Pakhtuns (The Nation, 2012). Increased public interest from NGO's and international watchdogs has ensured that rehabilitation of the displaced be done swiftly well. For instance, the Ghazi-Barotha project received an 'A' from the World Bank for attention to environmental and community impacts.

WAPDA in its report to the Punjab High Court rejected KPK's concern that Nowshera and Mardan will be inundated. According to WAPDA, the backwater effect of the Kalabagh Lake would end about 10 miles downstream of Nowshera.

4.3.6 Why the Critics Are Unconvinced

When one listens to educated critics of the Kalabagh Dam, one does not get the impression that they have yet to hear WAPDA's arguments. It seems that more is needed than awareness campaigns. Creditable as WAPDA's attempts are to assuage the concerns of smaller provinces, they have not worked as well as hoped.

As already noted, WAPDA's assurances that Punjab will give Sindh its legal share of water are ineffective for a basic reason: Sindhis claim that Punjab has repeatedly violated the Water Accord of 1991. Therefore, no future assurances by Punjab are credible. Sindhis claim that the water that reaches the farms in Sindh in consistently lower than IRSA's official figures. A popular version of this theory is that the mean annual flow of the Indus is lower than WAPDA claims. Punjab takes its share of water based on a fictitious total amount, and passes on the deficit to Sindh.

Until Punjab makes the process of water apportionment transparent, it cannot credibly deny these allegations, false as they may be. Credibility will involve surrendering control to a third party to monitor the process.

Considerable national resources have been spent on successive feasibility and impact assessment studies of the Kalabagh project. However, these studies have not enjoyed mutual credibility because the authors, and in fact WAPDA and the World Bank themselves, are not seen as objective. For scientific questions – like the inundation of Nowshera or the optimal environmental flows – experts exist in Sindhi and Pakhtun universities. They should be invited to contribute to the discourse. Issues like the verification of the apportionment of water are not technical – they need a neutral and credible enforcer. While more gauges at more canal outlets are direly needed, technology alone will not guarantee the credibility of results. In the absence of credibility and legitimacy, multiple truths will continue to coexist.

4.3.7 Policy Lessons

Given that three provincial assemblies have passed resolutions against Kalabagh dam, it is safe to say that Pakistan should move on to Bhasha dam. Still, the case should serve as a late lesson in the practice of water federalism in any diverse, democratic federation (India being another example). The measures suggested in this section should facilitate future mega-projects, including Bhasha dam.

4.3.7.1 Transparent, Neutral and Shared Implementation of the Water Accord

Pakistan is fortunate to have the Interprovincial Water Accord in place – observers wonder why it does not solve everything. The one big missing piece is the transparent and verified implementation of the allocations. A lack of transparency and accountability means that there is discretion, which corrodes belief in the fairness of the system. For a variety of murky and opaque reasons, some officials find themselves tweaking the system. In my conversations with these officials, they are the strongest advocates for moving to verification and transparency at all levels. Transparent audits would relieve the rank and file of water bureaucrats from top-down pressures.

Similar accords in other countries—the Colorado Compact in the US and the Murray-Darling Agreement in Australia—show (Briscoe, 2012) that once there is a clear agreement, there are three fundamental implementation requirements. First, that a rigorous, calibrated system for measuring water inflows, storages, and outflows be put in place. Second, that the measurement system be audited by a party which is not only scrupulously independent and impartial but is seen to be so by all parties. (In the case of the Colorado the Federal Department of the Interior is the 'river master'. In the Murray-Darling system, an individual from Western Australia is retained as the water auditor.) Third, reporting must be comprehensive and available in real time for all parties to see.

Some causes of interprovincial distrust run deep – such as the memory of the Punjab High Court sentencing Mr. Bhutto to death on the behest of an autocratic military regime. Yet other causes are easy to fix. When the provinces are satisfied that the existing water is being correctly apportioned, they might be more inclined to trust the federal government with additional storage. The Punjab Irrigation Department has recently taken a commendable step by publishing the discharge at every canal online in real time. Notice on their webpage (http://irrigation.punjab.gov.pk/, see below) the number of hits (over 1.3 million), the number of user complaints (over seventeen thousand), and the readily available customer service. This is a step in the right direction, which should be followed by more.

The federal government would be well advised to appoint a neutral auditor who would have the resources to measure all abstractions from the system and to report these in a public and transparent way. The chairman of the Indus River System Authority argues that only the Supreme Court of Pakistan enjoys the trust of all provinces. It can do a great service by appointing a water auditor.

4.3.7.2 Community Relations

Another silver lining is the *Ghazi Barotha Taraqiati Idara* (Ghazi-Barotha Development Institute), a shining example of public relations by WAPDA (see Fig. 47). From their website:

"The guiding principle for Ghazi Barotha Hydropower Project has been to maintain close contact between the engineering and environmental planners, social scientists, the local community groups and NGOs, right from the feasibility stage to Project construction. A Project NGO, namely Ghazi Barotha Development Institute (GBTI), was established and funded by WAPDA to assist in mitigating the genuine public concerns on the matters relating to land valuation and compensation, displacement of affectees and resettlement, loss of livelihood, employment and other social and environmental concerns. In addition to this, GBTI has implemented an integrated regional development plan and carried out development activities in the project affected areas."

WAPDA is well aware that in the eye of national and international scrutiny, it must allay all concerns about community impacts before it applies for international donor funding from ADB, USAID or the World Bank. In the other scenario of China funding Pakistan's next large dam, the Three Gorges Corporation is widely acclaimed for its performance in resettlement and rehabilitation. WAPDA is spending great effort in sophisticated community and environmental impacts studies of the Bhasha dam.

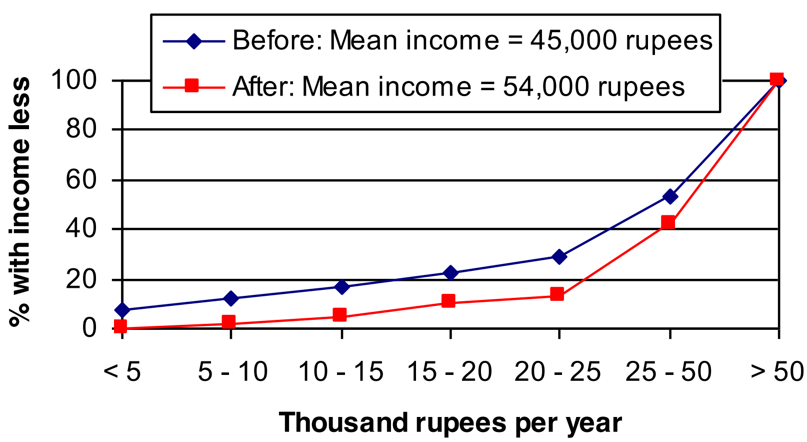


Figure 47: A tracking of the incomes of Ghazi-Barotha project affectees before and after the resettlement. Source: Harvard Kennedy School, Water and Development, Spring 2012

4.3.7.3 Royalty Sharing: Taking a Leaf from Brazil's Book

It is important to actively address the other legitimate issues relating to new storage: Who will pay? Who will get the contracts? Who will get royalties?

One proposal is to award the entire area occupied by the Kalabagh Dam to KPK. Then KPK will have the rightful ownership of the dam under the Constitution of Pakistan. Of equal concern is that hydropower royalties often go to the provincial government and are hardly seen by the affected district. In this matter, Pakistan can take a cue from Brazil. Brazil requires that hydropower royalties be distributed in the following way: 10% to the federal government, 45% to the state where the venture is located, and 45% to the municipal districts affected by the venture (World Commission on Dams, 2000).

4.3.7.4 Joint Production of Knowledge

It is evident that the technocratic approach cannot adequately serve a diverse, pluralistic democracy. Top-down prescriptive policy can aggravate the concerns of those not represented at the top. Pakistan seems to have become a stable democracy, and the Parliament represents the interests of every constituency. It is hoped, therefore, that when the Parliament orders the technical feasibility or impact study of the next large project, it will choose credible experts who enjoy the trust of all stakeholders. Prestigious universities exist in every province. The practice of having Pakistan's universities collaborate to solve policy issues – rather than outsource them to western consultants – will save taxpayers' money, foster better research, and minimize *ex post facto* challenges to the credibility of the studies.

4.3.7.5 'Do Not Let the Best Be the Enemy of the Good'

After signing off 25% of Pakistan's (naturally available) water to India in the Indus Water Treaty in 1960, President Ayub Khan faced detractors at home. He told them: "… very often the best is the enemy of the good and in this case we have accepted the good after careful and realistic appreciation of our entire overall situation… The basis of this agreement is realism and pragmatism…' The present-day water managers of Pakistan have taken this advice to heart by moving on to the Bhasha dam, which is expected to be complete by 2022.

The Bhasha dam has a price tag of $10-12 billion (WAPDA, 2010), roughly 2-3 times the cost of Kalabagh dam. Although it will produce more hydropower than Kalabagh, it will take 3 times as long to build as the Kalabagh dam. In dire electricity shortages, delay is expensive. It is ensconced in the mountains, giving it negligible irrigation potential, in contrast to Kalabagh dam that was located close to the plains. It will inundate 94 km of the Karakoram Highway, a vital route to China. It will destroy thousands of ancient rock carvings by the Indus Valley civilization.

However, decision makers in Pakistan acknowledge that the 45-year wait in the construction of the Kalabagh dam in itself has colossal costs associated with it (Abduhu, 2013). It is time to choose the next best option. Bhasha dam successfully avoids many of the fatal pitfalls of its competitor. It is located in Pakistan's *de facto* province, Gilgit-Baltistan. KPK has been more comfortable sharing royalties with G-B than with Punjab. It is truly seen as a means to redress the balance in the favor of 'late developers'. The fact that it is upstream of the Tarbela dam and has no diversion outlets puts Sindh's concerns to rest. Bhasha dam will displace only 30,000 people – as opposed to nearly 110,000 in the case of Kalabagh. The ease of consensus on Bhasha dam arguably makes it worth the forgone benefits of the controversial Kalabagh dam. Pakistan, I will argue, has been better off settling for Bhasha than chasing Kalabagh.

REFERENCES

Abduhu, S.. Engineers reiterate demand for starting KBD construction. The Nation, print edition, April 21, 2013. URL: http://www.nation.com.pk/pakistan-news-newspaper-daily-english-online/business/21-Apr-2013/engineers-reiterate-demand-for-starting-kbd-construction

Abro, R. (2012). Sindh MPAs dismiss Kalabagh Dam project. The Daily Times, December 7, 2012. URL: http://www.dailytimes.com.pk/default.asp?page=2012\12\07\story_7-12-2012_pg7_19

ADB (Asian Development Bank) and World Bank. 2010. "Pakistan Floods 2010 Damage and Needs Assessment." Pakistan Development Forum, Islamabad, November 14–15. 2010

Ahmad, M., A. Brooke, and G. P. Kutcher. 1990. "Guide to the Indus Basin Model Revised." World Bank, Washington, DC.

Ahmed, S., (2007). 'Water Balance and Evapotranspiration', Background Paper to the World Bank Country Water Assistance Strategy, Would Bank Pakistan

Ali, M., & Chaudhry, M. A. (1990). Inter- regional farm efficiency in Pakistan's Punjab: a frontier Production function study. *Journal of Agricultural Economics*, *41*(1), 62-74.

Ali, G., S. Hasson, and A. M. Khan. 2009. "Climate Change: Implications and Adaptation of Water Resources in Pakistan." GCISC-RR-13, Global Change Impact Study Centre, Islamabad, Pakistan.

Archer, D. R., N. Forsythe, H. J. Fowler, and S. M. Shah. 2010. "Sustainability of Water Resources Management in the Indus Basin under Changing Climatic and Socio Economic Conditions." Hydrology and Earth System Sciences 14: 1669–80.

Bhutto, B. (2009). *Reconciliation*. HarperCollins.

Bookhagen, B. and D. Burbank,2010. Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge, Journal Of Geophysical Research, VOL. 115, F03019, doi:10.1029/2009JF001426

Briscoe, J. and Qamar, N., 2007. Pakistan's Water Economy: Running Dry, World Bank Report Series.

Duloy, J. H., and G. T. O'Mara. 1984. "Issues of Efficiency and Interdependence in water resource investments: lessons from the Indus Basin of Pakistan." World Bank Staff Working Paper 665. World Bank, Washington, DC.

Falkenmark, M. 1989. The Massive Water Scarcity Now Threatening Africa: Why Isn't it Being Addressed? Ambio 18(2):112-118.

Falkenmark, M. and C. Widstrand 1992. Population and Water Resources: A Delicate Balance. Population Bulletin 47(3):1-36.

Falkenmark, M. and G. Lindh 1974. How Can We Cope With the Water Resources Situation by the Year 2015? Ambio 3(3/4):114-122.

Falkenmark, M., J. Lundqvist and C. Widstrand 1989. Macro-Scale Water Scarcity Requires Micro-Scale Approaches. Natural Resources Forum 13(4):258-267.

Fant, C., A. Gueneau, K. Strzepek, S. Awadalla, W. Farmer, É. Blanc and C. Schlosser, 2012: CliCrop: A Water-Stress and Irrigation Demand Model for an Integrated Global Assessment Modeling Approach, MIT JPSPGC Report 214, April, 26 p.

FAO, 2012: AQUASTAT (http://www.fao.org/nr/water/aquastat/main/index.stm).

Gardelle, J., Berthier, E., & Arnaud, Y. (2012). Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature geoscience*, *5*(5), 322-325.

Gilmartin, David. Scientific empire and imperial science : colonialism and irrigation technology in the Indus Basin, Journal of Asian studies, 1994,53,1127

Giosan, L., Clift, P. D., Macklin, M. G., Fuller, D. Q., Constantinescu, S., Durcan, J. A., ... & Syvitski, J. P. (2012). Fluvial landscapes of the Harappan civilization. *Proceedings of the National Academy of Sciences*, *109*(26), E1688-E1694.

GPPC, 2010. “Task Force on Climate Change Final Report.” Islamabad, Pakistan

Gregory, J. and Miller, S. (2000), Science in Public: Communication, Culture and Credibility, (London: Perseus)

Hasnain, S. I., 2002: Himalayan glaciers meltdown: Impact on South Asian rivers. FRIEND 2002—Regional Hydrology: Bridging the Gap between Research and Practice, H. A. J. van Lanen and S. Demuth, Eds., IAHS Publication 274, 417–423.

Hewitt, K. (2005). The Karakoram anomaly? Glacier expansion and the'elevation effect,'Karakoram Himalaya. *Mountain Research and Development*, *25*(4), 332-340.

Immerzeel, W. W., Droogers, P., De Jong, S. M., & Bierkens, M. F. P. (2009). Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. *Remote sensing of Environment*, *113*(1), 40-49.

Immerzeel, W. W., L. P. H. van Beek, and M. F. P. Bierkens. 2010. “Climate Change Will Affect the Asian Water Towers.” Science 328 (5984): 1382–85.

Indus River System Authority, ‘Apportionment of Waters of Indus River System between the Provinces of Pakistan: Agreement 1991 (A chronological expose)’, undated.

IPCC (2007). Climate change 2007: Impacts, adaptation and vulnerability. Cambridge: Cambridge University Press.

Iqbal, M. M., M. A. Goheer, S. A. Noor, H. Sultana, K. M. Salik, and A. M. Khan. 2009a. “Climate Change and Rice Production in Pakistan: Calibration, Validation and Application of CERES-Rice Model, GCISC-RR-15.” Global Change Impact Studies Centre (GCISC), Islamabad, Pakistan.

———. 2009b. “Climate Change and Agriculture in Pakistan: Adaptation Strategies to Cope with Negative Impacts, GCISC-RR-16.” Global Change Impact Studies Centre, Islamabad, Pakistan.

———. 2009c. “Climate Change and Wheat Production in Pakistan: Calibration, Validation and Application of CERES-Wheat Model, GCISC-RR-14.” Global Change Impact Studies Centre GCISC-RR-14, Islamabad, Pakistan.

IUCN, 2011. “Dialogue on Riparian Issues of the Indus River in Pakistan”. URL: http://www.iucn.org/news_homepage/news_by_date/2011_news_gb/march_2011/?7061/Dialogue-on-riparian-issues-of-Indus-River-in-Pakistan

Kahlown, M. A., Raoof, A., Zubair, M., & Kemper, W. D. (2007). Water use efficiency and economic feasibility of growing rice and wheat with sprinkler irrigation in the Indus Basin of Pakistan. *Agricultural water management*, *87*(3), 292-298.

Kargel, J. S., Abrams, M. J., Bishop, M. P., Bush, A., Hamilton, G., Jiskoot, H., et al. (2005). Multispectral imaging contributions to global land ice measurements from space. Remote Sensing of Environment, 99, 187−219.

Kheshgi, K. “KBD impossible after provinces opposition, says Asfandyar”. The News, print edition, December 9, 2012. URL: http://www.thenews.com.pk/Todays-News-2-147477-KBD-impossible-after-provinces-opposition-says-Asfandyar

Kulkarni, A. V., Bahuguna, I. M., Rathore, B. P., Singh, S. K., Randhawa, S. S., Sood, R. K., et al. (2007). Glacial retreat in Himalaya using Indian remote sensing satellite data. Current Science, 92, 69−74.

Laghari, A. N., D. Vanham, and W. Rauch. 2011. "The Indus Basin in the Framework of Current and Future Water Resources Management." Hydrology and Earth System Sciences 14 (8): 2263–88.

Lectures by John Briscoe in the Harvard Kennedy School, IGA-435: Water and Development, Spring 2012.

Lieftinck, P., R. A. Sadove, and T. A. Creyke. 1968. Water and Power Resources of West Pakistan: A Study in Sector Planning. Baltimore: Johns Hopkins Press.

Mastny, L., cited 2000: Melting of earth's ice cover reaches new high. World Watch Institute, Washington, DC. [Available online at http://www.worldwatch.org/alerts/000306.html.]

Meehl, G.A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J.F.B. Mitchell, R.J. Stouffer and K.E. Taylor, 2007: The WCRP CMIP3 multi-model dataset: A new era in climate change research. Bull. Amer. Met. Soc., 88: 1383–1394.

Mehmood. A. (2012). LHC Verdict on Kalabagh Dam Stirs Up a Hornet's Nest. Dawn, Novenber 29, 2012. URL: http://dawn.com/2012/11/30/lhc-verdict-on-kalabagh-dam-stirs-up-hornets-nest/

N. D. Gulhati, 1973. Indus Waters Treaty: An Exercise in International Mediation, Allied Publishers, Bombay.

NAS, Himalayan Glaciers: Climate Change, Water Resources, and Water Security, 2013

NASA, "NASA Pouring Funds, Scientists and Satellites into Pakistan Flood." What On Earth? Posted October 28, 2010. URL: http://blogs.nasa.gov/cm/blog/whatonearth/posts/post_1288240080113.html

Paltsev, S., Reilly, J. M., Jacoby, H. D., Eckaus, R. S., McFarland, J. R., Sarofim, M. C., ... & Babiker, M. H. (2005). *The MIT emissions prediction and policy analysis (EPPA) model: version 4*. MIT Joint Program on the Science and Policy of Global Change.

Pakistan Agricultural Research Council, Wheat and Barley Research Program, 2005. URL: http://www.parc.gov.pk/1subdivisions/narccsi/csi/wheat.html

Pakistan Water Statistics Handbook, Ministry of Water and Power. Accessed October 9, 2012. URL: http://www.wspakistan.com/index.php?Type=Home&Page=Home

PMD, 2011. "Outlook for Monsoon Season (July–September 2011)." National Weather Forecasting Centre, Pakistan Meteorological Department, Lahore. Accessed at: http://pakmet.com.pk/MON&TC/Monsoon/monsoon2010..html

Punjab Development Statistics, Punjab Bureau of Statistics, 2012. URL: http://bos.gop.pk/?q=system/files/Development-Statistics-2012.pdf

Qazilbash, I. 2008. The World Bank: Pakistan's Water Economy Background Paper 5: Water Balances and Evapotranspiration.

Sheikh, M. M., N. Manzoor, M. Adnan, J. Ashraf, and A. M. Khan. 2009. "Climate Profile and Past Climate Changes in Pakistan." Research Report GCISC-RR-01, Global Change Impact Study Centre, Islamabad, Pakistan.

Shrestha, M. L., and A. B. Shrestha, 2004: Recent trends and potential climate change impacts on glacier retreat/glacier lakes in Nepal and potential adaptation measures. OECD Global Forum on Sustainable Development: Development and Climate Change, Paris, France, OECD, 5–14.

Singh, P. & S. K. Jain (2003) Modeling of streamflow and its components for a large Himalayan basin with predominant snowmelt yields, Hydrological Sciences Journal, 48:2, 257-276, DOI: 10.1623/hysj.48.2.257.44693

Singh, P., & Bengtsson, L. (2005). Impact of warmer climate on melt and evaporation for the rainfed, snowfed and glacierfed basins in the Himalayan region. *Journal of Hydrology*, *300*(1), 140-154.

Smakhtin, V., C. Revenga, and P. Döll, 2004: A Pilot Global Assessment of Environmental Water Requirements and Scarcity. Water International, 29(3): 307–317.

Strzepek, K., and C. A. Schlosser, 2010: Climate change scenarios and climate data, Development and Climate Change World Bank Discussion Paper #9 (October 2010), 26 pages.

Strzepek, K., C.A. Schlosser, A. Gueneau, X. Gao, É. Blanc, C. Fant, B. Rasheed, and H. Jacoby, 2012b: Modeling Water Resource Systems under Climate Change: IGSM-WRS. MIT JPSPGC Report 236, December, 54 p. (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt236.pdf).

The Nation print edition, "WAPDA Comes Out in Support of the Kalabagh Dam", August 8, 2012. URL: http://www.nation.com.pk/pakistan-news-newspaper-daily-english-online/national/08-Aug-2012/wapda-comes-out-in-support-of-kalabagh-dam

The Nation, print edition, "PMLN for Rehab of Mangla Dam Affectees", June 10, 2011. URL: http://www.nation.com.pk/pakistan-news-newspaper-daily-english-online/national/10-Jun-2011/PMLN-for-rehab-of-Mangla-Dam-affectees

The World Bank, Pakistan: Priorities for Rural Development and Agriculture, 2011. Permanent URL: http://go.worldbank.org/KQ3CN5O0J0

UNOCHA (United Nations Office for the Coordination of Humanitarian Affairs). 2011. "Pakistan Monsoon 2011 Situation Report 14.

WAPDA, 2010. Brochure on Bhasha Dam. URL: http://www.wapda.gov.pk/htmls/future-index.html

Wildlife of Pakistan, 1994. URL: http://www.wildlifeofpakistan.com/IntroductiontoPakistan/climateofPakistan.htm

World Commission on Dams (Ed.). (2000). *Dams and Development: A New Framework for Decision-making: the Report of the World Commission on Dams, November 2000*. Earthscan.

World Glacier Monitoring Service, cited 2002: Glacier mass balance data 2000/01. [Available online at www.geo.unizh.ch/wgms/.]

Yu, W., Yang, Y.-C., Savitsky, A., Alford, D., Brown, C., Wescoat, J., Debowicz, D., Robinson, S. 2013. The Indus Basin of Pakistan: The Impact of Climate Risks on Water and Agriculture. Washington, DC: World Bank.

Zakaria, V., 2007. The World Bank: Pakistan's Water Economy Background Paper 3: Water and Environmental Sustainability