HYDROLOGICAL IMPLICATIONS OF CLIMATE CHANGE IN PAKISTAN

(A Case Study of Climate Change and its implications on Surface Water Resources of Pakistan)

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Submitted in partial fulfillment of the requirements of the

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IN THE NAME OF ALLAH, THE MOST MERCIFUL AND BENEFICIENT

Dedicated to My Younger Brother

Mr. Muhammad Iqbal

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ABSTRACT

Water sustains life on earth. Water is not everywhere but where there is water there is life. For an agrarian country like Pakistan, climate change poses major challenge to water management system. The melt water of mountain glaciers feeds major rivers which serve as water banks for fulfilling the water demands of growing population. Anthropogenic loads on environment have significantly altered the global climate pattern and earth's polluted environment is losing its natural resilience to cope with the climate variations. Rapidly and abruptly changing climate has induced intense impacts in hydrologic cycle of Pakistan. Glacial water resources are melting at an alarming rate (Jilani et al., 2007 & Bajracharya et al., 2006) glacial retreat. There is likelihood of disappearance of these glaciers due to rapid glacier melt caused by the higher temperature and as a result river flows are likely to decrease in many regions (IPCC, 2007). Peak river inflows of major rivers are the climate responsive indicator of surface water availability and under the present study, data of summer and winter inflow peaks of three major western rivers (Indus, Jhelum & Chenab) have been analyzed for the last three decades. It has been found that annual peak inflow of river Indus has experienced maximum reduction at Kotri over last 30 years where highest reduction of winter annual peak inflows was observed at river Indus at Kalabagh during the same period. Contrary to this, annual winter inflows of rivers Chenab (at Marala) and Jhelum (at Mangla) have almost doubled. As the impacts of climate change in the next few decades are unavoidable even if we go far the strictest mitigation efforts, so it is imperative to formulate and implement suitable response strategies & well-organized adaptation measures for addressing these interim impacts of climate change. Also, to cater extensive consequences of climate change, new water management strategies, infrastructure and political efforts are required to well conserve the national water resources and prevent their further decline.

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(ZAFAR IQBAL)

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FORWARDING SHEET

The thesis entitled, "Hydrological Implications of Climate Change in Pakistan" submitted by Mr. Zafar Iqbal, Registration No. 15-FBAS/MSES/S08 in partial fulfillment of Master of Studies in Environmental Science has been completed under my guidance and supervision. I am satisfied with the quality of student' research work and allow him to submit this thesis for further process as per IIU rules and regulations.

Date: 13/4/2010

Signature:

Name: Dr. Rashid Saeed

Chapter 1

INTRODUCTION

The world population is expected to increase from six billion in 2000 to nine billion in 2050. Water supplies are becoming insecure due to unchecked population growth, urbanization, water pollution and extensive scale agriculture. At present, approximately 33% of world population is facing the medium to severe water stress (Jones, 2009). In Pakistan, rapid population growth and environmentally unsustainable practices are increasingly putting stress on the natural resources, especially on water resources. Climate change shaped by global warming is melting the glaciers; country's major source of freshwater resources. With a very low natural resource base, Pakistan is facing the challenge of meeting the water needs of a mounting population. Water scarcity and power crisis are major concerns associated with the worsened water situation (Piracha and Majeed, 2008).

Management of scarce natural resources, waste management and the potential vulnerabilities to natural hazards & climate change are the most significant environmental concerns in Pakistan. It is increasingly recognized that change induced by the global warming, is casting its shadows in the form of deteriorated water and air quality, land pollution, biodiversity & habitat loss, rapid deforestation, land degradation and desertification etc (GOP[1], 2009). Most of the country's area is arid or semi-arid. Above

500 mm rainfall is received over only 8% of the total area of the country (ADB, 2008). Natural resources of the country like agricultural land; water and forests etc sustain Pakistan's rural population estimated over 60 percent of total population. These rapidly degrading natural resources need effective policy interventions in order to update and refine assessments of their status and use patterns (World Bank, 2006).

Rapid increase in population, poverty and urbanization are non-climatic factors adding to the severity of these environmental problems. Of the estimated environmental degradation cost of Rs. 365 billion per year (equal to 6% of GDP), 50% is attributed to illness and premature mortality caused by air pollution, 30% to waterborne diseases due to inadequate water supply, sanitation and hygiene whereas remaining 20% to reduced agricultural productivity due to soil degradation (World Bank, 2006).

1.1 Background

Pakistan is at increased risk of flooding, erosion, mudslides and GLOF during the wet season. Intensification of monsoon activity, increase in glaciers melting, and/ or synchronization of both may result flood disasters in Himalayan catchments. The run away of this main source of our water resources will jeopardize the livelihood of millions of population. The acute water shortage will result in longer drought and land degradation by 2050s (UNFCCC, 2007).

Global Climate Change is expected to hit hard the South Asian's economies with greater dependency on agriculture and water resources. It will have serious impacts on monsoons patterns, frequencies and intensities of rain spells on temporal and special scale, causing melting of glaciers thus increasing the frequency of floods and droughts. Where water availability is reduced, the communities will either have to adapt to use less water or bring water from farther a field at greater cost; agriculture will be affected badly resulting in low productivity; lower river flows will cause reduction in Hydel power generation and resultantly power failures/shortages will affect the economic and social life of the communities (IPCC, 2007).

Pakistan is an agricultural country and conservation of water resources is gear of its development. The water economy is lifeline for the country. Significant temperature increase has been observed over the Hindu-Kush Mountains of Pakistan resulting in GLOF. During the period of last 30 years, Himalaya-Gangetic Region has experienced a warming trend of 2.7 degree centigrade. The pre-monsoon warming of entire South Asian Region was observed as 0.87 degree centigrade during May 2009 since 1979 (Gautam et al., 2009).

In Pakistan, temperature increases are attributed to excessive deforestation and desertification. Summer temperatures of May and June have significantly increased during the four decades and particularly so during the warmest decade of 1990-1999. A general cooling by 0.1 to 0.3°.C in rural towns and a warming of 0.7° C in cities was observed during this period besides an increase in precipitation at a number of locations by 10 to 30%. An overall increase in precipitation of 44% at Quetta, 35% at Islamabad, 39% in Lahore and 37% in Peshawar was noted whereas a decrease of 38% in Karachi (Beg, 2006).

1.2 Significance of the Study

Unfortunately, there exists no systematic information on climate change in Pakistan. A dilemma lies in minds whether climate change is a fashion or reality. Owing to low literacy rate, most of our population is quite unaware of the climate change. Also, the government has not yet devised any policy on climate change so there is a very large question mark hanging over the idea that how government of Pakistan will adopt to serious threats associated with the climate change. The present study will help in formulating more efficient adaptation & mitigation measures best suited to our own climate change scenario. Especially in the water sector, where we are facing water stress, this work will substantially assist and add to improve decreased water availability in many arid and semi-arid regions.

21st century is the century of water and most harmful risk associated with the management of water resources is the Climate Change. With each passing year, adverse impacts of climate change are becoming more discernible. Climate change is a burning issue of global concern and so are its impacts. Climate change impacts can be seen anywhere in the world irrespective of the fact that where do its sources lie.

Water is a principal natural resource and competition for scant water resource can lead to regional and international conflicts. The current dispute of unbiased water distribution between Pakistan and India has enhanced the magnitude of the fact that sincere efforts are needed at national level to preserve existing water resources and to efficiently combat with potential threats confronted to water sector. The impacts of climate change may exaggerate economic losses, prevailing poor law & order situation in the country besides deteriorating the social structure, which ultimately will compel the masses for migration to relatively safe and rich locales, states or nearby countries. The conflicts on trans-boundary water distribution may also lead to international war (Schubert et al., 2003).

The findings of the research will help in reducing increased risk of floods and droughts in many regions and ultimately reduce damages and deaths caused by extreme weather events. This perhaps will be a fruitful endeavor to better pull off ultimate goal of acquiring environmental sustainability of our fresh water resources.

1.3 Aims and Objectives

The 4th Assessment Report of IPCC reveals so many uncertainties about the future availability of freshwater resources. It has been observed that at the local or regional levels, climate simulation model results are affected by large uncertainties. These models have made little progress in predicting more unanimously and more reliably the global amplitude of climate changes and their geographical distributions (Le Treut et al. 2008).

It has now become imperative to develop climatic record and replication based on the climate changes; the country had actually observed so far and is facing recently. The paramount preparation for managing unpredictable future climate change need to be identified and recognized in the context of water resource management. What actually required is to first recognize future threat of climate change and then go for integrated climate risk management.

The present study aspires to clearly identify the reality of change in our climate, investigate hydro-climatic trends besides analyzing the frequency & intensity of extreme weather events induced by climate change in Pakistan. Pakistan is most likely target region of hampering climate change; vulnerable to increased intensity and frequency of its impacts. Study aims to:-

- Analyze recent climatic trends in extreme river inflows of three major western rivers (Rivers Indus, Jhelum & Chenab) in Pakistan
- Find out the effect of climate change on surface water availability in Pakistan
- Study the frequency & intensity of climate-induced extreme weather events experienced by the country
- Investigate regional hydro-climatic trends of climatic changes
- Review major hydrological concerns of global climate change

1.4 Scope of the Study

The present study involves a detailed analysis of peak summer and winter annual inflows of rivers Indus (at Tarbela, Kalabagh and Kotri), Jhelum (at Mangla) & Chenab (at Marala) experienced over the last 30 years and carry out an assessment of the existing climatic trends on surface water resources in Pakistan. Summer and winter peak inflow data of last 30 years experienced by three major rivers has been examined in order to achieve the objectives of the study. In addition, regional experience of extreme weather events in Pakistan has also been included in the study report.

Chapter 2

LITERATURE REVIEW

Climate change is the change in global climate in the form of alterations in the precipitation, temperature and weather patterns due to anthropogenic emission of greenhouse gases into the atmosphere. It is dynamic environmental change on such a massive scale that unsustainable human activities must be stopped to impede this change and effectively respond to its adverse effects (UNEP, 2008).

Pakistan with a total land area of 796,095 sq km has quite complicated and gorgeous physiographical features ranging from snow-covered peaks of Himalayas, the Karakorum & the Hindukush to lower Indus plain intervened by the mountain valleys, western mountains, plateaus and vast deserts. Pakistan is a land of great climatic contrasts with four different seasons; winter from December to March, pre-monsoon season (including spring & summer season) from April to June, Monsoon season (Rainy season) from July to September and Post Monsoon from October to November (PANCID, 2008). Current population of the country is approximately 181 million and is likely to swell up to 335 million in 2050 (PRB, 2009).

Pakistan's climate is characterized by the low rainfall and extreme variations in temperature. Less than 200 mm annual rainfall is received on about 60 % of the total land area. Average annual rain falling on the southern slopes of Himalayas and the sub mountainous areas ranges from 760 to 1270 mm. Temperature variation is extreme; extreme minimum can slump to -27° Celsius in the north (at Skardu) in winter and rise up to extreme maximum of 52° Celsius in the southern parts during summer (PMD, 2006).

Flow of many rivers in the Hindu Kush-Himalaya is dependent upon the glacier melt during the summer season (Barnett et al., 2005). Higher temperatures associated with global warming result into increased glacier melt. River flows are likely to increase in the short term due to de-glaciation process but the contribution of glacier melt will gradually decrease over the next few decades due to global warming. Rainfall varies in magnitude, time of occurrence and aerial distribution. In Pakistan, mean annual precipitation changes from 100 mm in southern parts of Lower Indus Plain to over 750 mm near the foothills in the Upper Indus Plain. The entire canal commanded Indus plain receives annual average seasonal rainfall of 221 mm (PANCID, 2008).

Water circulates between the earth and atmosphere in different phases formulating a hydrological cycle. In the first phase, water moves from earth into atmosphere through evaporation and transpiration. Water vapours are randomly scattered in the sky through moving air masses. Warm air masses transport these vapours to comparatively colder regions where vapours are condensed into clouds. Second phase is the precipitation in which water from the clouds (atmosphere) falls on earth in the form of rain, snow or hail etc. The major portion of precipitated water that directly flows on the earth's surface in the form of natural stream (major rivers and local nullahs etc which finally drain into lakes or sea) constitutes the 3rd phase of hydrological cycle and is called surface runoff or surface flow. In the final phase, rest of the water coming from the atmosphere seeps into earth and either used by the plants or further finds it way into ground to become part of groundwater supply of earth (Kenneth et al., 1998).

2.1 Climate Change Dilemma and Hydrologic Cycle

The movement of water through various phases of hydrological cycle is unpredictable both in time and area and accordingly results into climatic extremes like heavy rains, excessive overflow of natural streams, flooding and drought in the nearby areas. Some people raise the concern that climate changes naturally and the nature will adjust the changes in global climate as it had been in the past. It is true that the Nature has remained quite resilient with climate variations in the past. However, the anthropogenic loads on our environment have substantially increased since the Industrial Revolution. This blemished abuse with the climate has exceeded beyond the natural balance of climate improvement and earth's polluted climate system is losing its natural resilience to cope with the climate variations.

Some of the long-wave infrared radiation emitted by the sun is not reflected back into space and is absorbed by greenhouse gases naturally occurring in the atmosphere. This radiation is transformed into heat, resulting in a stable average temperature of 15°C in the Earth's atmosphere. Since the industrial revolution, human societies are affecting this natural balance, resulting in the disturbance of normal climatic cycles. During the last 50 years, there is gradual increase of global mean temperatures of approximately 0.45°C and the sea level rise, caused by thermal expansion, approximately equals 18cm (IEMA, 2005).

2.2 Global & Regional Concerns of Hydro-Climate

Climatic extremes lead to change in all components of the global freshwater system. The average temperatures & precipitation are expected to increase in general in many river basins. The increased average temperature of the surface of Earth (15.4°C) may further rise by 1° -3.5° C by the year 2100. During 20th century mean sea level rose by

0.17 meters and by 2100, it is expected to rise between 0.18 to 0.53 meters or approx. up to 1.75 feet (UNFCCC, 2007). Here are some of the major global and regional apprehensions of the climate change.

2.2.1 Depletion of Snowmelt Water Resources (Glacier Melt)

Reduction of frozen water resources is associated with interaction of warming atmosphere with Cryosphere. The rate of melting water resource depletion is strikingly rapid. Except Andes and Europe, the glaciers all over the globe are receding. Alaska's glaciers have hitherto experienced the highest retreat followed by the glaciers of Northwestern USA & Southwestern Canada. Himalayan glaciers are at third in depletion race. Many small glaciers, e.g. in Bolivia, Ecuador, and Peru will disappear within the next few decades, adversely affecting people and ecosystems (IPCC, 2007).

Glaciated regions like Hindu Kush-Himalaya and the South-American Andes melt and drain into various rivers, which are regulated by glacier-melt water during the summer season. Higher temperatures are generating increased glacier melt and there is danger of drastic decrease in landmass of these glaciers. Numerical model simulations for Northern Hemisphere glaciers show reductions up to 60% by 2050 (Schneeberger et al., 2003). Pakistan's glaciers are spread over an area of about 16933 Km^2. Siachen, Hispar, Biafo, Batura and Baltoro are glaciers of Pakistan having lengths 75, 53, 50, 57 & 62 kms. The melting of Himalayan glaciers and their associated runoff pattern is being adversely affected by the global warming. Rate of retreat of Siachen glacier is 31.5m per year (Jilani et al., 2007). Different glaciers feeding in Chenab River have retreated at the rate of 6.81 to 29.78 m/year (Bajracharya et al., 2006). Gangotri glacier in Himalaya is retreating at an average rate of 18m per year (Samjwal et al., 2007).

Batura glacier supply melt water to River Hunza in northern Pakistan which ultimately flows into the Indus River. Ice cover of Batura glacier had reduced from 98 km^2 in 1992 to 81km^2 in the year 2000 whereas ice-free patches had increased from 25 km^2 in 1992 to 42km^2 in the year 2000. There is decrease of about 17 km^2 in Batura glaciers during the period from 1992 to 2000. Biafo Glacier, the 3rd largest glacier in the Karakorum is situated in the Baltistan area of Ladakh. This glacier feeds Barldu River, which joins the Shigar River falling ultimately into the Indus River. Snow and ice cover, measured as 92.807 km^2 in 1992, had reduced to 86.25 km^2 (Jilani et al., 2007).

2.2.2 Water Stress

Water scarcity is measured either by per capita water availability (Falkenmark indicator) or by ratio of withdrawals to long-term average annual runoff. When per capita water availability is below 1000 m^3/yr or ratio of withdrawals to long-term average annual runoff is above 0.4, the situation is called water stress situation (Ahmed et al., 2003). Water use per capita and in particular, irrigation water use, increases with temperature and decreases with precipitation. Water used in irrigation accounts for almost 70% of global water withdrawals. Demographic and economic growth, changes in life style, and expanded water supply systems are increasing the water use in most of the countries over the last few decades (Shiklomanov, 1997).

Higher temperatures in snowmelt-fed river basins lead to reduced flow in the long run and thus decreased water supply during the peak demand seasons like in summer causing a water and food famine. Warmer world would have more evaporation potential. Water vapors concentration in atmosphere will increase. Uncontrolled population growth and higher rate of evaporation estimated under increased temperatures will increase drinking and agricultural water demand at domestic, commercial and industrial level. Pakistan is susceptible to face more intense water needs under projected warming where more than 95% fresh water is utilized for irrigated agriculture (Pimental et al., 1997). Pakistan is placed in the list of hot spots with high vulnerability to abrupt climate change (Schubert et al., 2007) where anticipated temperature increase is likely to alter the hydrologic cycle; it may reduce water resource availability to a large extent.

2.2.3 Excessive Withdrawal & Contamination of Groundwater

Groundwater recharge rates and groundwater level is likely to be affected by the climate change. Fresh water use is increasing globally which in turn is increasing the demand for groundwater. Low flows in snow-dominated basins will be compensated by excessive groundwater withdrawal. In high latitudes, thawing of permafrost will cause changes in groundwater level and quality. Climate change can lead either to drought or increase in frequency and magnitude of floods, hence, groundwater recharge may accordingly decrease or increase, particular, in semi-arid and arid areas (IPCC, 2007).

In Pakistan, acute shortages in surface water will increase groundwater withdrawals leading to drastic reduction in the quantity and circulation beneath the surface of earth. Untreated industrial & urban effluents and toxic fertilizer's drainage from agricultural fields, discharged into the major rivers, are polluting the river and lake waters and increasing the risk of contamination of groundwater (Sindh Vision, 2007).

2.2.4 Flood Hazards

A warmer climate is more perilous with its increased climate variability. It may increase the risk of both floods and droughts. Different types of floods like river floods, flash floods and urban floods can occur because of different driving factors like intense long-lasting precipitation, snowmelt, and dam break due to ice jams or landslides.

Intensity of floods depends on precipitation intensity, volume, timing, antecedent conditions of rivers and their drainage basins (IPCC, 2007).

During the last sixty one years in Pakistan, the total losses ascribable to floods include more than 7,963 deaths in around 100,654 villages affected adversely whereas cumulative financial loss due to past floods exceeds Rs 385 billion (GOP[2], 2008). Lai Nullah has experienced extreme flood years of 1981, 1988, 1997 and 2001. 2001 flood event was ever largest among the recorded events and a national disaster. A total of 74 human lives were lost, about 400,000 people were affected, 742 cattle head perished, 1,087 houses were completely and 2,448 partially damaged. Estimates indicate a damage/loss of more than USD 0.25 billion to infrastructure, Government and private property (Kamal, 2007).

2.2.5 Risk of Severe Droughts

Warmer climate may lead to an increased risk of droughts in river basins largely dependent on the snowmelt, especially during the period of high demand. Longer droughts often result into extreme weather events followed by catastrophic floods. Current trend shows that semi-arid and sub-humid regions of the globe are more vulnerable to the increased drought in the future. These regions have suffered from more intense and repeated unprecedented droughts. Uncertainties are expected to increase due to global warming ultimately resulting into more likely and intense cyclonic activities and rainfall events in drought prone areas where soil erosion and land degradation will further accentuate the situation (IPCC, 2007).

Droughts are likely to catastrophically disturb the weather pattern and cause widespread damage to the biological potential of land, extinction of animal & plant and devastation of human life and economy (GOP[3], 2009).

Pakistan experienced the worst drought of the history from 1999 to 2000 triggered by the history's strongest El Nino event in which surface water availability was reduced by over 30%. Baluchistan, Sindh and southern Punjab were the worst hit areas where thousands of animal died, thousands acre of orchards were badly damaged and a large number of people migrated to neighboring regions putting enormous pressure on natural resources of less affected areas (Ahmed et al., 2003).

2.2.6 Water Erosion Problem

Unchecked deforestation is triggering the problem of water erosion and sediment transport. Sediment load is transported with glacier movement and excessive river flows and is deposited in large amounts where velocity of flow is decreased i-e in the upstream of major dams and reservoirs. This exceptionally decreases the storage capacity of major reservoirs (Sethi, 2005). Water storage reservoirs in Pakistan are losing their live storage capacities due to this problem pushing the country into list of water stress countries within next two years (PANCID, 2008).

Pakistan suffers seriously sedimentation problem in large water reservoirs. Unsustainable land use practices in the watershed lead to excessive deforestation, which increases the erosive potential of soil. Combined live storage capacity of three major reservoirs of Tarbela, Mangla and Chashma was 15.6 MAF at the time of their construction. At present, combined live storage capacity of Tarbela, Mangla and Chashma reservoirs is less than 12 MAF, which is predicted to fall up to 10.50 MAF by 2025 due to the sedimentation problems (GOP^2, 2009).

Hilly terrain, particularly Northern area of Pakistan, is experiencing extreme landslides and dam burst disasters resulting into intolerable socio-economic losses besides loss of precious human lives. In future, water erosion linked with increased rainfall intensity will further aggravate ensuing fatalities and socio-economic damages, particularly damages to infrastructure associated to water storage, regulation and management.

2.2.7 Glaciers Lakes Outburst Floods (GLOFs)

Higher temperatures endanger increased glacier melt and drastic decrease in landmass of these glaciers. Short term consequences of this alarming glaciers retreat due to global warming will be worst increased river flows and in the long run the contribution of glacier melt toward the river flow will gradually decrease over the next few decades. Rapid melting of glaciers may lead to catastrophic flood events known as Glacier Lakes Outburst Floods (GLOF). Glacial lakes are potentially very hazardous (GOP[3], 2009).

2.2.8 Rainfall Variability

Average precipitation is projected to increase during the 21st century. However it does not necessarily mean that mostly wet spell will prevail all over the world. Net change in river flows and groundwater recharge would be determined by the changes in precipitation and evaporation. Only 1% per year increase in carbon dioxide emission may result in 10% or more water supply reduction for several hundred million to a few billion people by the year 2050. 25% increase in precipitation has been observed since the last 100 years in Pakistan whereas the projected precipitation using 17 GCMs also shows an increase with large uncertainties (GOP[3], 2009).

It has been estimated that rainfall pattern in south Asian region will change in a range of 5% to 50% by the year 2070. Rainfall pattern will follow a decreasing trend in monsoon shadow zones where monsoon does not reach at present. Also the winter precipitation is expected to decrease in volume. This will probably shift peak river flows from spring to winter in many areas due to early snow melt with lower flows in summer and autumn (IPCC, 2007).

The average rise in temperature of ocean water was 0.2°C higher than last 50 year's average. Increased sea water temperature is likely to increase the intensity and frequency of rainfall in many areas. Like in Pakistan, precipitation has in general increased at a number of locations by 10 to 30% during the last four decades. During the four decades periods from 1960-1999, an overall increase in precipitation of 44% at Quetta, 35% at Islamabad, 39% in Lahore and 37% in Peshawar was noted whereas a decrease of 38% in Karachi (Beg, 2006).

Historical changes in the rainfall pattern of major cities of Pakistan can be seen in the Table 2.1.

Table 2.1 Rainfall Pattern in Major Cities of Pakistan

(Rainfall in mm)

City/ Period	1961-1970	1981-1990	1991-1999
Badin	237	243	259
Jacobabad	83	134	141
Hyderabad	209	165	142
Lahore	503	733	698
Karachi	254	162	158
Quetta	189	355	272

Source: (Beg, 2006)

2.2.9 Seashore Dilapidation

Pakistan has 1050 km long coastline along the border of the Sindh and Balochistan provinces. Seawater intrusion is swallowing rich aquatic ecosystem of mangroves found in the Indus Delta. These mangroves provide food and shelter during larval stage of the life cycle for some 80% of the commercial fish species caught from water. According to National Institute of Oceanography (NIO), Pakistan, the sea level at Pakistan's coastline shows an increasing trend of 1.1 mm/year which is well within global average range of 1.7±0.5 mm/year for the 20th Century (GOP[3], 2009).

Coastal strips of South and South East Asia are predicted to be more vulnerable to climate change. Inadequate fresh water flows in deltaic region pose major threats to aquatic life of the area. The intensity of seawater intrusion is increased by sea level rise. Sea level rise is also endangering coastal wetlands and mangroves for being hit by extreme tropical cyclones, tsunamis and storm surges etc (IPCC, 2007).

2.2.10 Shrinking Wetlands

Wetlands are fundamental ecosystems that provide globally significant social, economic and environmental benefits. Out of total 225 significant wetlands with only 1% of the total surface area in Pakistan, 19 have been internationally recognized. Hindu Kush, the Karakoram Range, and the Himalayas constitute northern highlands with famous peak of K2 or Godwin Austin (8,611 m high; the second highest peak in the world), and Nanga Parbat at 8,126 m, the twelfth highest. More than fifty peaks reach above 6,500 m. Pakistan is facing land degradation due to water erosion, wind erosion, salinity and water logging. Land desertification is mainly due to soil erosion, loss of soil fertility, flash floods, salinity, deforestation (PANCID, 2008).

2.3 Hydrologic Consequences of Climate Change

Climate change projects adverse and severe consequences for future water availability. Drought problems are projected for regions, which depend heavily on glacial melt water for their main dry-season water supply. More than one-sixth of the Earth's population is dependent for their water supplies on melt water from glaciers and seasonal snow packs (Immerzeel et al., 2009).

2.3.1 Effect on Water Resources

Evaporation rate of surface waters of earth are increasing with higher temperature and this increased concentration of water vapours is further escalating the global warming phenomenon due to fact that water vapours in air also act as vibrant greenhouse gas. This situation stimulates increased climate variability with more intense rainfall and frequent droughts. In monsoon areas, the mountains mainly determine precipitation distribution. Higher temperatures may cause availability of water from snow-fed rivers to increase in the short term, but it would eventually decrease due to receding snow cover and glaciers. This would have serious consequences for a country like Pakistan, where one major snow-fed river supplies two-thirds of the total fresh water flow (PMD, 2009).

2.3.2 Frequency and intensity of extreme events

The frequency and intensity of extreme events has remarkably increased causing widespread tremendous socio-economic loss and damage. Unlike historical examples, recent events provide evidence of anthropogenic climate changes. In 1991, a catastrophic cyclonic storm in Bangladesh left 100,000 people dead. Later in 1998 catastrophic flood inundated two thirds of land area of Bangladesh. Two third of Bangladesh came under water; over 30 million people were rendered homeless, and hundreds of thousands faced hunger and disease. In September of 1998, Bangladesh was flooded again due to "five days continuous 50-years record" rainfall. Flooding twice in the same monsoon season was a rare event in Bangladesh (Jamil, 2004).

Pakistan has also faced extreme weather events like unprecedented heavy rainfalls, droughts, floods, storms and cyclonic in past. Theses catastrophes have exploited the precious water resources of the country besides hampering the socio-economic values. Yemyin cyclone, which hit coastal areas of Balochistan during the year 2007 and ever-extreme flash floods experienced during year 2008 in hill torrents of southern Punjab & NWFP, killed hundreds besides huge damage to agricultural lands and other private & public infrastructure (GOP^2, 2009).

2.3.3 Effects on ecosystems

Severe droughts induced by the climate change may have adverse effect on plants and animals in the natural environment. Extreme climate variations may bring radical alteration in population size, species distribution and reproduction cycle on various time scales. In animals, other implication may be migration events. There is great risk to land resources also from global warming. Permafrost, frozen ground in Alaska, is subjected to melting causing sinking of trees & houses and also costly road repairs in summer at many places (Jamil, 2004).

2.3.4 Effects on aquatic system

Major climatic variations have serious implications on in marine systems. Particularly fish populations are more vulnerable to be affected badly. Two-thirds of all sea fish species are sustained in Coral reefs under a fairly narrow temperature range. Populations of many coral fish species have drastically decreased due to sea surface temperature rise by 1^0 C besides extensive mortality for a 3^0 C increase. Mangrove forests, situated along the coast in South Asia, Africa and other sub-tropical and tropical zones, grow above the water and provide protective habitat for feeding and spawning of a number of tropical fish species (Jamil, 2004).

2.3.5 Effect on Agriculture

Agriculture sector is potentially the most vulnerable to major climate changes. About three-fourth of the world's poorest people live in rural areas and depend upon agriculture for their livelihood. The land degradation and desertification linked to global warming are witness to adversity of agriculture sector. Agriculture intensification and agriculture intensification embedded by rapid population increase are deteriorating the environment leading to enhanced vulnerability and disruption potential of climate change. Water logging and salinity are other environmental issues associated with surplus groundwater and hamper agricultural production (Cynthia et al., 2004).

2.3.6 Social & economic impact

Extreme weather events, such as floods and droughts, are a major source of harmful climate impacts. Health of people is highly at risk to regional climate change. During the flood events, there is great likelihood of spread out of water-borne diseases possibly. It has been extensively experienced that flooding increases the prevalence of diarrhea and respiratory diseases besides hunger and malnutrition. Conversely, water shortages bring about similar health problems because people, due to limited and inaccessible supplies, are bound to get precarious and unsafe water from nearby supply location. Highest socioeconomic costs to human habitation are associated with the increased magnitude and frequency of extreme events (Jamil, 2004).

2.4 Regional Hydrological Cycle under Changing Climate

Pakistan is blessed with all kinds of resources, especial the water resource. The climate conditions vary from extremely cold winters to very hot summers. Various climatic factors like amount & distribution of rainfall, snowfall, snowmelt and temperature etc establish hydrologic characteristics of a particular region. Glaciers contribute 60-80 % in generating the total flow of River Indus upstream of Tarbela Dam and 30-50% for River Kabul. Rainfall contributes 30-35% in generating the total flow of River Indus upstream of Tarbela Dam with 65% for River Jhelum above Mangla and 20-30% for River Kabul. Snowfall contributes 5-10 % in total flow of River Indus upstream of Tarbela Dam with 35% for River Jhelum above Mangla and 20-30% for River Kabul. Groundwater is recharged from the rivers as well as from the seepage losses from the canals, watercourses and crop fields etc. The annul withdrawal of groundwater in Pakistan has been estimated 62 billion cubic meters (PANCID, 2008).

per capita availability of water in Pakistan is continuously decreasing since 1951. In 19[illegible] against the population of approximately 34 million, about 5260m^3 water was available per person to meet his annual demand. Gross per capita water availability in Pakistan declined to 2200 m^3 in early 1980, followed by further decrease up to 1350 m^3 2001. In 2010, 1066m^3 per-capita water is expected to be available to a population of above 167.72 millions. In 2025, decline in annual per capita water availability has been predicted up to 858 m^3 (Ahmed et al., 2003).

Pakistan is one of the world's most arid countries where less than 200 mm annual rainfall is received on 60 % area and above 500 mm over only 8% area (ADB, 2008). Pakistan Meteorological Department had analyzed climatic data of last 70 years (1930–2007) which revealed various climatic trends as given in Table 2.2.

Indus River system, being the major water source, is the lifeline for country's development. Low and erratic rainfall occurs during the monsoon season. In general, half of the country receives less than 200 mm of annual rainfall. Indus River flow is mainly generated through glacier melt whereas Chenab and Kabul rivers contain combined water from glacier melt and snowmelt. Jhelum River is mainly fed by snowmelt rainwater under summer monsoon system. Under the 1960 Indus Basin Treaty, Pakistan has the water rights of three western rivers (Indus, Jhelum and Chenab), whereas water rights of eastern rivers (Sutlej, Ravi and Bias) have been kept with India. A total average annual inflow of the western and eastern rivers is 142 MAF (GOP[3], 2009).

Table 2.2 Recent Climatic Trends in Pakistan

Rise in mean daily temperature of arid coastal areas, arid western/ northwestern mountains and hyper arid plains.	0.6-1.0°C
Decrease of winter and summer rainfall in coastal belt, hyper arid plains and humid areas.	10-15%
An increase in rainfall of monsoon zone	18-32%
Extreme minimum temperature	-27°C at Skardu in winter
Extreme maximum temperature	52°C in south during summer
Decrease in relative humidity over arid plains of Baluchistan	5%
Increase of solar radiation intensity over the southern half of country	0.5% to 0.7%
Decrease in cloud cover over central and southern Pakistan	3-5%
Temperature increase in northern parts	0.9°C
Increase in evapo-transpiration rate in northern parts	3-5%

Source: Pakistan Meteorological Department, Islamabad.

2.5 Regional Experience of Extreme Weather Events

In Pakistan, frequency of extreme events such as heavy rain, flash floods, dust/thunderstorms, hailstorm, heat waves, density and persistence of fog has increased significantly besides a visible shift in summer and winter weather pattern (GOP[3], 2009). The detail of some of major extreme weather events faced by the country in past is narrated as under:

2.5.1 Worst Flood of 1992

Pakistan faced two major catastrophic floods in 1992; 1st in July & August, and the second in September. Exceptionally heavy rains in July &August caused inundation of a large area of the province of Sindh experienced. In September, there were exceptionally high floods in the Jhelum and Chenab rivers besides very high flood in Indus at locations of Guddu, Sukkur and Kotri Barrage sites. Flood protection network, irrigation networks as well as C&W roads suffered significant damages. Heavy rains in the catchment areas of the Chenab and Jhelum Rivers caused the September flood. The flood in river Chenab also deteriorated irrigated land, vast stretches of roads, education and health facilities. Series of intense rains resulted extreme floods in the river Jhelum and its tributaries Poonch, Neelum, Kunar and Mahal. River water rose to unprecedented levels and the floating timber logs were held back against the bridge decks. The Kohala Bridge on the river Jhelum along with the bridges at Azad Pattan, Holar, Kuliari, Karote and Mangla were completely washed away. Northern areas also suffered widespread and scattered damage to infrastructure mainly due to torrential rains and land slides.The unprecedented flood in river Jhelum breached left marginal bund (LMB) in the reach at RD 12-17, upstream of old Rasul weir and water at the rate of about 50,000 cusec entered in Lower Jhelum Canal (LJC). The overflow from LJC as well as the river spillage caused breaches in irrigation channels besides extensively damage to seven bridges on LJC and a few bridges on R-Q. Heavy rains in the hilly areas around Rawalpindi, Murree, Attock, Jhelum and Chakwal caused extensive damage to the retaining walls constructed alongside roads due to landslides. Other structures like culverts; causeways were also damaged due to flash floods in hill torrents, spillage of local streams and inundation resulting from rains. In NWFP substantial damage occurred to road network including a number of major bridges. Garhi Habibullah Bridge on Kunhar River washed away completely and two bridges on the river Haro downstream of Khanpur Dam were partially damaged (GOP, 1994).

2.5.2 Drought of 1998-2000

Historical droughts faced by the areas now situated in Pakistan were of the years 1871, 1881, 1899, 1902, 1920, 1931, 1935 and 1951etc. Rainfall plays an important role in sustaining the agriculture as well as our life. Very scant rainfall occurred during the years from 1998 to 2000 in Pakistan. Unrelenting low precipitation over the river catchment areas put country's water resources under great stress & sufficient water supply was not available to meet the crop & community needs resulting hydrological drought conditions over the country (GOP^3, 2009).

2.5.3 Lai Nullah Flood of 2001

According to the information provided by the Pakistan Meteorological Department, Lai Nullah, situated in twin cites of Rawalpindi and Islamabad, experienced the largest among the recorded floods on 23 July 2001; the rainfall depth was recorded at 620 mm in 10 hours at the Islamabad station. Heavy rainfall was caused by a freak combination of disastrous weather events including (a) intense heating on the surface, (b) presence of mid latitude westerly trough and (c) moisture feeding through monsoon flow along Himalayas.

Lai Nullah has experienced extreme flood years of 1981, 1988, 1997 and 2001. 2001 flood event was ever largest among the recorded events and a national disaster. A total of 74 human lives were lost, about 400,000 people were affected, 742 cattle head perished, 1,087 houses were completely and 2,448 partially damaged. Estimates indicate a damage/loss of more than USD 0.25 billion to infrastructure, Government and private property (Ahmed, 2007).

2.5.4 February 2003 Wet Spell

Pakistan Meteorological Department reported extreme weather condition on 3rd week of February 2003 when persistent rains and snowfall were experienced for six days in upper parts of the country. Moist, warm air from the Arabian Sea interacted with cold air mass of central Russia and generated frequent occurrences of prolonged and excessive precipitation over northern Balochistan with snow over mountainous areas. In the first two days, more than 10 inches of snow fell over northwestern mountainous areas of country. Main reservoirs were recharged and filled to their capacity; only Mangla Dam level rose to more than 50 ft.

2.5.5 Flash Floods of Year 2003 in Sindh

As per historical record of Pakistan Meteorological Department, an El Nino cycle after persisting over four months ended in the end of winter season of 2003 and brought the heavy rains in Pakistan in February 2003. Another evidence of climate variability was observed in July 2003 subsequent to a severe drought in most parts of Sindh. After a prolonged absence of moderate to heavy rainfall, very heavy downpour on July 26, 2003 in Lower Sindh caused flash flooding in Southeastern parts of Sindh and Karachi. There was great loss of life and property in the area. A trough developed in Arabian Sea and resulted in heavy downpour during the last weak of July 2003 in southeast Sindh causing severe damages to loss of life and property. On 8th July 2003, Larkana received 209mm of rainfall in 24 hrs followed by moderate to heavy rainfall over coastal areas of country on 17th July 2003. The system reached its climax on 25th July when 200% to 300% above than normal heavy rainfall was observed in Karachi causing flash flooding. Also Chhor and Thatta received more than 400mm of rainfall during the spell. During this spell of furious flash floods, 235 persons were injured; 178 people lost their life whereas 9455 animals were reported dead besides grave loss of agricultural crops and other infrastructure damage.

2.5.6 Tropical Cyclones

Tropical cyclones come from weather systems originating from Bay of Bengal and to some extent from Arabian Sea and adversely impact coastal areas of Sindh and Balochistan. Over the past years cyclones tend to become recurrent all along the Pakistan's coastline. Thatta and Badin Districts of Sindh were seriously damaged by cyclone of 1999 where 0.6 million people were affected besides the loss of 202 lives. Cyclone Yemyin in 2007 was hit 26 districts of Balochistan and Sindh and resulted into widespread losses and damages. Approximately 2.5 million people were affected; 400 deaths were reported including 142 deaths in Karachi. Vulnerable low-lying regions in Sindh allow cyclone surges extend fairly to some distances inland. Intense winds normally accompany cyclones and they cause widespread damage (GOP, 2008).

2.5.7 Glacial Lake Outburst Flood (GLOF)

In Pakistan, although GLOF occurrence has not been usually documented in past but records indicate few GLOF events in Ghizar Valley in Ishkoman region in 1960 and in Hunza region in 1892-93. Shingo Basin, Astor and southern areas of Gilgit are also considered highly vulnerable to GLOF events. There are 2420 glacial lakes identified in Pakistan covering a total area of almost 126 Sq. Km. Among these identified glacial lakes, 52 are declared as potentially dangerous glacial lakes. These potentially dangerous lakes can burst anytime and cause flash floods due to which continuous risk prevails for the downstream inhabitants (NDMA, 2008).

As per the information available on the web site of National Disaster Management Authority, Islamabad, recent landslides in Hunza Valley has created an artificial lake stretched in reach of 11.5 kilometers with approximately 220 ft depth along the course of river Hunza River and downstream locales are under threat of dam burst failure.

2.6 Future Threats

Followings are some of major future threats of climate change linked with the management and conservation of water sector:

2.6.1 Less Adaptation Capacities

Developed nations have strong economies. Their cropping pattern, land use and water supply system need minor adjustment for combating projected climate change. Having enough adaptation capacity, most of the people in developed world, living in a specific climate, have already adapted to their local climate conditions through suitable agricultural practices, climate resilient housing and several other aspects of their life. Hence they are less likely to be damaged by the bad impacts of future climate changes. On the other hand, people living in under-developed world are poor and much more vulnerable to be hit by the hampering climate change. These countries have less capacity to adapt to climate changes; future climate change may swallow the decade's investment by wiping out entire localities, affecting agricultural land and causing widespread diseases. Average evaporation and precipitation are projected to increase during the 21st century, which will lead to changes in stream flow and groundwater recharge. Several hundred million to a few billion people are likely to suffer water supply reduction of 10% or more by the year 2050 corresponding to 1% per year increase in carbon dioxide emission (ESCAP, 1997).

2.6.2 Monsoon Disturbances

Current vulnerabilities to climate are leading in semi-arid and arid low-income countries like Pakistan and are strongly correlated with precipitation variability. Under warming conditions, the summer season will expand while winter will shrink (IPCC, 2007). Ultimately, the snowfall will occur for a shorter duration and melting will continue for longer period bringing drastic changes in mass balance. Consequently, snowmelt and supply of water will be available much earlier than the present and may be inadequate when required.

In Pakistan, global climate change may have serious impacts on the monsoons. Melting of glaciers may further accelerate and result in increased number of more severe floods and droughts. There will be acute reduction in annual inflows to water reservoirs, water shortage for agriculture, insufficient recharge of groundwater and sharp decline in per capita water availability. Climate change has key concern in South Asia where it may stimulate its extremes in the form of monsoon disturbance, El Nino Southern Oscillation, tropical cyclones, floods and droughts. There is a significant contribution of monsoon rainfall, snowmelt and glacier-melt in river flows of the region, especially the summer flows. Socio-economic conditions of the people living in the region are expected to be seriously hampered by the failure of monsoon which may have long-lasting effects on poor locales of less developed countries like Pakistan (GOP[3], 2009).

2.6.3 Temperature and Rainfall Variations

In the South Asian region, the temperature increase is estimated as from 0.4 °C to 2 °C in the year 2070 and a corresponding change in rainfall pattern is expected in the range of 5% to 50% (IPCC, 2007). 4th Assessment report of IPCC predicts that rainfall pattern will follow decreasing trend in monsoon season whereas overall winter precipitation will be less frequent and more intense. As the result recent climate concerns of more intense and increasing floods, droughts, and tropical cyclones will further continue to jeopardize the human settlements and economies in a relatively harsher way (GOP[3], 2009).

2.6.4 Sea Level Rise

IPCC scenarios project a rise in global mean sea level by 3 to 14 cm up to the year 2025 followed by the rise of 5 to 32 cm up to 2050 and 9 to 88 cm by the year 2100 (IPCC, 2007). However, spread of sea level rise at regional level will experience large uncertainties. Rate of sea level increase in Pakistan has been observed as 1.1 mm/year, which is well within global average range of 1.7±0.5 mm/year for the 20th Century. Severe social and economic disruption from projected sea level rise and storm surges may occur in areas lying along the Sindh-Makran coastline (GOP[3], 2009).

2.6.5 Ecological Impacts

Projected climate change may create extensive distress on natural ecosystem and human habitation. Recurrent floods and storms would increase loss of human life; risks for spread of fatal diseases would be increased besides further devastation of public and private infrastructure. Sea level rise could cause extensive loss of coastal wetlands and erosion of shorelines. Immense loss of biodiversity is expected in the form of extinction of many birds, fish and plant species through deterioration of aquatic and land ecosystems. Seawater intrusion may degrade water quality in coastal aquifers. Water supply will progressively more fall short of demand, which is already under-stress in Pakistan (Jamil, 2004).

Chapter 3

RESEARCH METHODOLOGY

Climatic change alters the variability of rainfall and the quantity of water available as runoff mostly accumulating as inflow upstream of a river rim station. It poses major challenges to water management systems due to increase in water demand associated with growing population. It has been estimated that more than one-sixth of the world's population live in glacier- or snowmelt-fed river basins and approximated the same figure (more than 1.1 billion people) have no access to safe drinking water (GOP[3], 2009). Flow of many rivers in the Hindu Kush-Himalaya is dependent upon the glacier melt during the summer season (Barnett et al., 2005). So, Pakistan depends greatly on melt water from mountain glaciers for agriculture, fisheries and forestry.

Climate change demands for new water management strategies, infrastructures, and political efforts to fill the gap between demand and supply of water (Schubert et al., 2007). Country's water resources are increasingly becoming scarce. More than 90% of the climate simulation models show the confidence that world water demand will increase due to population growth and economic development. Especially, water-scarce areas of the world will face acute water shortages due to climate change crisis (IPCC, 2007).

The present research involves investigating the annual maximum & minimum inflows and their associated annual surface water availability of three major rivers in Pakistan. For this purpose daily inflow data of last 30 years (1980-2009) of three major rivers were sieved to find out the annual maximum and minimum inflow values. River Indus inflow discharges at Tarbela, Kalabagh (to incorporate the effect of Kabul River) and Kotri (to incorporate the effect of eastern rivers) as well as inflow discharges of river Jhelum at Mangla and River Chenab at Marala have been incorporated in the study. Following approaches were adopted to reach the overall objectives of the study.

- Collection of Primary Data of river inflows (Rainfall data of catchment areas of main rivers was not provided by PMD due to official binding)
- Sorting out of the Data (Spread of data over the three decadal frame)
- Statistical Analysis of Data
- Interpretation of results

3.1 Collection of Primary Data

The primary data of last 30 years related to annual availability has been received from IRSA (Indus River System Authority) whereas river inflow (Runoff) data of three major rivers namely, Indus, Jhelum and Chenab has been collected from Federal Flood Commission Islamabad for the research work. Relevant secondary data was also perused so as to reach overall objectives of the study.

3.2 Sorting out of the Data

For each year, daily discharge data of major western rivers (Indus, Jhelum and Chenab) was examined to find out annual summer and winter peaks. Total annual water availability data was also spread over the two seasons: Kharif season (observed normally during summer) & Rabi season observed during winter days.

3.3 Statistical Analysis of Data

Annual summer and winter peak inflow data of last 30 years over the three decades. For each decadal timeframe, average annual inflow has been calculated. Highest and lowest inflow values have been calculated statistically and climate change oscillations have been derived by measuring the percentage deviation of highest and lowest inflow values above or below the average annual inflow. Finally average annual water availability values of last three decades (observed during Kharif and Rabi Season) have also been analyzed on the same pattern for each decade by using the appropriate statistical operation.

3.4 Interpretation of results

Historical annual inflow extremes of major rivers have been graphically plotted to find out the past and probable impacts of climate variability on rivers selected under the present study. Trends in river inflows and their associated annual water availability have been found besides to investigate rainfall and temperature extremes. At the end, intensity and frequency of extreme inflows have been provided besides to predict future impact of climate change based on the various flood categories of three major rivers of Pakistan as given in Table 3.1.

Table 3.1 Flood Limits of Rivers Indus, Jhelum and Chenab

(Figures in cusecs)

RIVER	Gauge Site	Design Storage Capacity	Flood Classification				
			Low Flood	Med Flood	High Flood	Very High Flood	Exceptionally High Flood
Indus	Tarbela	1,500,000	250,000	375,000	500,000	650,000	800,000
	Kalabagh	950,000	250,000	375,000	500,000	650,000	800,000
	Kotri	875,000	200,000	300,000	450,000	650,000	800,000
Jhelum	Mangla	106,000	75,000	110,000	150,000	225,000	300,000
Chenab	Marala	1,100,000	100,000	150,000	200,000	400,000	600,000

Source: Pakistan Meteorological Department, Islamabad.

Chapter 4

DATA ANALYSIS, RESULTS AND DISCUSSIONS

River flows in many regions of the world are likely to decrease due to rapid glacier melt caused by the higher temperature (IPCC, 2007). In Pakistan, peak inflows are experienced in summer season due to high concentration of monsoonal rainfall and glaciers-melt whereas relatively less intense inflows are observed in general during the winter season mainly due to winter rainfall at various downhill rim stations besides outflows from upstream reservoirs (GOP^2, 2009). Following trends has been examined in last 30 years' summer and winter inflows of three western rivers of Pakistan.

- Trends in extreme annual inflows of River Indus at Tarbela, Kalabagh and Kotri during summer and winter season
- Trends in extreme annual inflows of River Jhelum at Mangla during summer and winter season
- Trends in extreme annual inflows of River Chenab at Marala during summer and winter season
- Trends in total annual water availability during Kharif and Rabi season.

Detail investigation of above trends is described as under:

4.1 Trends in extreme annual inflows of River Indus at Tarbela

River Indus is the largest river of Pakistan. Melting of Karakorum and Hindu Kush (KHK) glaciers, snowfall and rainwater generates total flow of river. With an average altitude of 6,000 meters, Karakorum extends from Hunza valley to Shyok River. Its western end lies in Pakistan. Himalaya ranges are the snow caped steep hill peaks with huge glaciers situated in south of Karakorum with an average height of 4,000 ft. Along the China and Afghanistan border, there lies Hindu Kush region constituting the watershed of river Swat, a major tributary of river Kabul (Sethi, 2005). Beginning at the heights of the world with glaciers, the river feeds the ecosystem of temperate forests, plains and arid countryside. Together with the rivers Jhelum, Chenab, Ravi, Sutlej, Beas and two tributaries from the North West Frontier side (rivers Swat and Kabul), the Indus forms the Sapta Sindhu (Seven Rivers) delta of Pakistan.

4.1.1 Variation in Peak Annual Inflows (Summer inflows)

Data analysis of maximum annual inflows of river Indus observed at Tarbela during last 30 years (from 1980 to 2009) is given in Table 4.1 which shows a mixed trend of inflow variation over last three decades.

It was observed that the annual average inflow of 1st decade (1980-1989) has increased by 8.86% than annual average inflow of 2nd decade (1990-1999). Further, average annual inflow of 3rd decade (from 2000-2009) decreased by 12.07% as compared with the average annual inflow of 2nd decade. This trend confirms that the 1990s decade was the warmest complete decade on earth (Sparks & Menzel, 2002).

Table 4.1 Peak Annual Inflow Variation of River Indus at Tarbela (Summer season)

(Discharge in Cusecs)

1980-1989		1990-1999		2000-2009	
Year	**Max inflow**	**Year**	**Max inflow**	**Year**	**Max inflow**
1980	289,000	1990	376,000	2000	389,000
1981	314,000	1991	327,600	2001	281,000
1982	334,000	1992	358,100	2002	348,000
1983	385,000	1993	332,100	2003	340,000
1984	318,000	1994	391,500	2004	237,000
1985	301,400	1995	480,000	2005	391,000
1986	357,800	1996	402,000	2006	448,000
1987	322,400	1997	400,000	2007	308,000
1988	433,600	1998	365,000	2008	308,000
1989	448,600	1999	382,000	2009	304,000
Total	3,503,800		3,814,300		3,354,000
Avg. (per year)	**350,380**	**381,430**		**335,400**	
Maximum	**448,600**	**480,000**		**448,000**	
Variation (%)	**28.03**	**25.84**		**33.57**	
Minimum	**289,000**	**327,600**		**237,000**	
Variation (%)	**-17.52**	**-14.11**		**-29.34**	

Average inflow of River Indus observed at Tarbela during the last 30 years has been statistically calculated as 355,737 cusec. During the last 30 years period, river Indus received highest annual maximum inflow of 480,000 cusec (year 1995) with an intensification of 25.48% above annual average value of 2nd decade (1990-1999) whereas a lowest annual peak of 237,000 cusec (year 2004) was observed with a recession of -29.34% as compared to average annual of 3rd decade (2000-2009). Upper limits of climate change oscillation were observed in the form of recession of -29.34 % (year 2004) or intensification of 33.57% (year 2006) in annual river inflow.

Keeping in view the flood limits given in Table 3.1 (provided in previous chapter), it was found that among the last 30 years, river Indus at Tarbela reservoir experienced 12 medium flood years, 17 high flood years and a low flood year as shown in the Figure 4.1. Floods, droughts and cyclones are the key climatic events (Sharma & Devesh, 2008). Figure 4.1 shows that climate change has resulted in increased number of extreme weather events ranging from medium to high level flooding in the upper catchment of Tarbela dam.

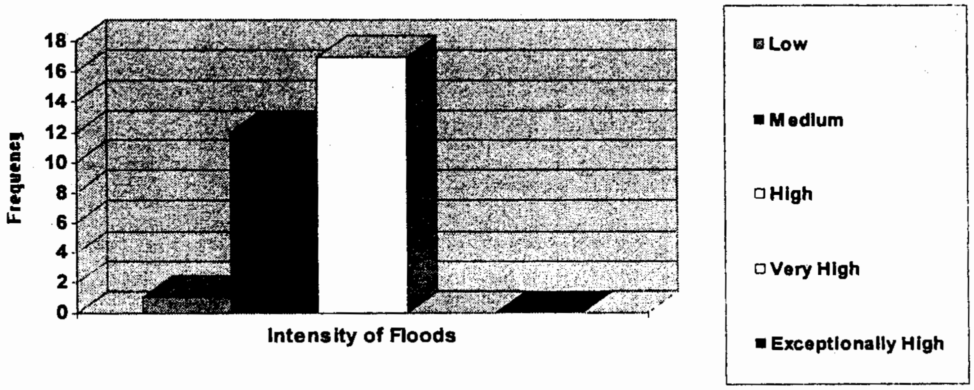

Figure 4.1 Flood Frequency & intensity of River Indus at Tarbela

Figure 4.2 shows a reduction trend observed over the last 30 years in peak annual inflows of river Indus at Tarbela. There is an insignificant change in annual river inflow of river Indus at Tarbela showing a steady response to climate change. A very inconsequential reduction trend of 0.64 % was observed in peak annual inflows of summer season as indicated by the slope of dotted line in the Figure 4.2.

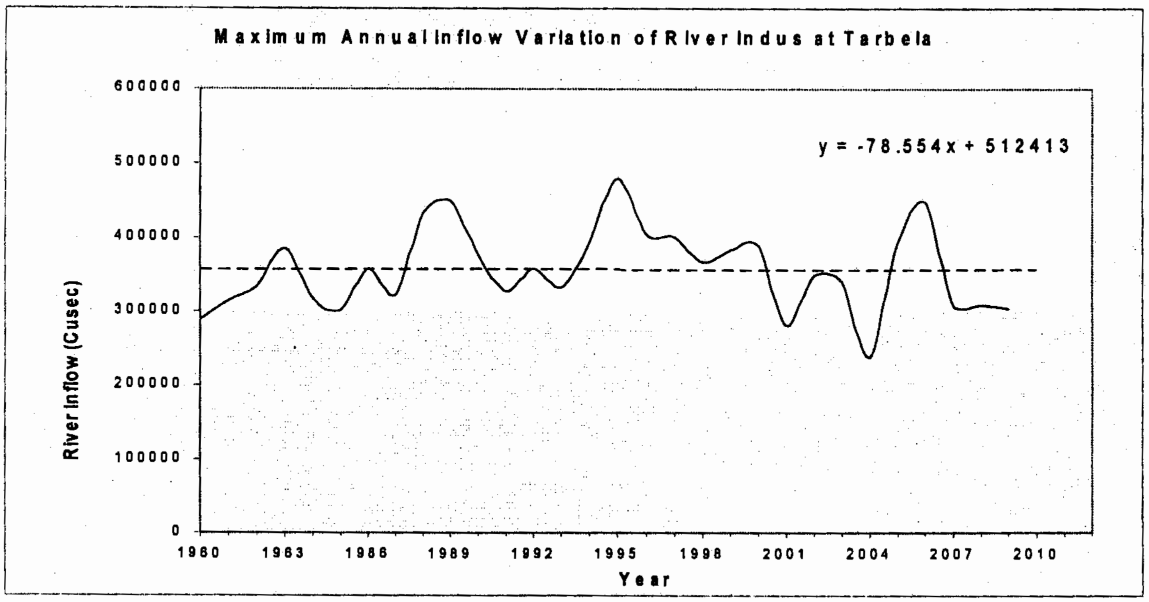

Figure 4.2 **Variations in Peak Annual Inflow of River Indus at Tarbela (Summer season)**

4.1.2 Trend in Minimum Annual Inflows (Winter Season)

Analysis of lowest annual inflow values of winter season experienced over last three decades by river Indus at Tarbela during last 30 years is given in Table 4.2. During the 1st decade (1980-1989), annual average minimum inflow was calculated as 13,260 cusecs which increased by 10.33% up to 14,630 during the decade from 1990-1999. However, reduced annual average inflow was observed during 3rd decade (2000-2009) by a decrease of 9.02%. Average winter annual inflow of River Indus observed at Tarbela during the last 30 years was worked out as 13,733 cusec. During the last 30 years period, river Indus received peak annual winter inflow of 16,700 cusec with an intensification of 25.94% above average value during the year 1981 whereas a lowest annual inflow of 8,300 cusec with a recession of -37.41% was observed in 1980. Climate induced floods (Sharma & Devesh, 2008) intensified to maximum rise (25.94%) in 1981 and intensity of floods dropped to lowest level of -37.41 % in 1980 as compared with an annual average value of 1st decade (1980-1989).

Table 4.2 Minimum Annual Inflows variation of River Indus at Tarbela (Winter Season)

(Discharge in Cusecs)

1980-1989		**1990-1999**		**2000-2009**	
Year	**Min inflow**	**Year**	**Min inflow**	**Year**	**Min inflow**
1980	8,300	1990	16,400	2000	13,200
1981	16,700	1991	16,200	2001	10,000
1982	14,300	1992	16,200	2002	8,900
1983	13,700	1993	15,800	2003	11,900
1984	14,000	1994	15,200	2004	15,000
1985	13,300	1995	13,300	2005	15,000
1986	13,400	1996	15,300	2006	16,500
1987	12,900	1997	10,400	2007	15,600
1988	13,000	1998	14,500	2008	11,500
1989	13,000	1999	13,000	2009	15,500
Total	132,600		146,300		133,100
Avg. (per year)	**13,260**	**14,630**		**13,310**	
Maximum	**16,700**	**16,400**		**16,500**	
Variation (%)	**25.94**	**12.10**		**23.97**	
Minimum	**8,300**	**10,400**		**8,900**	
Variation (%)	**-37.41**	**-28.91**		**-33.13**	

An increasing trend of winter annual river inflows was observed as indicated by the slope of dotted line in Figure 4.3 over the last 30 years. Like the summer inflows, river Indus shows a steady response to climate change as a insignificant rising trend of 1.01 % in annual winter inflows was observed at Tarbela reservoir.

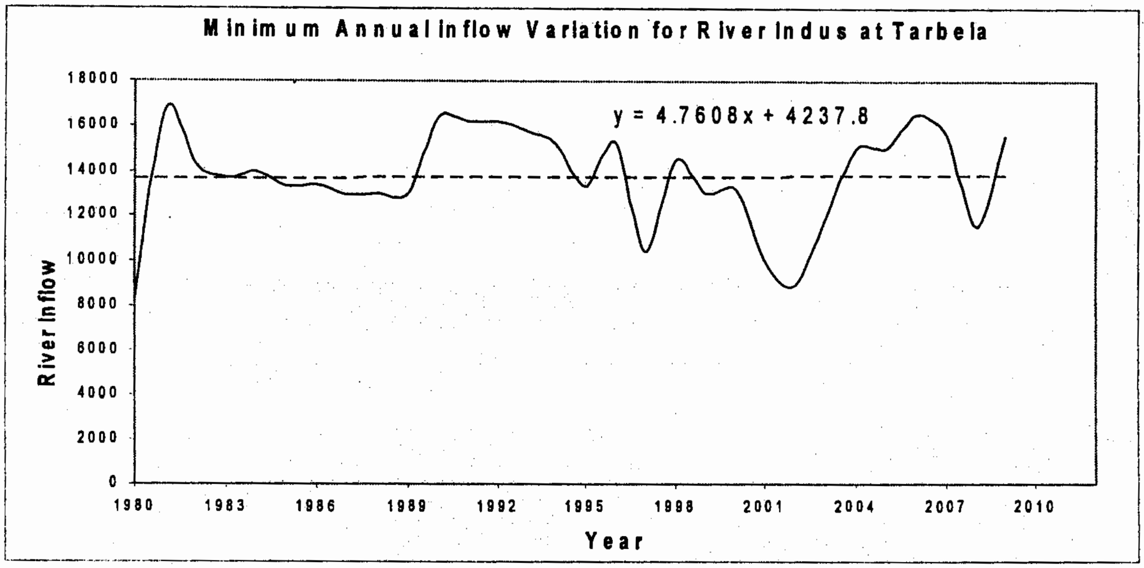

Figure 4.3 Minimum Annual Inflows Variation of River Indus at Tarbela (Winter Season)

4.2 Trends in Extreme Annual Inflows of River Indus at Kalabagh

River Kabul Joins River Indus upstream of Kalabagh rim station (Jinnah Barrage). For overall flow of river Kabul, rainfall contributes 20-30% in generating the total flow of River Kabul besides glacier melt-water for 30-50% (PANCID, 2008).

4.2.1 Trend in Peak Annual Inflows (Summer Season)

Peak annual inflows of river Indus observed at Kalabagh during last 30 years (from 1980 to 2009) have been analyzed as given in Table 4.3. A mixed trend of river inflow was observed during the last 30 years. During the 1st decade (1980-1989), average annual inflow was statistically calculated as 419,140 cusecs which significantly increased by 25.48% during the 2nd decade (from 1990-1999). After the warmest decade of 1990s, a considerable decrease of 27.22% was observed in annual average inflow of 3rd decade (2000-2009). Last 30 year's average inflow of River Indus observed at Kalabagh was statistically calculated as 442,633 cusec. During the last 30 years period, highest annual summer inflow of 842,100 cusec (year 1992) with an intensification of 60.11% above annual average of 2nd decade whereas a lowest annual summer inflow of 247,200 cusec (year 1987) with a recession of -41.02% was observed.

Table 4.3 Peak Annual Inflows variation of River Indus at Kalabagh (Summer Season)

(Discharge in Cusecs)

1980-1989		**1990-1999**		**2000-2009**	
Year	**Max inflow**	**Year**	**Max inflow**	**Year**	**Max inflow**
1980	373,800	1990	525,800	2000	268,700
1981	361,000	1991	448,800	2001	420,300
1982	459,200	1992	842,100	2002	387,100
1983	470,000	1993	363,100	2003	407,400
1984	471,400	1994	493,900	2004	252,600
1985	307,400	1995	551,500	2005	523,100
1986	482,600	1996	429,200	2006	497,600
1987	247,200	1997	660,700	2007	367,900
1988	488,500	1998	480,700	2008	346,600
1989	530,300	1999	463,700	2009	356,800
Total	4,191,400		5,259,500		3,828,100
Avg. (per year)	**419,140**	**525,950**		**382,810**	
Maximum	**530,300**	**842,100**		**523,100**	
Variation (%)	**26.52**	**60.11**		**36.65**	
Minimum	**247,200**	**363,100**		**252,600**	
Variation (%)	**-41.02**	**-30.96**		**-34.01**	

Graph given in Figure 4.4 indicates a reduction of 9% in annual peak inflows at Kalabagh during the period from 1980 to 2009. This decreased trend is clearly reflected by the slope of dotted line shown in Figure 4.4.

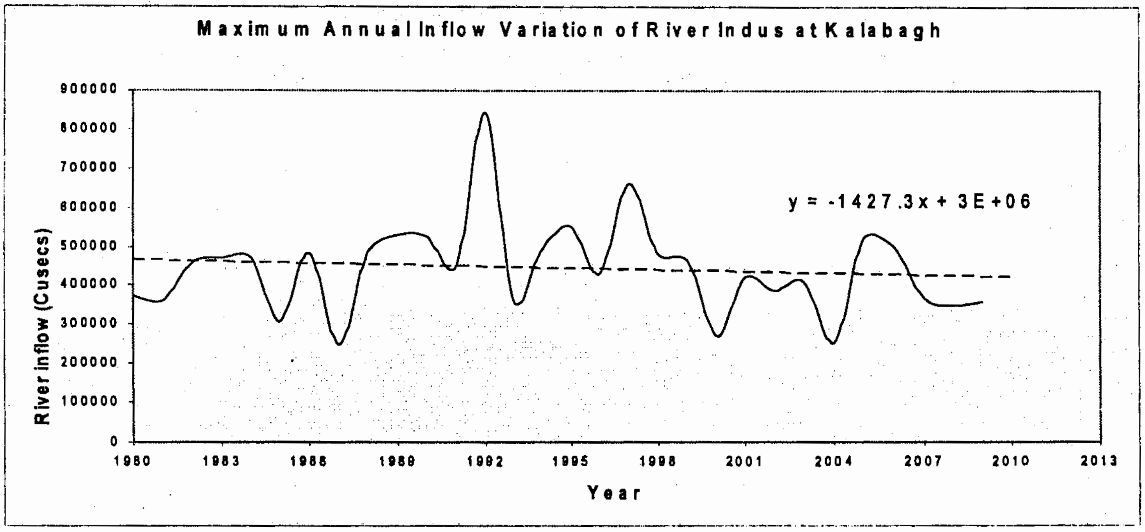

Figure 4.4 Peak Annual Inflows Variation of River Indus at Kalabagh (Summer Season)

As per the flood limits given in Table 3.1, it was found that, river Indus at Kalabagh experienced 02 exceptionally high floods, 03 very high floods, 15 medium flood years, nine (09) high flood years and a low flood year among the last 30 years as evident from Figure 4.5.

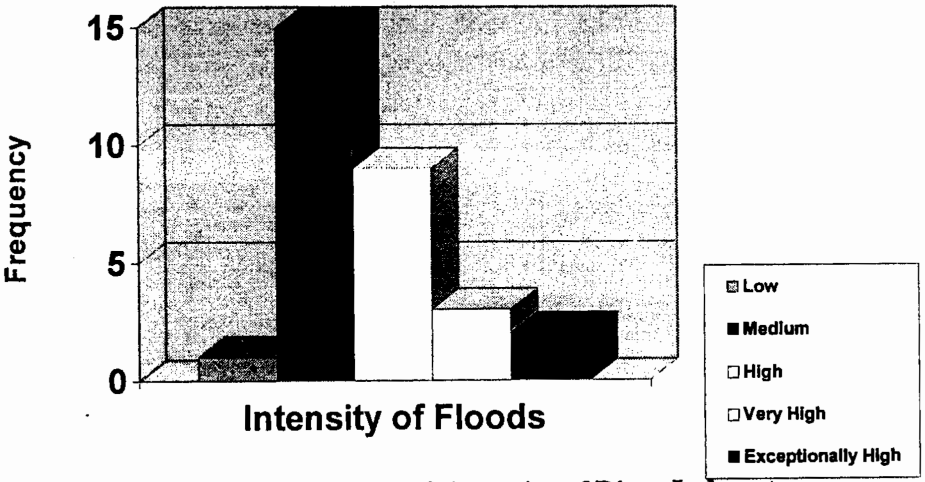

Figure 4.5 Flood Frequency & intensity of River Indus at Kalabagh

Pakistan faced catastrophic flood peak (year 1992) due to exceptionally heavy rains in July, August and September in the hilly areas of Rawalpindi, Murree, Attock, Jhelum and Chakwal (GOP, 1994).

4.2.2 Variation in Minimum Annual Inflows (Winter Inflows)

Table 4.4 gives analysis of minimum annual inflows of river Indus observed at Kalabagh during last 30 years (from 1980 to 2009).

Table 4.4 Variation in Minimum Annual Inflows of River Indus at Kalabagh (Winter Season)

(Discharge in Cusecs)

1980-1989		1990-1999		2000-2009	
Year	**Min inflow**	**Year**	**Min inflow**	**Year**	**Min inflow**
1980	15,800	1990	13,300	2000	19,700
1981	24,800	1991	25,100	2001	8,900
1982	23,200	1992	31,600	2002	9,900
1983	17,800	1993	26,200	2003	10,700
1984	17,100	1994	13,200	2004	17,700
1985	18,700	1995	26,200	2005	16,300
1986	19,400	1996	16,600	2006	15,100
1987	15,000	1997	17,900	2007	17,000
1988	16,600	1998	17,900	2008	17,400
1989	13,500	1999	18,500	2009	12,800
Total	181,900		206,500		145,500
Avg. (per year)	**18,190**	**20,650**		**14,550**	
Maximum	**24,800**	**31,600**		**19,700**	
Variation (%)	**36.34**	**53.03**		**35.40**	
Minimum	**13,500**	**13,200**		**8,900**	
Variation (%)	**-25.78**	**-36.08**		**-38.83**	

Annual winter inflows of river Indus observed at Kalabagh also show a mixed trend over last three decades. During the 1st decade (1980-1989), annual average minimum inflow was numerically calculated as 18,190 cusecs which increased by 13.52% up to 20,650 cusec during the 2nd decade from 1990-1999.

Conversely, annual average inflow reduced (29.54%) to 14,550 cusec during 3rd decade (2000-2009). Winter annual inflow of River Indus of last 30 years was statistically calculated as 17,797 cusec at Tarbela. A receding trend of winter annual river inflows was observed. Figure 4.6 represents minimum values of winter annual inflows plotted year-wise for a period of last 30 years at Kalabagh. Graph shows a significant reduction trend of 27.62% in annual winter inflows at upstream Kalabagh during the period from 1980 to 2009.

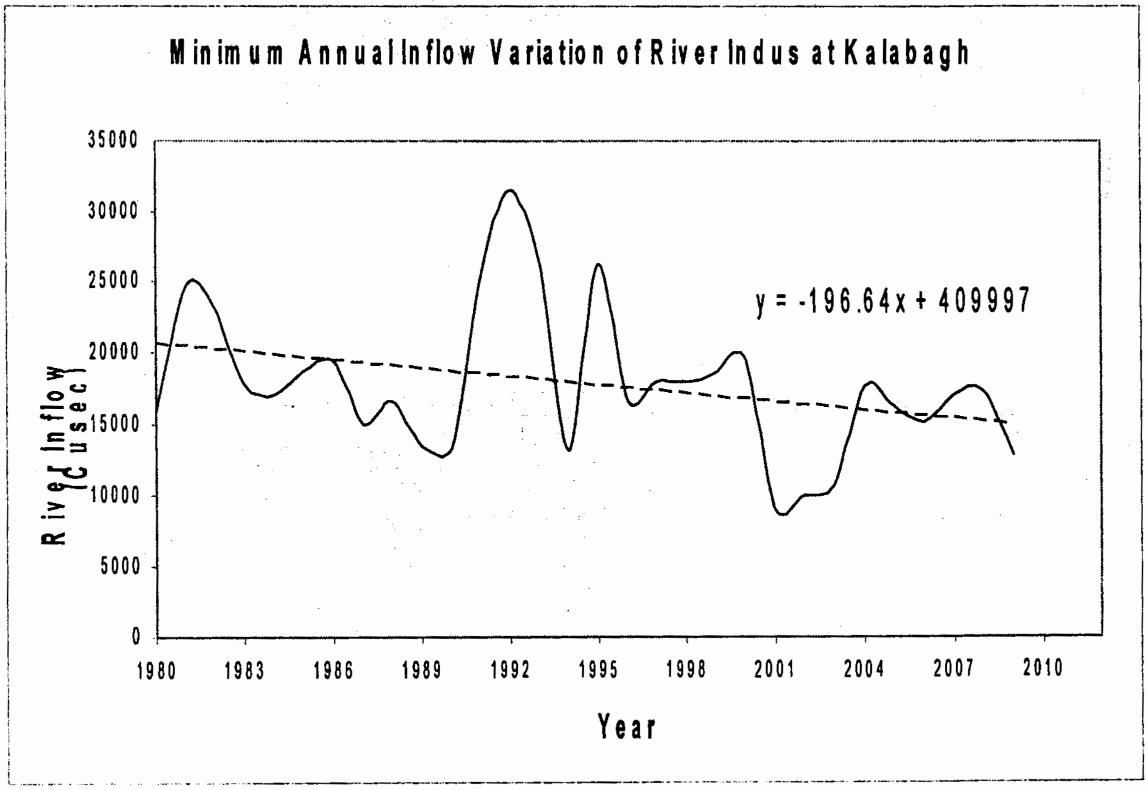

Figure 4.6 **Minimum Annual Inflows Variation of River Indus at Kalabagh (Winter season)**

4.3 Trends in Extreme Annual Inflows of River Indus at Kotri

Upstream of Kotri rim station, River Indus accumulates the occasional inflows of eastern rivers as well as the seasonal outflows of river Jhelum and Chenab. These inflows not only sustain the lives and livelihood of the inhabitants of fertile Indus delta but also the rich mangrove forests that happen to be the nurseries of fish species.

4.3.1 Variation in Peak Annual Inflows (Summer Season)

Peak annual inflows of river Indus observed at Kotri during last 30 years (from 1980 to 2009) were analyzed as given in Table 4.5.

Table 4.5 Peak Annual Inflows variation of River Indus at Kotri (Summer Season)

(Discharge in Cusecs)

1980-1989		1990-1999		2000-2009	
Year	**Max inflow**	**Year**	**Max inflow**	**Year**	**Max inflow**
1980	282,900	1990	308,000	2000	66,500
1981	171,500	1991	302,500	2001	93,300
1982	250,100	1992	688,600	2002	120,000
1983	493,900	1993	366,900	2003	150,900
1984	370,000	1994	825,200	2004	47,000
1985	186,000	1995	403,600	2005	310,500
1986	502,900	1996	413,400	2006	373,200
1987	156,100	1997	321,200	2007	157,300
1988	660,600	1998	295,900	2008	326,000
1989	309,900	1999	220,760	2009	120,500
Total	3,383,900		4,146,060		1,765,200
Avg. (per year)	**338,390**	**414,606**		**176,520**	
Maximum	**660,600**	**825,200**		**373,200**	
Variation (%)	**95.22**	**99.03**		**111.42**	
Minimum	**156,100**	**220,760**		**47,000**	
Variation (%)	**-53.87**	**-46.75**		**-73.37**	

A mixed trend of river inflow was observed during the last 30 years. During the 1st decade (1980-1989), average annual inflow was calculated as 338,390 cusec which significantly increased by 22.52% up to 414,606 cusec during the 2nd decade (from 1990-1999). After the warmest decade of 1990s, a considerable decrease of 57.42% was observed in 3rd decade (2000-2009) in annual average inflow. Last 30 year's average inflow of River Indus observed at Tarbela was statistically calculated as 309,839 cusec.

During the last 30 years period, climate change induced highest annual summer inflow of 825,200 cusec (1994) with an intensification of 99.03% above average annual inflow value (of 2nd decade) whereas a lowest annual summer inflow of 47,000 cusec with a recession of 73.37% was observed in 2004. Himalayan glaciers provides 70-80% of their melt water to river Indus and with warming climate these glaciers will no longer maintain the moderate flow of the river (Sharma & Devesh, 2008). Figure 4.7 also shows a drastic reduction of 48.19% in peak annual inflows at Kotri during the period from 1980 to 2009 as indicated by the slope of dotted line in the Figure 4.7.

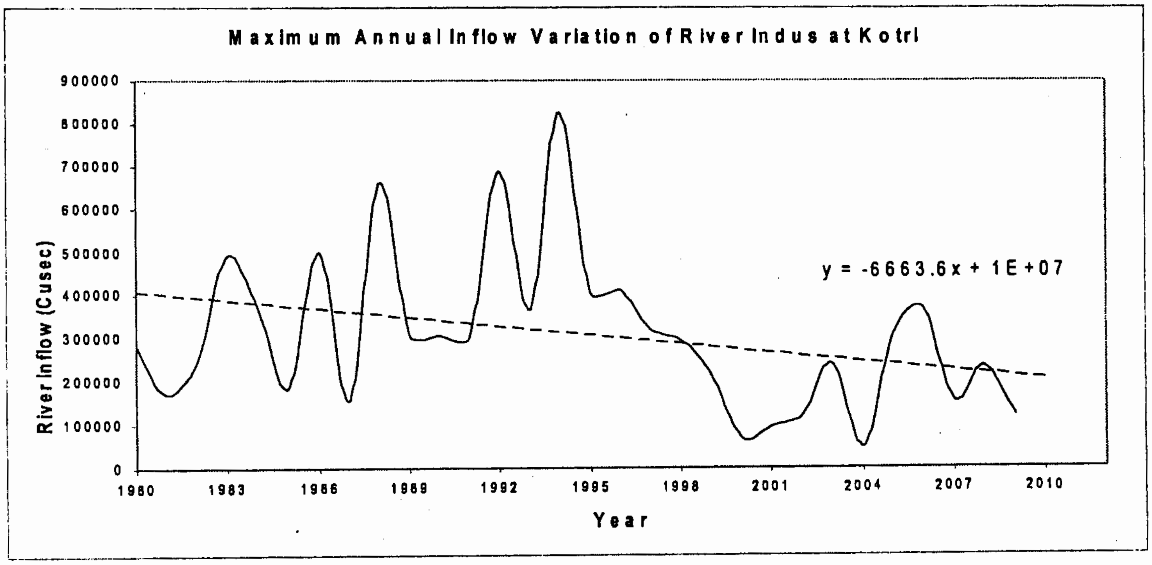

Figure 4.7 **Peak Annual Inflows variation of River Indus at Kotri (Summer season)**

Upto 20% of world population lives in the river basins that might inevitably be affected by increased flood events in the course of global warming (Klienin and Petschel, 2008). River Indus at Kotri experienced 01 exceptionally high flood, 02 very high floods, 02 high floods, 10 medium flood years and 6 low flood years among the last 30 years. The frequency and intensity of flood events caused by the extreme weather events are graphically expressed in Figure 4.8. Sharma & Devesh, 2008 has described that climate change will surely exacerbate the problems of irregular and low flow in Indus river basin. Figure also shows such a response of river flow to climate. It is quite obvious that climate change has caused large fluctuation in peak inflows during the period from 1980 to 1995 with a rising trend. Thereafter there is sudden drop in annual peak inflow values up to 2001.

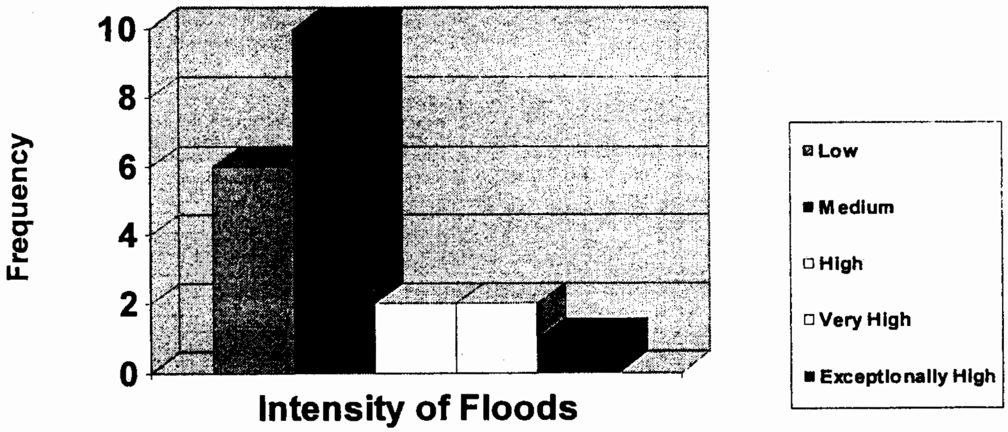

Figure 4.8 Flood Frequency & intensity of River Indus at Kotri

4.3.2 Variation in Minimum Annual Inflows (Winter Inflows)

Table 4.6 provides analysis of minimum annual inflows of river Indus observed at Kotri during last 30 years (1980 to 2009). Annual winter inflows of river Indus observed at Kotri show a varied trend over last three decades. During the 1st decade (1980-1989), annual average minimum inflow was numerically calculated as 1,540 cusecs, which increased to 3,570 cusec during the 3rd decade from 1990-1999.

Table 4.6 Minimum Annual Inflows variation of River Indus at Kotri (Winter season)

(Discharge in Cusecs)

1980-1989		**1990-1999**		**2000-2009**	
Year	**Min inflow**	**Year**	**Min inflow**	**Year**	**Min inflow**
1980	1,100	1990	2,100	2000	500
1981	2,100	1991	1,500	2001	200
1982	3,000	1992	2,100	2002	1,200
1983	1,600	1993	2,800	2003	1,100
1984	3,300	1994	6,700	2004	1,500
1985	500	1995	9,600	2005	1,600
1986	400	1996	4,300	2006	1,600
1987	200	1997	1,200	2007	1,400
1988	200	1998	2,100	2008	1,600
1989	3,000	1999	3,300	2009	1,400
Total	15,400		35,700		12,100
Avg. (per year)	**1,540**	**3,570**		**1,210**	
Maximum	**3,300**	**9,600**		**1,600**	
Variation (%)	**114.29**	**168.91**		**32.23**	
Minimum	**200**	**1,200**		**200**	
Variation (%)	**-87.01**	**-66.39**		**-83.47**	

Conversely, annual average inflow reduced to 1,210 cusec by a decrease of 66.11% during 3rd decade (from 2000-2009). Average winter annual inflow of River Indus observed at Kotri during the last 30 years was statistically calculated as 2,107 cusec. The severe drought conditions prevailed in 2000 due to very scant rainfall in Sindh and Baluchistan provinces of Pakistan. Baluchistan received 35-50% less rainfall than the normal over 20%

of its area and the remaining area also received 5-20% less rainfall. Thar district in Sindh was adversely affected by the extreme water shortage and forced thousands of the people to flee from their houses (Schubert et al., 2003).

Figure 4.9, represents winter annual river inflows variation of last 30 years observed at Kotri and plotted year-wise. Graph spots a reduction of 12.68% in annual river inflows at upstream Kalabagh during the last 3 decades (1980 to 2009) as indicated by the dotted line in the graph. Peak of winter inflow (year 1995) is the water yielded by the summer flood peaks of 1995 at Kotri synchronized with either above-normal outflows coming from eastern rivers (Ravi and Sutlej) or excessive winter rainfall in the catchment area of Kotri barrage.

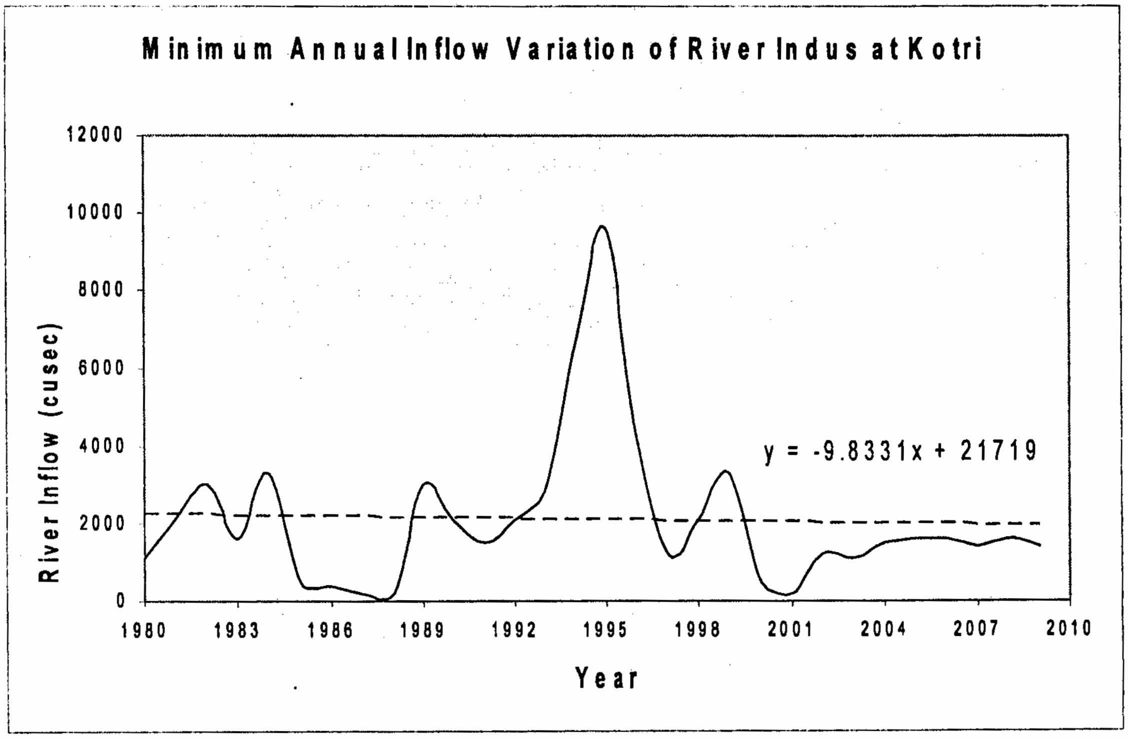

Figure 4.9 Minimum Annual Inflows variation of River Indus at Kotri (Winter season)

4.4 Trends in Extreme Annual Inflows of River Jhelum at Mangla

Mangla reservoir is a multipurpose project mainly constructed for diverting the water supplies of three western rivers to eastern rivers and also to generate power as well as conserve and control floodwater through significant reduction in flood peaks.

4.4.1 Variation in Peak Annual Inflows (Summer Season)

Peak annual inflows of river Jhelum observed at Mangla during last 30 years (from 1980 to 2009) were analyzed as given in Table 4.7.

Table 4.7 Peak Annual Inflows Variation of River Jhelum at Mangla (Summer season)

(Discharge in Cusecs)

1980-1989		1990-1999		2000-2009	
Year	**Max inflow**	**Year**	**Max inflow**	**Year**	**Max inflow**
1980	117200	1990	105000	2000	230700
1981	101400	1991	121400	2001	95400
1982	102900	1992	895200	2002	145500
1983	178800	1993	134300	2003	173000
1984	72600	1994	115200	2004	76300
1985	117000	1995	272300	2005	122000
1986	188900	1996	214700	2006	142000
1987	133100	1997	608000	2007	99800
1988	265000	1998	120600	2008	100100
1989	173800	1999	123900	2009	71900
Total	1450700		2710600		1256700
Avg. (per year)	**145070**	**271060**		**125670**	
Maximum	**265000**	**895200**		**230700**	
Variation (%)	**82.67**	**230.26**		**83.58**	
Minimum	**72600**	**105000**		**71900**	
Variation (%)	**-49.96**	**-61.26**		**-42.79**	

A mixed trend of river inflow was observed during the last 30 years. During the 1st decade (1980-1989), average annual inflow was calculated as 145,070 cusecs which significantly increased by 86.85% during the 2nd decade (from 1990-1999) due to 1992 and 1994 floods. Thereafter, a considerable decrease of 53.64% was observed in 3rd decade (2000-2009) in annual average inflow. Last 30 year's average inflow of River Jhelum at Mangla was statistically calculated as 180,600 cusec. In September 1992, there were exceptionally high floods in the Jhelum and Chenab due to heavy rains in the catchment areas of the Chenab and Jhelum Rivers (GOP, 1994). Climate change induced highest annual summer inflow of 895,200 cusec (year 1992) with an intensification of 230.26% above the annual average inflow of 2nd decade (1990-1999) whereas record lowest annual summer inflow of 71,900 cusec with a recession of 42.79% below the annual average inflow of 3rd decade (2000-2009) was observed recently in 2009. Figure 4.10 represents annual river inflow variation of last 30 years observed at Mangla.

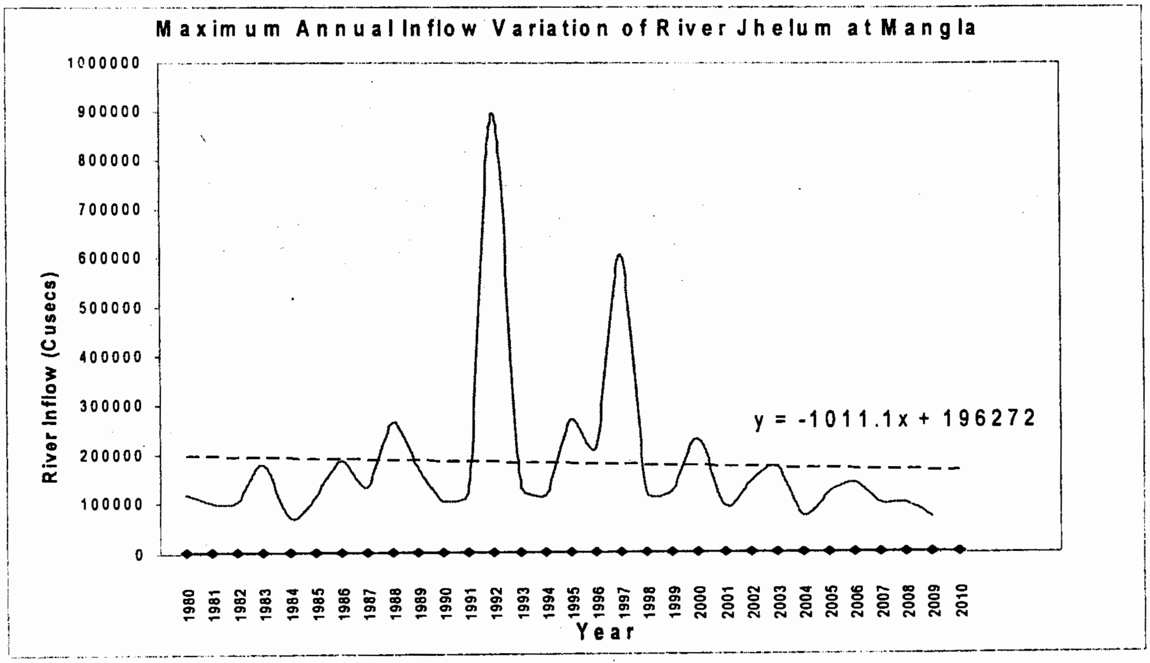

Figure 4.10 Peak Annual Inflows Variation of River Jhelum at Mangla (Summer season)

As indicated by the slope of dotted (trend) line in the figure 4.10, there is a reduction of 14.75% in annual river inflows at Mangla during the last 30 years (1980 to 2009). In view of the flood limits given in Table 3.1, it was found that among the last 30 years, River Jhelum at Mangla experienced 5 exceptionally high floods, 5 very high floods, 11 medium flood years, 7 high flood years and two low flood years. Figure 4.11 shows that climate change has resulted in more intense and frequent flood events of medium to exceptional high category at Mangla over the last three decades.

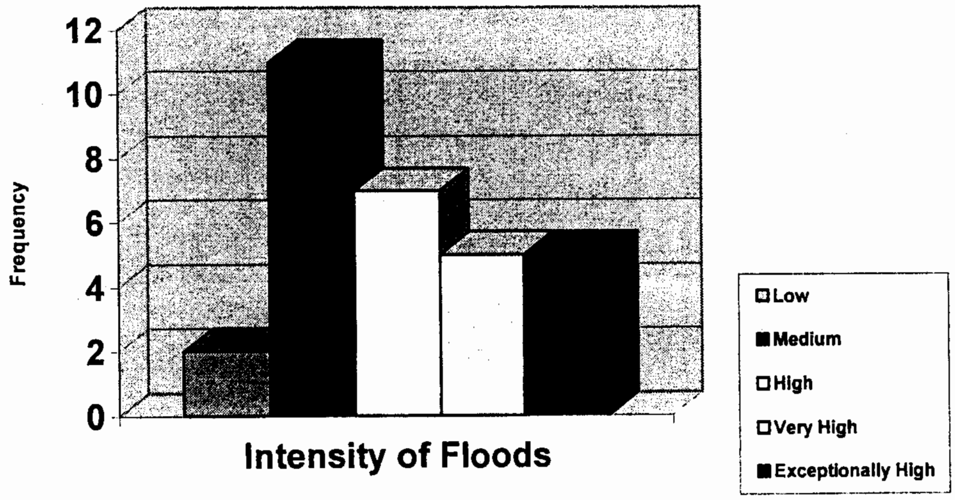

Figure 4.11 Flood Frequency & intensity of River Jhelum at Mangla

4.4.2 Variation in Minimum Annual Inflows (Winter Inflows)

Table 4.8 gives analysis of minimum annual inflows of river Jhelum observed at Mangla during last 30 years (from 1980 to 2009). Annual winter inflows of the river show growing trend over last three decades. During the 1st decade (1980-1989), annual average minimum inflow was calculated as 4090 cusecs, which increased by 15.16% up to 4710 cusec during the decade from 1990-1999, followed by the further increase of 10.4% during 3rd decade (from 2000-2009).

Table 4.8 Minimum Annual Inflows Variation of River Jhelum at Mangla (Winter season)

(Discharge in Cusecs)

1980-1989		**1990-1999**		**2000-2009**	
Year	**Min inflow**	**Year**	**Min inflow**	**Year**	**Min inflow**
1980	5,100	1990	3,800	2000	2,800
1981	2,800	1991	7,000	2001	3,900
1982	2,400	1992	4,300	2002	3,600
1983	3,800	1993	4,100	2003	3,300
1984	3,300	1994	5,200	2004	8,200
1985	3,400	1995	6,900	2005	7,000
1986	6,600	1996	5,000	2006	7,000
1987	5,300	1997	5,000	2007	5,400
1988	3,000	1998	3,300	2008	4,400
1989	5,200	1999	2,500	2009	6,400
Total	40,900		47,100		52,000
Avg. (per year)	**4,090**	**4,710**		**5,200**	
Maximum	**6,600**	**7,000**		**8,200**	
Variation (%)	**61.37**	**48.62**		**57.69**	
Minimum	**2,400**	**2,500**		**2,800**	
Variation (%)	**-41.32**	**-46.92**		**-46.15**	

Last 30 years' average minimum annual inflow of River Jhelum at Mangla was statistically calculated as 4,667 cusec. The slope of dotted line in Figure 4.12 shows an increasing trend of river inflows at Mangla experienced over the last 30 years. Climate change has increased winter annual river flow of Jhelum River during the last 30 years showing an unusual response in contrast to reduction trend of winter inflows of river Indus at Kalabagh and Kotri.

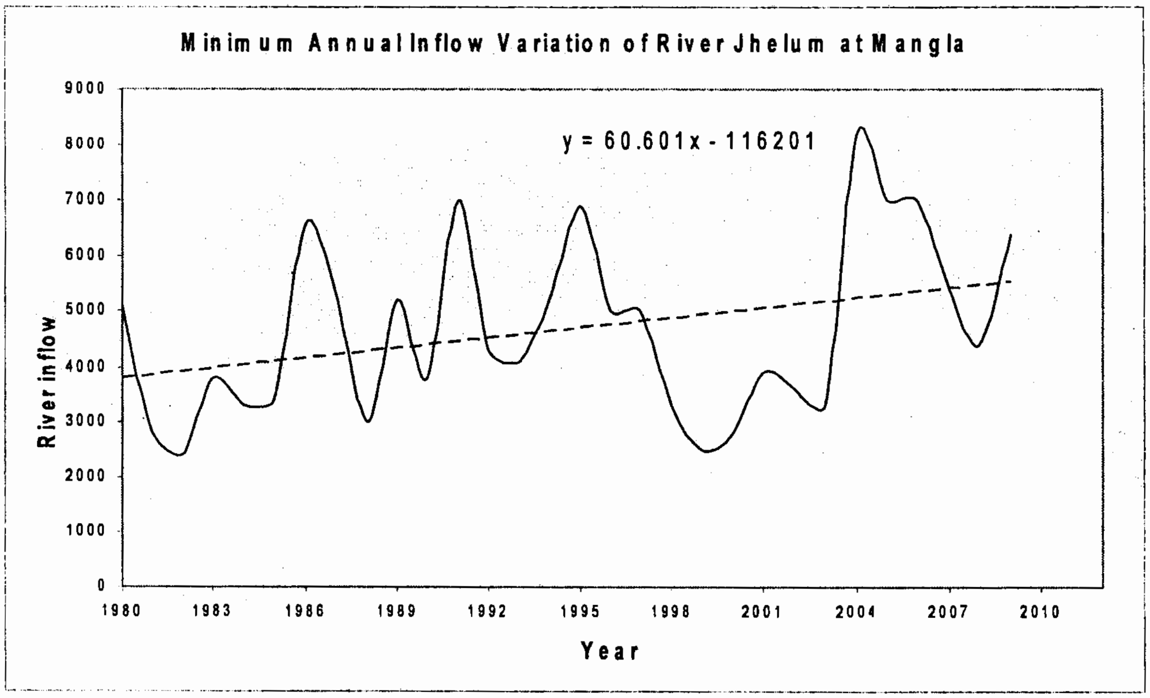

Figure 4.12 Minimum Annual Inflows Variation of River Jhelum at Mangla

4.5 Trends in Extreme Annual Inflows of River Chenab at Marala

The origin of River Chenab is located in Pir Punjal Range of Indian Held Kashmir where Tawi rivers feed river Chenab as it enters Pakistan. Excessive flows of river Chenab threaten Wazirabad and Gujrat districts. Average flow of river Chenab has decreased from 26 MAF during the period from 1922-61 to 12.38 MAF in 2001 (Jilani et al., 2007) due to acute climatic variations in the catchment area of river Chenab. Glaciers feeding in Chenab River have retreated at the rate of 6.81 to 29.78 m/year (Samjwal et al., 2006).

4.5.1 Variation in Peak Annual Inflows (Summer Season)

Peak annual inflows of river Chenab observed at Marala during last 30 years (from 1980 to 2009) were analyzed as given in Table 4.9. A mixed variation of annual peak inflows of river Chenab was observed during the last 30 years.

Table 4.9 Peak Annual Inflows Variation of River Chenab at Marala (Summer Season)

(Discharge in Cusecs)

1980-1989		1990-1999		2000-2009	
Year	**Max inflow**	**Year**	**Max inflow**	**Year**	**Max inflow**
1980	217,400	1990	159,200	2000	242,600
1981	335,900	1991	120,500	2001	164,500
1982	154,900	1992	576,300	2002	242,800
1983	193,500	1993	331,200	2003	148,800
1984	156,900	1994	267,400	2004	125,400
1985	242,400	1995	423,500	2005	345,500
1986	241,800	1996	744,500	2006	333,000
1987	114,100	1997	718,300	2007	146,500
1988	253,000	1998	148,200	2008	197,000
1989	363,800	1999	190,300	2009	128,900
Total	2,273,700		3,679,400		2,075,000
Avg. (per year)	**227,370**	**367,940**		**207,500**	
Maximum	**363,800**	**744,500**		**345,500**	
Variation (%)	**60.00**	**102.34**		**66.51**	
Minimum	**114,100**	**120,500**		**125,400**	
Variation (%)	**-49.82**	**-67.25**		**-39.57**	

During the 1st decade (1980-1989), average annual inflow was numerically calculated as 227,370 cusecs which significantly increased by 61.82% during the 2nd decade (from 1990-1999). After the warmest decade of 1990s, a considerable decrease of 43.61% in annual average inflow was observed in 3rd decade (2000-2009). Last 30 year's average inflow was statistically calculated as 267,603 cusec. During the last 30 years period, highest annual summer inflow of 744,500 cusec (year 1996) was observed with an intensification of 102.34% above annual average inflow value of 2nd decade whereas a lowest annual summer inflow of 114,100 cusec with a recession of 49.82% was observed in 1987. Heavy rains in the catchment areas of the Chenab and Jhelum Rivers cause the flooding in river Chenab (GOP, 1994). Keeping in view the flood limits given in Table 3.1, it was found that among the last 30 years, river Chenab at Marala experienced 4 exceptionally high floods, 12 very high floods, 7 high flood years and 7 medium flood years. The intensity and frequency of such floods is represented in the Figure 4.13.

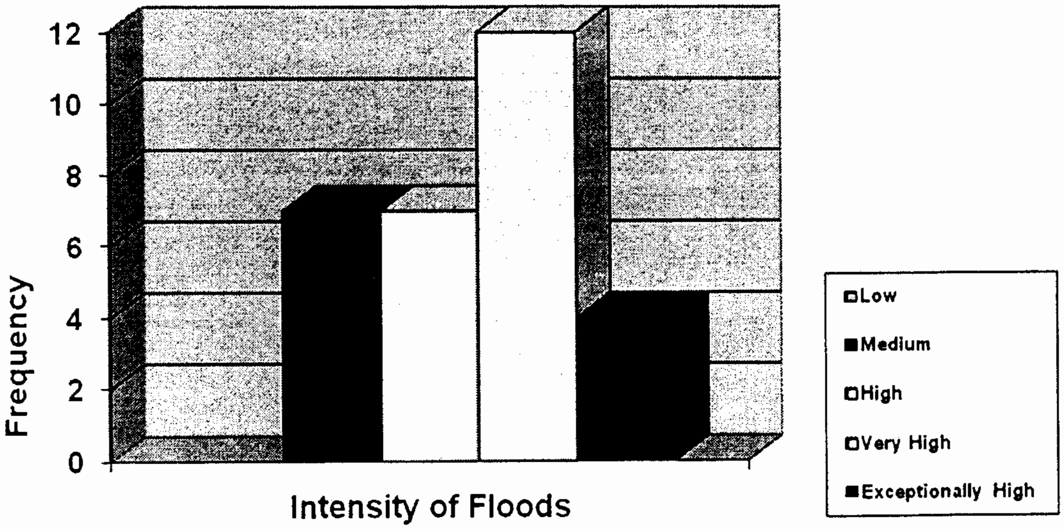

Figure 4.13 Flood Frequency & intensity of River Chenab at Marala

Average flow of river Chenab has decreased from 26 MAF during the period from 1922-1961 to 12.38 MAF in 2001 (Jilani et al., 2007) due to acute climatic variations in the catchment area of river Chenab. Glaciers feeding Chenab River have retreated at the rate of

6.81 to 29.78 m/year (Samjwal et al., 2006). Figure 4.14 depicts annual river inflow variation of last 30 years, observed at Marala for river Chenab. As indicated by the dotted line in the Figure 4.14 there is a minor reduction of 2.73% in annual river inflows at Marala during the period from 1980 to 2009.

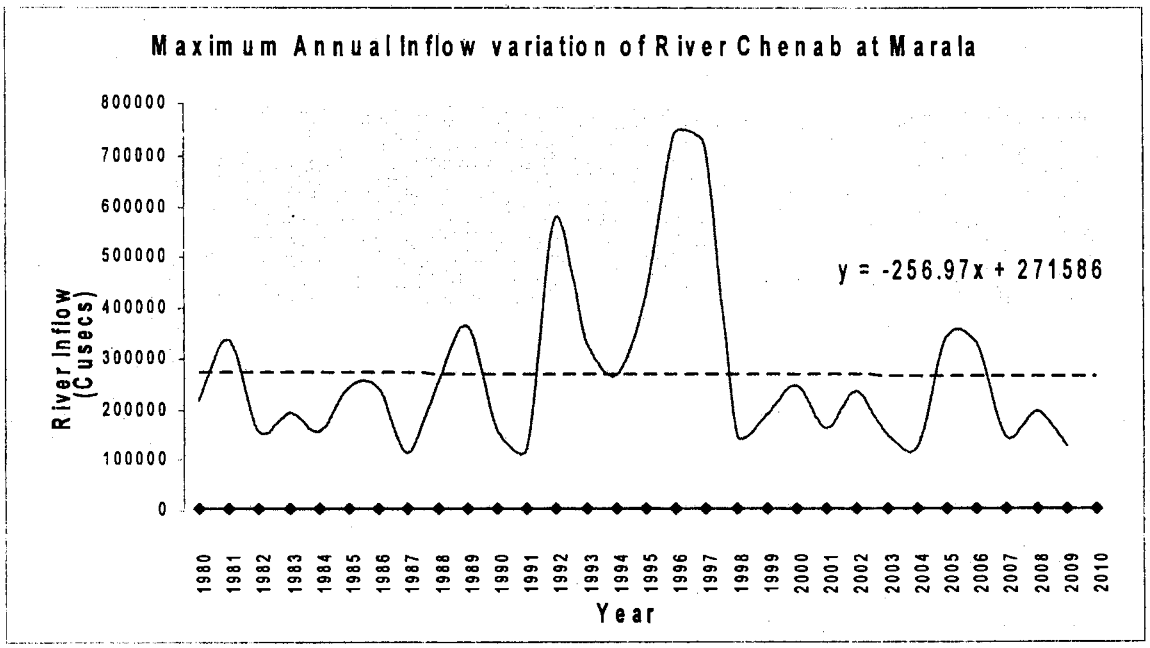

Figure 4.14 Peak Annual Inflows Variation of River Chenab at Marala (Summer Season)

4.5.2 Variation in Minimum Annual Inflows (Winter Inflows)

Table 4.10 gives analysis of minimum annual inflows of river Chenab observed at Marala during last 30 years (from 1980 to 2009). Annual winter inflows of river Chenab observed at Marala show a relatively increasing trend over last three decades. During the 1st decade (1980-1989), annual average minimum inflow was calculated as 3980 cusecs which increased by 33.17% up to 5300 cusec during the decade from 1990-1999. Annual average inflow slightly reduced to 5210 cusec during 3rd decade (from 2000-2009). Average winter annual inflow of River Indus observed at Tarbela during the last 30 years was statistically calculated as 4830 cusec.

Table 4.10 Minimum Annual Inflows Variation of River Chenab at Marala (Winter Season)

(Discharge in Cusecs)

Serial #	1980-1989		1990-1999		2000-2009	
	Year	Min inflow	Year	Min inflow	Year	Min inflow
1	1980	3000	1990	6600	2000	5500
2	1981	5100	1991	5100	2001	4000
3	1982	5000	1992	5100	2002	3200
4	1983	0	1993	5100	2003	5300
5	1984	0	1994	5000	2004	6400
6	1985	5600	1995	8500	2005	5700
7	1986	6000	1996	1200	2006	4400
8	1987	5500	1997	7000	2007	5900
9	1988	5900	1998	6400	2008	5100
10	1989	3700	1999	3000	2009	6600
Total		39800		53000		52100
Avg. (per year)	**3980**		**5300**		**5210**	
Maximum	**6000**		**8500**		**6600**	
Variation (%)	**50.75**		**60.38**		**26.68**	
Minimum	**0**		**1200**		**3200**	
Variation (%)	**-100.00**		**-77.36**		**-38.58**	

In general, a growing trend of winter annual river inflows was observed as shown in the Figure 4.15. The slope of dotted line indicates a significant increase of 47.98% in minimum annual inflows of river Chenab at Marala during the last 30 years. Like the winter annual inflows of river Jhelum, winter annual river flow of river Chenab have also increased during the last 30 years although there was no inflow received at Marala during the 1983 & 1984. Warmest decade of 1990s significantly increased the annual inflow average by bringing glacier melt water into catchment area of Chenab River.

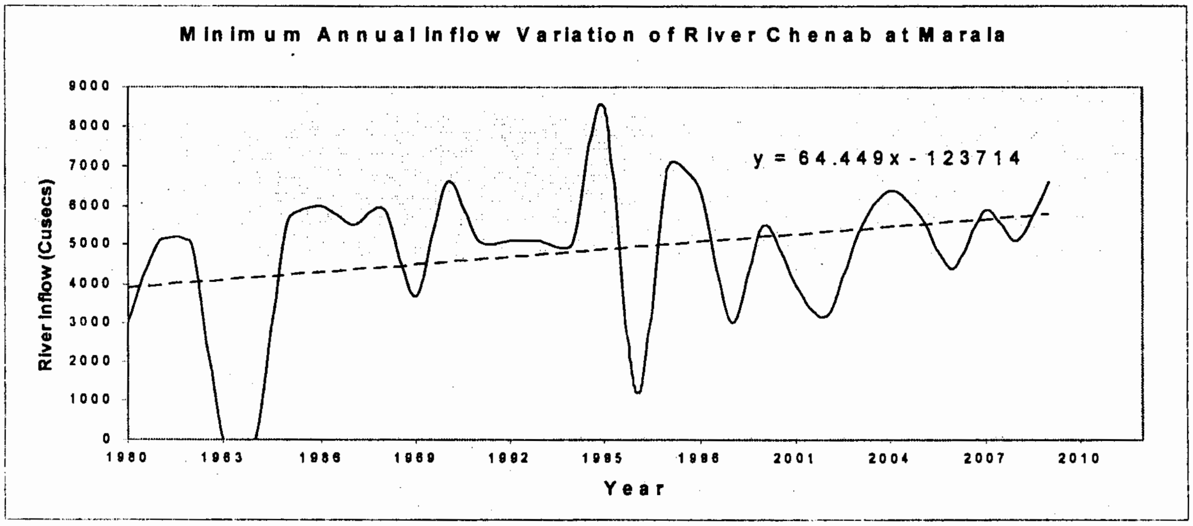

Figure 4.15 Minimum Annual Inflows Variation of River Chenab at Marala (Winter Season)

4.6 Trends in Annual Water Availability

Indus River System is the main source of water supply in Pakistan for fulfilling the domestic and industrial water requirements of major cities besides irrigation. Melting fast of the glaciers will lead to a creeping emergency due to fact that freshwater availability in Pakistan has fallen from 5,200 cubic meters per capita in 1947 to around 1,000 cubic meters per capita at present. Annual water availability is 142 MAF whereas the annual canal withdrawals are 104 MAF. Water availability at farm gate is 106 MAF comprising 62 MAF of surface water and 44 MAF of groundwater (GOP, 2008). The Indus River system supports the agricultural water supply for a population of 130 million people besides contributing about 45% of the electrical energy for Pakistan (Jilani et al., 2007). Historical variation in annual flow-rates of major rivers in Pakistan is shown in the Table 4.11.

Table 4.11 **Annual flow-rates of major rivers in Pakistan**

River	Average Annual Flow (1922-61) MAF	Average Annual Flow (1985-95) MAF	Average Annual Flow (2001-02) MAF
Indus	93	62.7	48.0
Jhelum	23	26.6	11.85
Chenab	26	27.5	12.38
Ravi	7	5.0	1.47
Sutlej	14	3.6	0.02
Kabul	26	23.4	18.9

Source: (Jilani et al., 2007)

There are two seasons in a year for major crops grown in Pakistan. Kharif season, which extends from May to October and Rabi season extending from November to April. Annual water availability data observed during Rabi and Kharif season during the last 30 years (from 1980 to 2009) was analyzed as given in Table 4.12. This analysis shows a mixed trend of water availability over decadal timeframe. During the 1st decade (1980-1989), annual water availability was numerically calculated as 138.31 MAF, which significantly increased (by 11.66%) up to 154.432 MAF during the 2nd decade (from 1990-1999). While in disparity considerable decrease of 20.31% in annual water availability was observed in 3rd decade (2000-2009). Average annual water availability over last 30 years was statistically calculated as 138.60 MAF. Yearly data of past 30 years was also plotted graphically as shown in Figure 4.16 in order to find the climate change induced variations in the annual water availability. It was observed that annual water availability as decreased over the last 30 years by 11.12% and if the trend continues at the same rate in future, it is expected to further decrease by 25% by the end of 21st century.

Table 4.12 Variation in Annual Water Availability (in MAF) during Kharif & Rabi Season

1980-1989				1990-1999				2000-2009			
Year	**Kharif**	**Rabi**	**Annual**	**Year**	**Kharif**	**Rabi**	**Annual**	**Year**	**Kharif**	**Rabi**	**Annual**
1980	108.84	23.14	131.98	1990	102.01	29.31	131.32	2000	107.45	22.12	129.57
1981	109.81	26.58	136.39	1991	130.98	35.14	166.12	2001	86.33	16.56	102.89
1982	117.69	22.93	140.62	1992	141.53	30.57	172.1	2002	79.85	17.28	97.13
1983	97.1	25.27	122.37	1993	138.62	31.06	169.68	2003	94.94	23.06	118
1984	128.28	21.67	149.95	1994	104.68	22.8	127.48	2004	115.61	22.14	137.75
1985	115.99	18.93	134.92	1995	138.02	27.79	165.81	2005	82.14	30.56	112.7
1986	91.66	26.04	117.7	1996	129.7	28.93	158.63	2006	121.22	23.95	145.17
1987	116.38	30.27	146.65	1997	137.49	23.76	161.25	2007	111.83	30.84	142.67
1988	111.79	29.28	141.07	1998	110.1	32.22	142.32	2008	105.87	19.99	125.86
1989	136.56	24.84	161.4	1999	124.93	24.68	149.61	2009	95.91	23.01	118.92
Total	1134.1	249	1383.05		1258.06	286.3	1544.32		1001.2	229.51	1230.66
Avg. per year	113.41	24.9	**138.31**		125.806	28.63	**154.432**		100.12	22.951	**123.07**
Maximum	136.56	30.27	**161.4**		141.53	35.14	**172.1**		121.22	30.84	**145.17**
Minimum	91.66	18.93	**117.7**		102.01	22.8	**127.48**		79.85	16.56	**97.13**

Source: IRSA

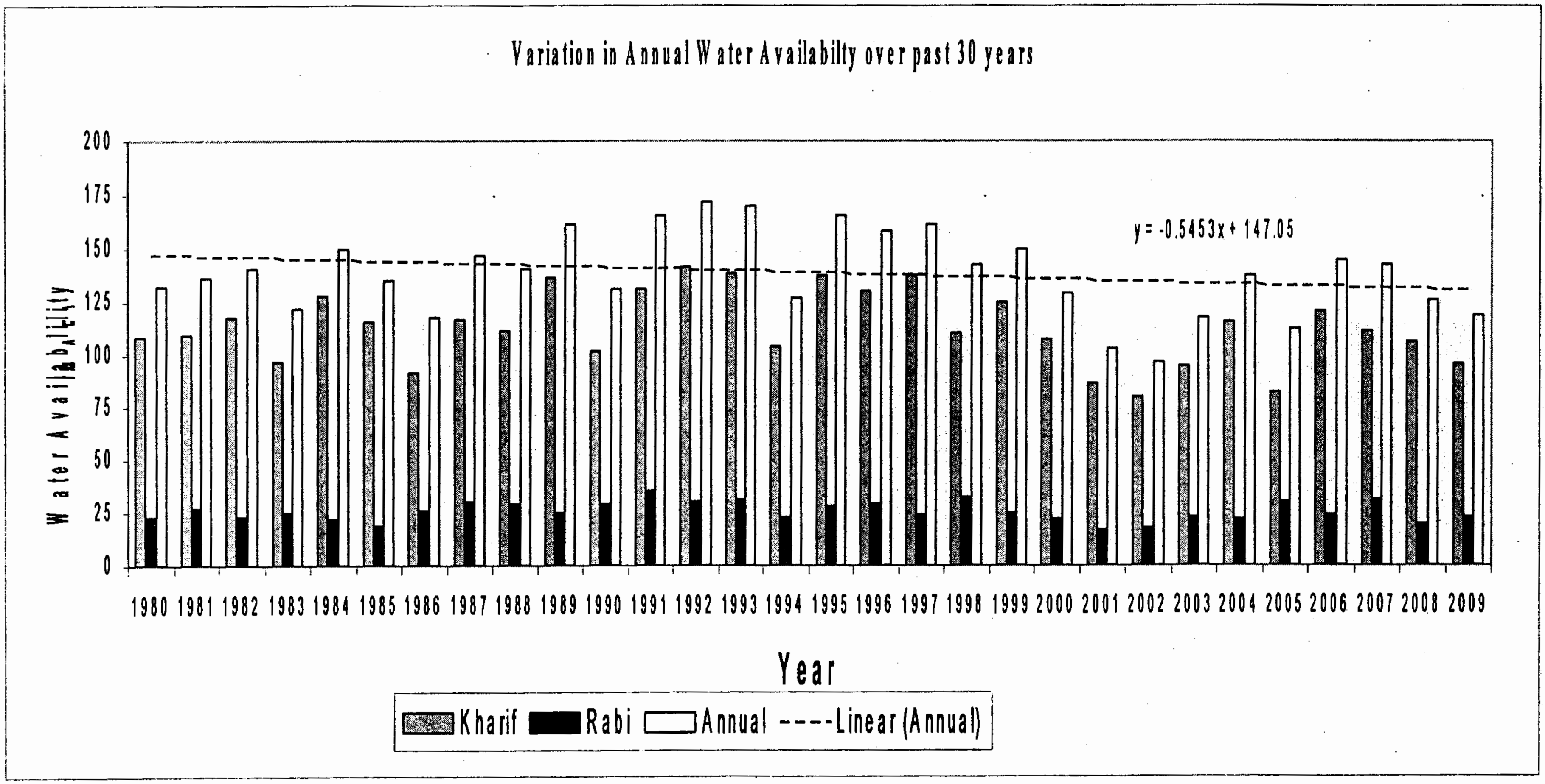

Figure 4.16 Variations in Annual Water Availability during Kharif & Rabi Season

Chapter 5

CONCLUSIONS & RECOMMENDATIONS

Climate change poses major challenges to water management system in Pakistan. Country's major rivers mainly depend upon the melt water of mountain glaciers. These glaciated mountains are water banks for fulfilling the water demands of growing population. Innovative water management strategies, infrastructure and political efforts are required to efficiently conserve scarce water resources, prevent their further decline, and go far environmentally sustainable improvements in the water sector. It has been predicted that during 21st century climate change will put great stress on fragile ecosystems and lead to water and food shortages (IPCC, 2007).

The present study derives various implications of climate change on surface water resources in Pakistan. The Indus River System, being the most important source of water, sustains agricultural water supply for 130 million people and generates hydropower approximately equivalent to 45% of the electrical energy in Pakistan (Jilani et al., 2007). Associated with the decrease in annual inflow peaks of summer and winter, annual water availability in Pakistan has also shown a decreasing trend. Based on the extensive data analyses, provided in the preceding chapter following conclusions were made:

- Peak annual (summer) inflows of rivers Indus, Jhelum & Chenab have considerably reduced over the last three decades.
- Maximum reduction of 48.19% was found in annual inflow peaks of summer season at Kotri for river Indus observed over the last three decades.
- Maximum decrease of 27.62% was found in minimum annual (winter) inflow in river Indus at Kalabagh whereas annual minimum (winter) inflows of rivers Jhelum and Chenab have almost doubled over last three decades.
- There is a very inconsequential reduction (0.64%) in peak annual inflows of river Indus at Tarbela.
- At Kalabagh River Indus has experienced significant reductions both in summer & winter annual peaks over the last 30 years.
- Peaks (summer) annual flows of Indus River at Kotri have become halved during the last three decades. Like summer peaks, annual winter peaks also show a receding trend at Kotri.
- It was found that annual average water availability has decreased over the last 30 years by 11.12%.

Recommendations:

Climate change impact is very uncertain. It may produce excessive floods at one location while severe droughts at some other place in different timeframe. What actually required is to be prepared for adapting to these impacts in such a way that detrimental effects of climate change are minimized. Rather we must develop our skills to determine the ways to achieve potential benefits from rigorous response of climate change also. Based on the findings of the study given in the previous chapter, following recommendations have since been derived.

- Annual river flows in Pakistan are decreasing due to increased variability of climate. There is a dire need to store more water for meeting the water needs of growing population. Hence, construction of new climate resilient storages infrastructure is the urgent need of the time.
- The excessive rain/flood water available during the summer season may be stored for subsequent use in dry period, particularly in areas susceptible to famine/ water scarce conditions.
- Climate resilient crops can be grown in water dearth areas.
- Deforestation activities must be banned in all vulnerable areas, particularly in the catchment areas of large reservoirs. Excessive deforestation activities in the watersheds of our major reservoirs have resulted in drastic reduction in storage capacity due to increased sedimentation. Land use patterns in all such watersheds also need special attention.
- In addition to construction of large storage reservoirs, flood detention ponds and surge reservoirs may be constructed to safely absorb the high floods reducing the risk of extensive damages and losses. These water storage cushions will ensure safety of existing dams and barrages during exceptionally high floods. Also, potentially dangerous water, trapped in flood detention ponds may be diverted again into river for beneficial use at later stage during the lean flow periods.
- Drastic reduction in inflows of river Indus at Kotri and Kalabagh is threatening the lives and livelihood of the people of fertile Indus plain (downstream Kalabagh) and Indus delta (downstream Kotri). In order to meet the anticipated deficiencies of water, worldwide adopted method to store excessive rainwater like roof top rainwater harvesting may serve better in urban areas during

monsoon season when there are frequent rainfall. In less populated areas of NWFP and Baluchistan, rainwater harvesting techniques should be adopted to conserve maximum water falling on earth for its potential use to meet domestic and agricultural purposes. Modern scientific water conservation practices and high efficiency irrigation systems can significantly increase water use efficiency.

- Special attention is required to main a suitable outflow from Kotri barrage to check sea water intrusion which is threatening the agriculture fields of Indus delta and rich mangrove forests sustaining revenue generating fishing industry.
- A glacier melt monitoring and glacial disaster forecast system need to be established in Northern Areas of Pakistan for effective management of GLOFs and their associated flash floods. This will help reduce losses to life and property in the downhill areas.
- Future research may be focussed in analyzing the monthly extreme inflows of major rivers to find out the anticipated impacts of climate change on living and non-living environment.

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