EFFECT OF CLIMATE CHANGE ON MOUNTAIN WATER RESOURCES: THE CASE STUDY FROM EUROPEAN ALPS & HIMALAYA REGION

Dissertation

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DEDICATION

This humble effort is dedicated to my two little daughters, Mashaal Nasir and Iqra Nasir, who taught me the biggest lesson of life and that is to always stay consistent in my goal and never stop trying because failure starts once you stop trying. They were key motivation behind my work because they are the most wonderful gifts I have ever been blessed with in my entire life.
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ABSTRACT

Mountain regions are the most important and reliable supply sources of global fresh water resources, but their future role in fresh water availability is likely to be changed during projected 21st century climate change. In this context, future water availability scenario is analysed through a modeling approach developed to project future changes in two distinct hydrological characteristics flow regimes and subsequent water availability in two sampling catchments located in middle & high altitude mountain ranges of Austrian Alps & Karakorum Range Pakistan respectively. A spatially distributed hydrological modeling system PREVAH was developed & applied to simulate the catchment hydrological processes. The climate change scenarios were incorporated within model simulations by means of the so-called delta approach. The modeling results of the first case study area Kitzbühel Ache catchment located in Austrian Alps predict a shift from a rainfall-snowmelt dominated flow regime to a rainfall dominated flow regime in future. A decrease in snow accumulation and a shortening in snow cover duration is also observed. Due to the projected changes in seasonal precipitation amount, change in form (snow to rain), a change in seasonality of stream flow and available water resource occurs. There will be an increase in winter flow, and a decrease in spring, summer and autumn flow. The typical low flow period during winter shifts to a low flow period during late summer and autumn. The observed changes are significant on monthly and seasonal scales than on an annual basis. However, the magnitude of the effect at all scales depends strongly on the choice of the scenario. The changes in mean available water is assessed through the difference b/w total flow and environmental flow (Q95) regime, model simulations project higher water availability trends in winter and decreasing trends in summer. However, at mean annual scale, most of the scenarios show slightly higher available water. These results indicate that the downstream regions depending on upstream mountain water resources, particularly in summer, may face decline in water availability at the end of 21st century. These values and observations provide a future vision within middle mountainous catchments in the European Alps.

The modeling results of the other case study area Hunza catchment are based on the sensitivity analysis of the hydrological parameters towards the hypothetical climate change scenarios. The modeling results show that the increase in temperature produces large increase in late spring and summer flow volume and subsequently in total flow volume. Contrary to findings in Kitzbühel Ache catchment, the temperature regime of this particular high altitude basin (over 7500 m a.s.l) from autumn to early spring months is below freezing point, therefore the increase of 1 to 4°C have no any significant influence over the form of precipitation or melting process, and hence no significant change observed in seasonal flow volumes, except in late spring & summer. In nutshell, flow volume increased (more than 75%) is available only in melt season summer as like in present conditions. Therefore, due to seasonality of river flow (where more than 2/3 water will be available in just short span of few weeks in summer) and decreasing capacity of existing dams, this study highly favours the construction of new reservoirs. The additional storage capacity would not only result in reducing the magnitude of potential threats of increasing flood events, but would also enhance the controlling and regulating capacity of existing dams.

The water distribution in Indus Basin Irrigation System (IBIS) is fully controlled and regulated through large reservoirs. Thus, predicted flow trends would contribute in successful forward-looking management of existing and proposed reservoirs on Indus River and accordingly let a better and long-lasting control of water supply for irrigation and power supplies. Furthermore, study also provides a solution under current & future sustainable water resource development & management within the Indus Basin. The recommended options can be adopted for other large basins in semi-arid to arid regions.
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1 INTRODUCTION

1.1 BACKGROUND

Nowadays, the sign of climate change and its impacts on freshwater resources are widely being reported and discussed among scientific communities. There is now a general consensus that the negative impacts of climate change on freshwater systems outweigh the benefits. All of the regions assessed in IPCC Fifth Assessment Report plainly show the overall negative impacts of climate change on freshwater resources. Particularly the freshwater resources in semi-arid & arid regions are severely exposed to the impacts of climate change (IPCC, 2014). The IPCC with very high confidence reported that many of river basins in these regions would suffer a massive decrease in water resources due to climate change. Mountain regions are the most important and reliable sources of fresh water for both, themselves and their surrounding lowlands. The head water source of many world river basins originates from mountain regions. Due to increased precipitation and decreased evapotranspiration with altitude, the mountain regions are characterized by high discharge values (Weingartner et al., 2007). Their contribution in total water supply to global population is far greater than its areas (Viviroli and Weingartner, 2004). More than 50% of the world’s total fresh water supply for irrigation, industrial use, and home consumption comes from mountain regions. However, their future role in global water resources would likely be altered from anticipated climate change. Mountain areas due to their fragile nature (sharp variation in topography, vegetation, soils, and spatial & temporal differentiation in snow cover at very short distances) are very vulnerable to small changes in climatic parameters, e.g. temperature, precipitation (Beniston, 2003; Beniston M., 2012; Islam et al, 2017). Therefore, an understanding of climate change impacts on hydrological cycle of mountain watersheds and subsequent water availability is critical for sustainable future water resource planning and management within mountain watersheds and their lowland regions.

The IPCC in their latest findings projected that the future change in global average temperature are expected to be in the range of 1.5 to 4.5 °C by the end of 2100, depending on the prevailing emissions scenario (Gobiet et al, 2014; Heinrich et al, 2013; IPCC, 2014). Most importantly, the amplitude of change in observed and projected temperature is large in mountain regions- approximately 3 times higher than the global average (Nogues-Bravo et al. 2007; Beniston M., 2012). The rate of warming in the lower troposphere increases with altitude, i.e. temperatures will increase more in high mountains than at low altitudes. This makes mountains one of the most vulnerable regions on the earth (Islam et al, 2017). The sensitivity of most important mountain hydrologic processes, like melting glaciers and reduced snow cover durations, has been manifested in many recent studies, e.g. (Barnett et al, 2005; Haeberli et al., 2007; Huss et al., 2007; Vanham and Rauch, 2009a; Diolaiuti et al, 2011; Beniston M., 2012; Ceppi et al, 2012; Immerzeel et al, 2012; Kotlarski et al, 2012; Laghari et al, 2012a; Scherrer et al, 2012; Steger et al. 2013; Springer et al, 2013; Strauss et al, 2013; Gobiet et al, 2014; Wiltshire, et al, 2014; Marty et al, 2017). The extent of vulnerability will likely be worsened over coming decades (Meehl et al., 2000; Jones and Reid, 2001; Palmer and Räisänen, 2002; IPCC, 2014; Kohler et al, 2014). Due to projected climate change, the IPCC forecasts warmer and drier conditions in coming decades. A warmer climate may mean high evaporative loss, increased liquid to solid precipitation ratio, lower accumulations of snow in the winter,
reduced snow cover days, early and faster snow melting in spring, and massive glacier retreats in summer (Cayan et al. 2001; Paul et al., 2004; Payne et al. 2004; Lapp et al. 2005; Bogataj, 2007; Laghari et al., 2012a & c; Steger et al. 2013; Kohler et al, 2014; Marty et al. 2017). This would all mean a drastic alteration in hydrological cycle of mountain regions.

The change in hydrological cycle is likely to alter the seasonality of Mountain Rivers. Recently many modelling investigations have observed that any change in climatic parameters, i.e. temperature and precipitation patterns, will change significantly the snow storage and subsequently alter both timing and volume of the discharge regime of Mountain Rivers (Etchevers et al., 2002; Schaefl, 2005; Stewart et al., 2005; Zierl and Bugmann, 2005a; Maurer et al., 2007; Bates et al., 2008a; Vanham et al., 2009c; Elsner et al, 2010; Kerkhoven et al, 2011; Beniston M., 2012; Déry et al, 2012; Laghari et al, 2012a; Springer et al, 2013; Strauss et al, 2013; Gobiet et al, 2014; Kohler et al, 2014; Kang et al, 2016; Islam et al, 2017) and accordingly the water availability in downstream regions (Viviroli et al., 2011; Beniston and Stoffel, 2013). This may have severe implications on freshwater systems and their management (Kundzewitz et al., 2007), particularly in areas with heavy summer water demands such as irrigation intensive lands (Barnett et al. 2005; Sauchyn et al. 2006; Parry et al., 2007), and the river basins where the relation of water supply to water demand is already critical (Coudrain et al., 2005; Hagg and Braun, 2005; Solomon et al., 2007; Viviroli et al., 2007; Vuille et al., 2008; Laghari et al, 2012b; IPCC, 2014; Kohler et al, 2014). One of the regions likely to be most affected is the Indian subcontinent. The vulnerability of this region is most critical because the major impact of climate change would be on hydrology, water resources, and agricultural economy. In this subcontinent, water encompasses the cultural, social, economic and political fabric in the lives of some 1.5 billion people. The region is gifted with great rivers that are the lifelines of the regional agro-based economies. Irrigation is the backbone of the agricultural system. Many of rivers, e.g. Ganges, Brahmaputra, and Indus, flow from the Hindu Kush-Himalayan “water towers.”

The Indus Basin, home of some 193 million people, is highly dependent on water supply from Hindu Kush-Himalaya region (Immerzeel et al., 2010; Kaser et al., 2010). Snow/glaciers are a major landscape feature of the region, which are sensitive to increases in temperature. They contribute more than half of the annual average flow of the Indus River and around 50-90% of its tributaries. But with rising temperatures, the glaciers of the Hindu Kush-Himalaya are retreating more rapidly than the global average (Barnett, Adam, and Lettenmaier 2005). Climate change, as predicted, may fundamentally change the hydrological system of this region. The few analytical studies that exist suggest that climate change could alter the timing and rate of ice melt, with an increase in annual runoff in the initial years, followed by a decrease in annual river flows (if the glaciated area is shrinking- long-term glacier retreat first increases water availability, later this trend will reverse and water availability will start to decrease). This poses an unprecedented threat to economy and food security of the region. So in coming decades, achieving water security will be the challenge and a top priority in regional agenda- a pre-requisite for food security, economic growth and development of the region. Achieving this requires substantial investment as climate change may affect the overall water availability and function & operation of existing water infrastructures, e.g. run of river hydropower schemes, structural flood defenses, drainage and irrigation systems, and particularly the large reservoirs through which all water flows are controlled & regulated, as well as water management practices. The analysis of mountain water resources under changing climate is thus crucial, as economic...
activities rely heavily on mountain fresh water resources and their distribution through existing water infrastructures, therefore any changes in water availability can have directly or indirectly serious impacts on the lives and livelihoods of the millions of people living in the basin.

1.2 THESIS RATIONALE

Changing availability of freshwater resources is likely to be one of the most important consequences of projected 21st century climate change, critically affecting the potential for sustainable development of lives and livelihoods of the millions of people living in different regions of the world (IPCC, 2007; Bates et al., 2008; Todd et al., 2011). Mountain regions are considered as the most important and reliable sources of global fresh water. Understanding the potential changes in mountain water resources under anticipated climate change is thus critical for sustainable water resource development and management. To understand the anticipated climatic effect over mountain hydrology and subsequent impact over future water availability within the mountain watersheds and their lowland regions; two distinct catchments in two different mountain regions are selected for study. The first case study area Kitzbühel Ache catchment is located in the upper part of the Danube basin within European Alps in Tyrol region of Austria. The catchment is very well observed (monitored) and documented. Therefore, the model is first developed and applied on this sampling catchment, and later the same methodology is adopted for another sampling area called Hunza catchment. The Kitzbühl catchment area is very famous for winter sports (Skiing) and tourist attraction and plays an important role in regional economy. The catchment covers an area of about 323 km² and is characterized by a non-glacierized middle mountain range with altitudes ranging from 600 m to about 2400 m a.s.l. The hydrological regime of the catchment can be characterized with low flows in the winter caused by snow accumulation and high flows during snowmelt in spring or early summer (detail in section 4.7.1).

The other case study area (Hunza catchment) is located in the Upper Indus Basin within central Karakorum Range of greater Himalaya region- Pakistan. The catchment covers an area of about 13746 km² and is characterized by a high altitude glacierized mountain range with elevation ranging from 968 m at valleys to over 7500 m a.s.l at mountain tops. The area possesses paramount importance due to its abundant water supply contribution to its main river Indus. Due to continuous, stable and large water supply for regional irrigation system; it is considered as a backbone for regional agro-based economy. The flow regime is highly seasonal; with the highest flows occurring between June and September, when ice and snowmelt cause a combined peak discharge, while minimum flows occur during winter months, e.g., November to February, when the mean monthly flows are only about one-tenth of those in summer. The flow regime of catchment with substantial seasonal snow & ice contributions is likely to experience reduced storage and associated seasonal regime changes. The water distribution to downstream irrigation is generally controlled and regulated through large reservoirs (e.g. Tarbela, Mangla, and Bhakra) and connected contiguous irrigation system networks (number of canals & barrages). Thus any change in flow patterns and/or total water availability may severely affect the function and operation of existing water infrastructures. A modelling of possible impacts of climatic changes on various aspects of the hydrological cycle is thus critical for development and management of future water resource system.
In this context, the main objectives to be achieved are:

- To develop a suitable methodology to assess the impacts of climate change on the hydrological response in mountainous regions at catchment scale;
- To quantify the sensitivity of simulated mountain hydrological processes to changes in air temperature and precipitation;
- To document the uncertainty in estimations of future mountain hydrological processes due to uncertainty in climate model scenarios;
- To quantify the effect of simulated catchment hydrology to climate change on water availability for adjacent downstream region (i.e. Lower Indus Basin-LIB); and
- To evaluate current water resource management practices and recommend available options for future sustainable water resources management (WRM) within the basin.

The projected results of both catchment analyses would help planners, decision makers and any concerned persons/organizations to understand the consequences of climate change on hydrological variables (dynamics of snow & ice behaviour and subsequent change in total flow/flow patterns) and the impacts these have on downstream regions and accordingly devise decision and management support tools.
1.3 CONCEPTUAL FRAMEWORK FOR THE STUDY

The overall procedure adopted for study can be described by the following flow chart.

Figure 1-1: Conceptual framework for the study (SCD- Snow cover duration, SA- Snow accumulation, SM- Soil Map, PET- Potential evapotranspiration, AET- Actual evapotranspiration, BF- Base flow, SF- Surface flow, TF- total flow).
1.4 Thesis Format

The work done on impact of climate change on mountain water resources in this thesis is structured in several chapters.

After describing context of the work, motivation and overall study objectives in Chapter 1, the necessary relevant background literature is presented in Chapter 2. Literature survey includes all required concepts related to the thesis for e.g. global climate change, global emission scenarios, climate change scenarios and significance of mountain hydrology including any detrimental effect of observed or anticipated warming over mountain water resources.

Chapter 3 presents European Alps as a case study. Historical description of the hydro-climate system in Alps is provided. The temperature, snow-covers, glaciers and runoff are briefed.

In Chapter 4, various hydrological models are discussed rigorously. The types of models as well as the parameters used in developing models are discussed in details. The chapter also covers model selection and model development in general. Chapter ends with developing of models for case studies: the Kitzbüheler Ache catchment in European Alps and Hunza basin in Karakoram Range (Indus basin).

Chapter 5 is based on model application and structured as summarizing results of four papers attached in appendix A. Paper- A quantifies effect of climate change on hydrology of Kitzbüheler Ache catchment in Austrian Alps. The paper provides a wide uncertainty band in the future average monthly, seasonal and annual amounts of the hydrological parameters snow water equivalent, snowmelt, evapotranspiration and flow, for 13 different regional climate change scenarios while using semi-distributed hydrological model PREVAH. Paper- B includes discussion on future water availability whist maintaining necessary environmental flows.

The Hunza basin is considered as case study in paper- C. This paper analyses the sensitivity of most important catchment hydrological processes towards projected warming based on range of hypothetical scenarios, e.g. snowmelt patterns, glaciers patterns and stream flow patterns. Paper- D provides the quantitative assessment of future water availability for proposed large reservoirs to be constructed in Indus basin, keeping in consideration the present water availability.

Chapter 6 is based on summarizing results of three papers, E, F and G attached in appendix A. These papers highlight the Indus basin water resources management issues and challenges and provide comprehensive listing and description of available options and recommendations. Proposals are followed by study of two options of water resources management i.e. water supply management and water demand management.

Finally, chapter 7 ends the conclusions and recommendations for future work.
2 MOUNTAIN WATER RESOURCES UNDER CLIMATE CHANGE

2.1 GLOBAL CLIMATE CHANGE

Climate change is defined as “a change in statistical properties of weather patterns over periods of decades or longer” (Houghton et al. 2001). It is reality today, and happening at much faster rate than ever before. Over the past century (between 1900 and 2013), the average global temperature has risen up by about 1°C (Hartmann et al., 2013). This has been emerging in two phases, from 1910s to 1940s and more strongly from the 1980s to the present. This is primarily due to the perturbation in the balanced radiation system of earth’s surface. The perturbation may be due to natural internal processes (e.g., volcanic emission of atmospheric gases), external forcings (e.g., fluctuations in solar output), or to anthropogenic effects (e.g., greenhouse gas emissions). The latest IPCC (2014) findings clearly attribute the increase in average global surface temperature to human activities. Human activities have increased the greenhouse effect via the emission of long-wave-trapping gases e.g., CO$_2$, CH$_4$, and NO$_2$ (Crowley, 2000, Hengeveld, 2000, and IPCC, 2014). Since 1850, the atmospheric concentrations of these gases have significantly increased e.g., CO$_2$ by 30%, CH$_4$ by 145%, and NO$_2$ by 15% (IPCC, 2007). The latest report released by World Meteorological Organisation (WMO, 2015) states that the concentration levels of GHG have reached new highs in 2013, and the year 2016 was the hottest year on record (LeComte 2017). Global change is reality today, and many model-base projections of the future evolution of the Earth System also indicate that warming will continue for at least the next century. Quantifying anthropogenic warming is imperative in future climate projections, which are determined in large parts by future GHG emission scenarios, and subsequently being used for construction of climate change scenarios for analysing the climatic effect over catchment hydrology.

2.2 CLIMATE CHANGE SCENARIOS

“A plausible future climate that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change” (IPCC, 2001). A plausible future climate represents the difference between current and future climate projections simulated through climate models. Climate projections generally narrate the response of the climate system to the changes in radiative forcing, which correspond to future GHG emissions scenarios. Typically, coupled atmosphere-ocean general circulation model (AO-GCM) outputs based on changes in monthly or seasonal mean climate are used for scenario constructions. AO-GCM are considered as the most advanced tools currently available for simulating the response of the global climate system to changing atmospheric composition. However, these AO-GCMs have a relatively coarse horizontal resolution (on the order of a few 100s of kilometre) (Jasper et al., 2004). These shortcomings limit the direct application of their outputs for scenario constructions for detailed assessment of regional hydro-climatic change studies (Bronstert, 2004). They do not represent the complex topography of the mountain regions. To reduce the uncertainty related to coarse resolution of AO-GCMs, usually, most researches use different downscaling methods such as dynamic downscaling method and/or statistical downscaling method. By downscaling, we mean transforming AO-GCMs output to a scale useful for impacts analysis at catchment scale. In our study case, climate change scenarios are constructed through re-
Regional climate change projections (RCM simulations), as provided by the EU PRUDENCE project (Christensen and Christensen, 2007). The scenarios are based on two different greenhouse-gas emission scenarios (SRES A2 and B2) and on two different AO-GCMs (HadAM3H and ECHAM4/OPYC3). Most regional models still have a resolution of 50 km and one has a resolution of 25 km. This is still rather coarse for the project catchment, which fits within one raster cell of the regional model, but acceptable for the aims of our investigation. The constructed scenarios should not be viewed as prediction or forecast of future climate but a picture of possible future climates, based on some prior assumptions. The constructed scenarios are given in paper-A & B.

2.3 SRES EMISSION SCENARIOS

Emission scenarios are the likely imageries of how the future might evolve and are a tool with which to analyse how driving forces may influence future GHG emission outcomes. The driving forces such as demographic development, socio-economic development, and technological change are the major precursors behind the construction of SRES (Special Report on Emissions Scenarios) scenarios. The evolution of these cursors is highly uncertain. This results in a wide array of possible emissions paths of greenhouse gases & aerosols. Based on above driving forces, the SRES team defines 4 main storylines (the three scenario families A2, B1, and B2, plus three groups within the A1 family A1F1, A1T, and A1B), characterizing around 40 plausible future emission paths, which may evolve during the 21st century. Each path signifies different demographic, social, economic, technological, and environmental developments within family group. These emission paths often denoted as “SRES scenarios” were initially published in the IPCC Third Assessment Report (TAR) in 2001 and then in Fourth and Fifth Assessment Report (AR4, AR5) in 2007 & 2014 respectively. The scenarios support in climate change analysis, including climate modelling and the assessment of impacts, adaptation, and mitigation. The main scenario groups are summarized in Table 2-1 & Figure 2-1.

Table 2-1: Matrix of development levels represented by the four main SRES families (the three scenario families A2, B1, and B2, plus three groups within the A1 family A1F1, A1T, and A1B) (source: CCCSN, 2007)

<table>
<thead>
<tr>
<th>Scenario Group</th>
<th>A1F1</th>
<th>A1B</th>
<th>A1T</th>
<th>A2</th>
<th>B1</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population growth</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>GDP growth</td>
<td>Very High</td>
<td>Very High</td>
<td>Very High</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Energy use</td>
<td>Very High</td>
<td>Very High</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Land use change</td>
<td>Low- medium</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Oil/gas resource avail- ability</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Technological change</td>
<td>Rapid</td>
<td>Rapid</td>
<td>Rapid</td>
<td>Slow</td>
<td>Efficiency &amp; Dematerialization</td>
<td>Dynamic as usual</td>
</tr>
<tr>
<td>Change favouring</td>
<td>Coal, oil and gas</td>
<td>Balanced</td>
<td>Non-Fossil Fuel</td>
<td>Regional</td>
<td>Efficiency &amp; Dematerialization</td>
<td>Dynamic as usual</td>
</tr>
</tbody>
</table>
Figure 2-1: Summary characteristics of the four SRES storylines—Global population is expected to increase from today's 6.6 billion and peak at 8.7 billion in 2050, while in the scenarios with less globalisation and co-operation (A2 and B2), global population is expected to increase 10.4 billion (B2) and 15 billion (A2) by the end of the century (source: Nakicenovic et al. 2000).

2.4 THE SIGNIFICANCE OF MOUNTAIN WATER RESOURCES

The significance of mountain water resources can clearly be judged from the widely used terminology as the natural "water towers" of the world. Mountain regions, defined as areas over 1000 m above sea level (Ives et al., 1997), comprise only 27% of the earth's surface (Figure 2-2) but their contribution in total water supply to global population is far greater than its areas (Vivirolı and Weingartner, 2004). The high specific discharge values (due to increased precipitation and decreased evaporation rate with altitude), highly reliable runoff (due to the regularity of the melting process in spring and summer season), and compensatory effect of glacier storage for adjacent lowlands are the most important characteristics of these regions (Vivirolı et al., 2003; Weingartner et al., 2007). Their function as sources of large, reliable, and compensatory discharge for adjacent lowlands is the main reason why mountains could be entitled as the "water towers" of the world. Their role as fresh water supply to downstream population for irrigation, industry, domestic use and energy production has long been recognized by scientific community.
Since last two decades, the role of mountain waters have drawn considerable attention of the world community and have been first acknowledged in 1992 Rio Earth Summit and later by International Year of Mountains in 2002 and the subsequent International Year of Freshwater in 2003. In 2008, the United Nation’s General Assembly adopted Resolution 62/196 on Sustainable Mountain Development, and recognized mountains as the major source of most of the Earth’s freshwater supply and their contribution in poverty eradication. This was the first major political recognition and applause of earlier findings (i.e. Rodda 1994) that the greater part of the global water resources are originated from mountain regions. The investigation by (Meybeck et al., 2001) including all climate zones reveals that the mountain contributes to about 1/3 of total global discharge, while in global comparative assessment of selective basins, (Viviroli, 2001) concluded that the contribution from mountains to total runoff is about double to its surface area. Further, distinctions can be made at regional scale, where, mountain discharge can represent as much as 90-100% of the total flow in a catchment (Liniger et al., 1998; Viviroli et al., 2007a). The analysis by (Viviroli et al., 2003) highlights the significance of mountains to their lowland regions as per climatic locations, where mountains account for 20–50% of total annual discharge in humid areas, while in semi-arid and arid areas, the contribution of mountains to total annual discharge ranges from 55% to over 100% of total runoff of a river basin (Figure 2-3). The mountain contribution over 100% occurs when lowland runoff is less than mountain runoff due to groundwater recharge or withdrawals for irrigation purposes. Further, (Viviroli et al., 2007a; Weingartner et al., 2007) analysed the disproportional influence of mountain run-off as compared to surface area of the basin together with level of reliance of lowland areas on mountain water resources for various consumptive purposes (e.g. agriculture). Based on these criteria, they divided world river basins in four different groups (Figure 2-3). In a first group, from Nile to Indus River, the monthly mountain contribution exceeds total run-off in almost all months, highlighting the essential role of mountains for lowland regions in arid climate zones. The mountain contribution is extremely important due to intensive irrigation in dry lowland area.
In a second group, the contribution from mountains exceeds total run-off during at least one month. Although the monthly and annual contribution is much less than in the first group, still water supply from mountains is central for downstream region during dry seasons.

![Relative annual mountain flow contribution](image)

**Figure 2-3:** Mountain contribution in total basin flow in different river basins including its significance to their lowland regions. The basins in 1st & 2nd group are located in arid to semi-arid climate zones, while the remaining two groups are located in humid climate zone. Source: (Viviroli et al., 2003; Viviroli et al., 2007a; Weingartner et al., 2007).

The third group (i.e. Alpine rivers, Rhine, Danube, Rhone, and Po) consists of basins where mountain run-off is marginal to total run-off. Despite the humid climate and sufficient average water supply, the mountain contribution particularly in summer season is also vital for sustainable water availability in lowland region for this group. The fourth group is consisting of tropical basins, where the mountains have a low contributing potential to a wet lowland areas. The basins on average show strong humid conditions due to plenty of precipitation falling in lowland region.

It is now very clear that the role of mountains to their lowland areas is very critical, particularly in arid and semiarid regions. In these regions, mountains form wet islands, and their significance increases in proportion to the size of their glaciers and the durability and volume of snow cover, which acts as a reservoir for the dry season. Other large mountain systems critically important for water supply are the Rocky Mountains, the Andes, the Middle East mountains, the Atlas Mountains, and the mountains of South Africa. In humid climate regions, mountains are not of such great importance, although they still have a certain complementary as well as compensatory value. In addition, a number of regional ‘water towers’ found on each continent play a key role.
2.5 MOUNTAIN’S HYDROLOGY UNDER CHANGING CLIMATE

Mountains are a water reservoir of many regions of the world and the supply source of many world river basins originates from mountainous areas but their future role in global water resources could well be altered from anticipated climate change. Climate change is a reality today, and some of the best evidence such as melting glaciers, reduced snow cover durations comes from mountainous areas. Many scientists believe that the changes occurring in mountain ecosystems may provide an early glimpse of what may come to pass in lowland environments, thus act as early warning systems. Mountains exist in many regions of the world. High latitude mountain systems in the polar, sub-polar and boreal zones are located between 90°N and 55°N in the New World and between 90°N and 60°N in Eurasia. Mid-latitude mountain systems in the cool temperate and warm temperate zones are located between 55°N–60°N and 25°N, and 25°S and 60°S; low latitude mountains are located in the tropical zone between 25°N and 25°S (Figure 2-2). They differ in shape, extension, altitude, vegetation cover, and climate regime and thus are affected differently by climate change. The mountain climate varies sharply over very short distances; temperature change with increasing elevation and the windy slopes typically receive much higher precipitation than lee slopes. For example, the local climatic variations are very profound in Himalayan mountain range; wherein the southern slopes receive about 4000 mm annual precipitation while the northern slopes receive typically of about 200-300 mm. Similarly, the investigations about temperature change by (Beniston et al., 1997; Böhm et al., 2001; Diaz et al., 2003, De et al, 2011, Kohler et al, 2014) reported intense temperature rise in high elevational areas (Figure 2-2).

Figure 2-4: Increasing trend in annual mean air surface temperature from 1900 to 2013. Purple contours depict topography over 1000 m. Source (Kohler et al, 2014).
The observational temperature record of past century, mostly in Europe is at least comparable with, and greater in mountainous areas than, those observed at adjacent low lands. Direct and indirect measurements of global air temperature over past one hundred years shows periods of both cooling and warming, nevertheless in last 50 years the earth, in almost all locations, has experienced a dramatic warming trend (Figure 2-4). The temperature increase in last three decades is three times higher than ever recorded in early decades. However, the amplitude of changes in climatic parameters (i.e. mean temperature, temporal and spatial distribution of precipitation patterns) varies according to regions considered. The warming trend has been much greater in Himalayan region (Asia) than global average of 1°C over the last 100 years (Hartmann et al, 2013). The mean annual temperature analyses by (Vuille and Bradley, 2000) in tropical Andes for 1939-1998 period, indicates of about +0.6°C increase (0.1°C/decade). Similarly the data analysis in Pyrenees by (Bucher and Dessens, 1991) reported +0.9°C increase (+0.11°C/decade) for 1880-1950 period. In contrary to past century records, the (IPCC, 2014) in their findings, projected that the globe will warm between 1.5 °C and 4.5 °C by the period of 2085–2100, depending on the prevailing emissions scenario (Figure 2-5). Similar to the previous century, future temperature increases are expected to be stronger at high altitudes than the ground (Du et al., 2004; IPCC, 2007a, Bradley et al, 2009, Hartmann et al, 2013, Kohler et al, 2014).

Figure 2-5: Modelled changes in temperature from 1985-2005 to 2081-2100 according to a moderate to high emission scenario. White contours depict topography over 1000 m. Source: (Kohler et al, 2014).

Nogués-Bravo et al., 2006 conclusively reported that the magnitude of future projections will be two to three times greater than that recorded in the 20th century (Table 2-2). The average projected warming for global mountain systems as a whole up to 2040-2069 (A1F1 and B1) ranges from +3.21°C to +2.1°C and +5.3°C to +2.8°C for 2070-2099.
Table 2-2: Projected temperature trends in different mountain ranges over the world as reported by (Nogués-Bravo et al., 2006) for two 30-year periods (2040-2069) and (2070-2099) respectively. SD represents standard deviation of projected temperature among AOGCMs within each emission scenario.

<table>
<thead>
<tr>
<th>Mountain Group (Figure 2-2)</th>
<th>A1FI</th>
<th>A2</th>
<th>B1</th>
<th>B2</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2040-2069</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocky Mountains</td>
<td>3.3 °C</td>
<td>2.5 °C</td>
<td>2.3 °C</td>
<td>2.3 °C</td>
<td>0.5 °C</td>
</tr>
<tr>
<td>Andes</td>
<td>2.5 °C</td>
<td>2.0 °C</td>
<td>1.7 °C</td>
<td>1.7 °C</td>
<td>0.4 °C</td>
</tr>
<tr>
<td>European Alps</td>
<td>3.3 °C</td>
<td>2.5 °C</td>
<td>2.3 °C</td>
<td>2.3 °C</td>
<td>0.5 °C</td>
</tr>
<tr>
<td>Atlas</td>
<td>3.4 °C</td>
<td>2.6 °C</td>
<td>2.4 °C</td>
<td>2.4 °C</td>
<td>0.5 °C</td>
</tr>
<tr>
<td>Ethiopian + E. African Highlands</td>
<td>2.7 °C</td>
<td>2.1 °C</td>
<td>1.8 °C</td>
<td>1.8 °C</td>
<td>0.4 °C</td>
</tr>
<tr>
<td>Drakens Mt.</td>
<td>2.4 °C</td>
<td>1.8 °C</td>
<td>1.6 °C</td>
<td>1.6 °C</td>
<td>0.4 °C</td>
</tr>
<tr>
<td>High Asia (10)</td>
<td>5.0 °C</td>
<td>3.8 °C</td>
<td>3.6 °C</td>
<td>3.6 °C</td>
<td>0.7 °C</td>
</tr>
<tr>
<td>Hindukush-Himalaya</td>
<td>3.8 °C</td>
<td>2.9 °C</td>
<td>2.7 °C</td>
<td>2.7 °C</td>
<td>0.6 °C</td>
</tr>
<tr>
<td>Alps (New Zealand)</td>
<td>2.0 °C</td>
<td>1.5 °C</td>
<td>1.3 °C</td>
<td>1.3 °C</td>
<td>0.3 °C</td>
</tr>
<tr>
<td><strong>2070-2099</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocky Mountains</td>
<td>5.5 °C</td>
<td>4.3 °C</td>
<td>2.9 °C</td>
<td>3.2 °C</td>
<td>1.2 °C</td>
</tr>
<tr>
<td>Andes</td>
<td>4.2 °C</td>
<td>3.3 °C</td>
<td>2.3 °C</td>
<td>2.4 °C</td>
<td>1.0 °C</td>
</tr>
<tr>
<td>European Alps</td>
<td>5.3 °C</td>
<td>4.1 °C</td>
<td>2.9 °C</td>
<td>3.1 °C</td>
<td>1.1 °C</td>
</tr>
<tr>
<td>Atlas</td>
<td>5.4 °C</td>
<td>4.2 °C</td>
<td>3.0 °C</td>
<td>3.2 °C</td>
<td>1.1 °C</td>
</tr>
<tr>
<td>Ethiopian + E. African Highlands</td>
<td>4.6 °C</td>
<td>3.5 °C</td>
<td>2.4 °C</td>
<td>2.6 °C</td>
<td>1.0 °C</td>
</tr>
<tr>
<td>Drakens Mt.</td>
<td>4.4 °C</td>
<td>3.4 °C</td>
<td>2.3 °C</td>
<td>2.4 °C</td>
<td>1.0 °C</td>
</tr>
<tr>
<td>Hindukush-Himalaya</td>
<td>5.9 °C</td>
<td>4.8 °C</td>
<td>3.4 °C</td>
<td>3.7 °C</td>
<td>1.1 °C</td>
</tr>
<tr>
<td>Alps (New Zealand)</td>
<td>3.7 °C</td>
<td>2.9 °C</td>
<td>1.9 °C</td>
<td>2.1 °C</td>
<td>0.8 °C</td>
</tr>
</tbody>
</table>

The increases in temperature may mean winter precipitation falling more as rain instead of snow, less snow accumulations, early depletion of snow cover, rise in a snowline, faster glacier retreat, outburst of ice-dammed lakes and warming of perennially frozen ground etc. The latest (IPCC, 2014) analyses also projected robust precipitation increases in the monsoon regions and in middle and high latitudes, and a decrease in the subtropics (Figure 2-6).
The changes in temperature and precipitation will influence the seasonality of rivers. Recently many investigations observed that any change in climatic parameters i.e. temperature and precipitation patterns will change significantly snow storage of these regions and subsequently alter both timing and volume of the discharge regime of Mountain Rivers (Etchevers et al., 2002; Schaeffli, 2005; Stewart et al., 2005; Zierl and Bugmann, 2005a; Maurer et al., 2007; Bates et al., 2008a; Vanham et al., 2009c; Elsner et al, 2010; Kerkhoven et al, 2011; Beniston M., 2012; Déry et al, 2012; Laghari et al, 2012a; Gobiet et al, 2014; Kohler et al, 2014; Kang et al. 2016; Islam et al, 2017). The stream flow analysis by (Birsan et al., 2005; Barben et al., 2010; Beniston M., 2012) in Swiss Alps identified the increasing patterns in flow volume in all seasons except summer. In this season, when most runoff is provided on an annual basis, mixed signals are observed. The same conclusions were drawn in French Alps and Western United States (Cayan et al., 2001; Hamlet et al., 2005; Knowles et al., 2006; Mote et al., 2005; Regonda et al., 2005; Stewart, 2009; Stewart et al., 2005), which is attributed tentatively to a change in precipitation form (e.g. solid to liquid) and earlier snow melt due to a rise in air temperature. However, in coming decades, depending on altitude, early snowmelt may lead to frequent risk of landslides and flooding and severe summer water shortages may take place in regions that are dominated today by nival regimes. (Barnett et al., 2005) have identified these regions where seasonal snow fall have a significant influence over regional hydrological cycle (Figure 2-7).
As per global population estimates (2000), around one-sixth world population directly live within the domain of snowmelt dominated regions. The river basins depending on melt water, particularly in South, South-East and Central Asia are highly susceptible to climate change (Parry et al., 2007). The countries falling under arid to semi-arid climate zones and their agro-based economies highly dependent upon upstream mountain water resources (i.e. Pakistan, India) are also being considered very vulnerable to climate change. The relation of water supply to water demand is already critical in these countries. Therefore, the apprehensions about the future role of upstream mountain waters as large, reliable, and compensatory discharge for adjacent lowlands (intensive irrigated areas) increased manifold (Coudrain et al., 2005; Hagg and Braun, 2005; Solomon et al., 2007; Viviroli et al., 2007a; Vuille et al., 2008). According to (Haddeland et al. 2014) projections, countries in these regions may face more than 10% annual water shortages till mid of current century (Figure 2-8).
Several benchmark studies such as the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5); Third United Nations World Water Development Report (WWAP, 2009) and many other prominent studies (Barnett et al et al, 2005; Parry et al., 2007; Solomon et al., 2007; Bates et al., 2008a; Beniston et al, 2012, IPCC, 2014; Kohler et al, 2014, Kang et al. 2016; Islam et al, 2017) have recently highlighted the vital role of mountains. The investigations conducted over different mountainous regions of the world reported that most of the mountain reservoirs are melting due to increased temperatures and if current trends continue, many of the world glaciers will be vanished entirely by the end of this century. The impact of rising temperatures over glacier cover and volume has already been observed in all regions of the world. Table 2-3 shows the glacier retreat trends due to climate change in different mountain ranges of the World.
Table 2-3: Glacier retreat trends in different regions of the world. Source: (Mote and Kaser, 2007; UNEP, 2008; WGMS, 2008)

<table>
<thead>
<tr>
<th>World region</th>
<th>Glacierized area</th>
<th>Observed changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>South America</td>
<td>Tropical Andes, Patagonian ice fields</td>
<td>3.4% of area lost in the last 50 years. Recent thinning rates observed to be around 30m/yr</td>
</tr>
<tr>
<td>North America</td>
<td>Ice fields in Alaska, Canada</td>
<td>25% area lost in western Cordillera</td>
</tr>
<tr>
<td>European Alps</td>
<td>Alps, Caucasus mountains</td>
<td>50% area loss in the last 150 years</td>
</tr>
<tr>
<td>Tibetan Plateau</td>
<td>Tibetan Plateau</td>
<td>20% area lost since the 17th century with 90% of the glaciers retreating</td>
</tr>
<tr>
<td>New Zealand</td>
<td>Southern Alps</td>
<td>11% net ice volume lost in last three decades</td>
</tr>
<tr>
<td>Central Asia</td>
<td>Tien Shan, Pamirs</td>
<td>25-30% area loss in Tien Shan during the last century, 30-35% area loss in the Pamir, and more than 50% area loss in northern Afghanistan</td>
</tr>
<tr>
<td>Africa</td>
<td>Kilimanjaro, Mount Kenya, Ruwenzori Mountains</td>
<td>82% area loss over last century and 50% glaciers disappeared</td>
</tr>
<tr>
<td>Russia</td>
<td>Arctic range, islands, mountain range</td>
<td>50% retreat in the North Caucasus over the last 50 years</td>
</tr>
</tbody>
</table>

The well documented European Alps have already shrunk more than half of its total volume. This region have lost about 30-40% glacierized area and half of its ice volume between 1850 and 1975, another one-fourth of the remaining amount between 1975 and 2000 and one-eighth of leftover volume between 2000 and 2005 (Haeberli and Beniston, 1998; Haeberli et al., 2007). The Caucasus mountain glaciers have reduced to 50% of its original size. The well-known snow-capped crest of Mount Kilimanjaro has reduced to one-fifth of its original size (Global Mountain Summit, 2002), and the Mount Kenya’s largest ice reservoir now vanished to its one tenth original size. In Montana, the National Park’s largest glaciers have lost two-third of its size and it is projected that remaining glaciers may disappear completely in few decades (US Environmental Agency, 2000). The same retreating patterns were observed in Ecuador, New Guinea, Peru, Venezuela, Greenland, and East Africa (Mountain Partnership, 2004). The retreating rates in Himalayan glaciers are even faster than any other glaciers of the world. Glaciers in this region are thinning at the rate of 0.3 -1 m/year and retreating faster than the world average (Dyurgerov and Meier, 2005). For example, Gangotri Glacier depletion rate over the last three decades has been three times high than preceding 200 years (Srivastava, 2003). Many authors also reported intensive deglaciation in the Himalayan part of Nepal; from several meters to 20 m/year glacial retreat (Fujita et al., 2001; Fujita et al., 1997; Kadota et al., 1997). The glaciers in western China have lost one-fifth of its original size (Liu et al., 2006). The glacial area of the Tibetan Plateau has decreased by 4.5 % over the last two decades and by 7 % over the last four decades (CNCC, 2007). Contrarily, the glaciers on the
Pakistani side (North-western Himalayas, Karakoram and Hindukush) are mostly stable (Figure 2-9).

Figure 2-9: Glacier surges in Karakoram Range, Pakistan. Source: (Rankl et al. 2014).

The glaciers in these ranges exhibited mixed patterns: retreating till 60s, thickening and expansion in 70s and gradual retreat in 80s & 90s again (Hewitt et al, 1989, Hewitt, 2005; Rankl et al, 2014). Since late 90s, the expansion in more than 30 glaciers has been observed and the number of glacial surge incidences has been increased compared to long-term records (Hewitt, 2007, M. Rankl et al. 2014). These mixed responses may be strongly climate controlled, although different from east to west, and north to south. In spite of these findings, the available research on glacier retreat is still limited at present; projections regarding the future state of glaciers are difficult and subject to uncertainty. This was recently shown by the controversy about the false IPCC statement that the Himalayan Glaciers could be disappeared in next few decades (Rees and Collins, 2005; WWF, 2005; IPCC, 2010). Regardless of any controversy or contradicting findings about mild or massive projected changes, generally all studies indicate general trends: retreating of glaciers, which in long term, can have serious implications on adjacent lowland areas, and will ultimately result in less water availability, less hydropower potential and a decline in water based tourism (skiing etc.) and above all the increased risks of natural disasters.
3 THE CASE STUDY OF EUROPEAN ALPS

3.1 GENERAL

The Alps, spanning over the central part of Europe, play a vital role in accumulating and supplying water to the continent. The chain of this mountain region houses the headwaters of number of rivers i.e. Danube, Rhine, Po and Rhone; as such, they deliver vital ecosystem services both up and downstream region. The Alpine convention, 2009 clearly indicate that the Alps are the most vulnerable areas to climate change in Europe. The region have undergone an exceptionally high temperature increase of around +2°C between the late 19th and early 21st century, more than twice the rate of average warming of the Northern hemisphere (Figure 3-1).

![Figure 3-1: Average annual air temperature in the Alpine space 1760-2007 (black) and the global average 1858-2007 (grey). 1: last natural period – solar flux and volcanic activity dominant, 2: increasing influence of human activity – the period of aerosols, 3: start of the global warming period. Source: (Alpine convention, 2009).](image)

The increased temperature rate has severely affected alpine hydro-climate system, i.e. extensive glacier retreat, decline in snow cover duration, climbing of the snowline, changes in seasonal runoff regime etc. (Auer et al., 2007). It is projected that the changes in hydro-climate system will further be intensified in coming decades, leading to more droughts in summer, floods and landslides in winter and higher interannual variability in river runoff regimes. Projected water shortages and more frequent extreme events, combined with increasing water demand are likely to have severe adverse effects on ecosystem services, hence many sectors i.e. households, agriculture, energy production, forestry, tourism, and river navigation are very vulnerable to water shortages.

3.2 OVERVIEW OF ALPINE CLIMATE OVER THE PAST CENTURY

3.2.1 TEMPERATURE

According to the latest IPCC report (AR4), the global warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. Global mean surface temperatures have risen up by 1°C over the last 100 years (IPCC, 2014). During the 20th century most of Europe also experienced
increases in average annual surface temperature, with stronger warming over most regions in winter than in summer (Alcamo et al., 2007a). Recent observations confirm that the Europe has warmed more than the global average, particularly in mountain areas. At the alpine level, most of the temperature observations converge towards a general temperature increase. The values proposed for different meteorological stations in the Alps differ in terms of magnitude but the direction is the same: warming. The observational record in French Alps shows about 0.9°C mean annual temperature increase over the 20th century. The increase in annual mean of the daily maximum temperature was stronger and ranged between 0.9°C to 1.1°C. In German alpine part, the mean annual increase ranged between 0.5°C to 1.2°C during the 20th century. The same trend were observed in Swiss Alps, where about 1.47°C total temperature increase has been recorded between 1900 to 2006 period, with a more pronounced temperature increase in the last 40 years (0.4°C per decade). The overall mean alpine temperature is thought to have increased by up to +2°C for some high altitude sites. Moreover, this warming trend seems to have accelerated during the last decade. The database of the European project HISTALP contains monthly homogenized temperature time series dating back to 1760 for the whole alpine region. Climate variability and climate change is closely related to the long-term warming trend visible in the seasonal and annual mean temperature time series. Figure 3-2 shows the regional summer and winter temperature averages from 1760 to 2007 along with the annual range of temperature. The figure demonstrates an overall annual temperature increase of about 2°C from the late 19th century up until the early 21st century. The warming over the 20th century is more accentuated in summer than in winter. Inter-annual variability is higher in the cold season. During the last 25 years winters and summers have warmed at comparable rates, which is not typical for the regional climate evolution over the past 250 years. This has caused the extraordinary increase of the annual mean temperature by 1.2°C/25 years (lower right panel) which is unprecedented throughout the instrumental period.

Figure 3-2: Change in temperature for the Greater Alpine Region (GAR). Single year and 20 year smoothed mean GAR series from (1760–2007). Source: (EEA, 2009).
3.2.2 Precipitation

Several authors investigated precipitation trends at the Alpine scale, which leads somehow to controversial picture. The precipitation time series analyses by (Anfossi et al., 2002; Beniston, 2005b) have found non-significant trend over the past century. The analyses by (Brunetti et al., 2006) concluded that the significance of precipitation trends depends on the choice of time window considered. (Auer et al., 2005) analysed precipitation over last 200 years and detected two antagonistic precipitation trends: a wetting trend (since the 1860s) in the north-west of the Alps and a drying trend (since 1800) in the south-east. The analysis by (Widmann and Schär, 1997) have reported an increase of winter precipitation by 20-30% per 100 years in the western part of the Alps and a decrease of autumn precipitation by 20-40% to the south of the main ridge. A more recent analysis by (Schär and Frei, 2005) has also identified the similar trends: an increase in winter precipitation in the north-western part of Alps and decrease in autumn & summer precipitation in the south-eastern parts of Alps over the 20th century (Figure 3-3). Like in the Swiss Alps, the increase of mean winter precipitation for the 1901-94 period amounts to 15-20% and is statistically significant, but no significant trend found for other seasons. Similar trends were observed in other parts of Alpine space; increasing in winter and decreasing in summer & autumn, for example, (Schmidli et al., 2002) confirm these findings.

![Figure 3-3: Linear trend of seasonal mean precipitation in the Alps (1901–1990). Thick dash-dotted contours indicate significance at the 10% level. Source: (Schär and Frei, 2005).](image)

3.2.3 Alpine Glaciers

The most visible sign of climate change is the melting of the glaciers. They are not only sensitive to temperature fluctuations but also to variation in precipitation form (solid to liquid) and energy flux too. The changes observed in the Alpine glaciers are absolute sign of climate change and are visible to everyone. The wide-ranging glacial retreat has been happening for around 150 years, with a brief period of recovery and
glacial advance in the 1960s to 1980s in Alps. This advancing period has also been observed in other regions of the World such as the Pamir-Alai, Tien-Shan, etc. Alpine glaciers have lost about one-third in glacierized surface area and about half of their total volume around 1850 to 1975. Another one-fourth of the remaining volume has probably been lost between 1975 and 2000, and additional 10-15 % in the first half of this decade. The said retreating patterns could be observed through mass balance studies of some alpine glaciers (Figure 3-4). The annual mass balance was stable in 60s to 80s, but since then, retreating till to date. A temperature rise even over a short period can lead to a dramatic development. For example, the extreme 2003 summer heat wave caused a substantial glacier melting in Alps with a corresponding mean specific mass loss of (-3.5 m) water equivalent (w.e.), which is eight times higher than the annual mean of the 1960-2000 periods.

![Annual & Cumulative Mass Balance Variations](source.png)

Figure 3-4: Annual (left y-axis) and cumulated (right y-axis) mass balance of nine alpine glaciers. Source: (ClimChAlp, 2008).

Despite the apparent homogeneity in patterns of glacier surging and retreating at broader tempo-spatial scale; contrasts do appear over shorter and local/regional levels. The mass balance analyses of French glaciers over the period of (1900-1941) reported very little fluctuation in volumes, whereas, in next 10 years, massive deficit was reported due to strong summer ablations. During 1954 to 1981, again readvancement of several hundred meters in many glacier fronts is observed. Since 1982, the mass balances are in deficit due to a high level of summer ablation. The time series analyses of Italian glaciers (21% of the glacial alpine surface) shows the general trends as witnessed in other parts of the Alps or world; melting phase is spread over mid nineteenth century to date, with an exception in the period of 1960 to 1980. The analysis of cumulative variation of 104 glaciers over 1980-1999 period, indicates the percentage of progressing glaciers dropped from 66% in (1960-80) to 4% over (1980-1999), while the percentage of retreating glaciers increased from 12% in (1960-80) to 89% in (1980-1999). The study of Swiss glaciers, which occupy about half of the alpine glacier space, also reported negative mass balance since last one and half century. Since 1850, the length of many glaciers (e.g. Aletsch valley glacier, Trient mountain glacier, Pizol cirque glacier) has been reduced from 1 to 3 km (Figure 3-5).
During 1850 to 1973, the glacier equilibrium line (line b/w zone of accumulation and ablation) is almost 70-80 meters shifted to upward direction. The cumulative retreat is phenomenal in last few decades. The average decadal loss in size between 1985 and 1999 is about seven times higher than average from 1850 to 1973. In nutshell, if the warming trends continue the pace as projected, the alpine glaciers may be disappeared till the end of 21st century. This could have a serious repercussion for downstream regions. Melting of ice reserves complements the average water availability in downstream regions at present. But once these reserves are emptied than no such input during dry periods would occur. Thus, downstream regions depending upon upstream water resources may encounter water shortages in summer season in future.

3.2.4 ALPINE SNOW COVER

Snow cover plays an important role for mountainous systems, particularly in European Alps; it is a basic resource for winter tourism. Due to its strong water storage function, it contains huge quantity of solid precipitation in winter and releases it in upcoming spring and/ or summer, thus provides a regular and stable supply to a number of alpine river systems. The spread and depth of snow cover is not only linked to temperature and form of precipitation, but many other factors too have influence on the snow cover- like vegetation cover, slope, shade, winds etc. Not only these local or regional factors, macro scale factors too play the dominant role in controlling the timing and amount of snow in the Alps (Beniston et al., 2003 b). Changes in the amount of precipitation tend to affect the volume of snowfall, particularly the maximum snow accumulation, which usually occurs near the end of the winter at the onset of the melt season. On the other hand, increasing temperatures also leads to change in the form of precipitation and/ or early start of melting. Thus climate change have a very significant impact on snow accumulation or snow cover, particularly in Alps, where the warming trend is almost two to three times higher than global average. Since the last three decades, the observation record in Swiss Alps clearly reported significant decrease in duration and amount of snow cover. The decrease in snow cover below 1500 m are particularly visible, however this climatic sensitivity disappears at higher altitudes (Figure 3-6).
The visible decreasing trend in the number of snowfall days and depth at lower altitudes is primarily being attributed to the change in precipitation form from snow to rainfall due to increase in seasonal temperatures (Beniston, 2005a; Beniston et al., 2003b; Beniston et al., 2003a). However, the maximum snowfall period during 3 days and the total volume of daily fresh snow during the whole winter remain stable, but show extreme variability from year to year (Schneebeli et al., 1997). The extent of the snow season is primarily influenced by the various combinations of temperature and precipitation, the longest being related to the cold-moist winter mode, and the shortest to the warm-dry modes (Beniston et al., 2003a). In general, since last 3-4 decades, the length of the snow season is decreasing at most of the locations. The above mentioned negative trends were also observed in German part of Alps. Since the second half of the 20th century, about 30-40% decrease is observed in snow cover duration below 3000 m a.s.l. However, at higher altitudes the figure remained under 10% (Hennegriff et al., 2006).
The long term analyses of February-snow cover height and duration at Col de Porte site in French Alps over the period of 1960 to 2004 also indicates strong decrease in snow cover duration and height (Figure 3-7). The snow height above 1.5 m in early decades reduced to 3 to 4 times in last decades (Etchevers et al., 2002). The snow cover greater than 1 m is also reduced 5 times more than the early observed years. The investigation in Italian Alps also reported the similar trends. The snow accumulation at Lago Valsoera weather station (2440 m, Gran Paradiso range) in Italian Alps was 40 % below mean values of period (1959-2002) (ClimChAlp, 2008).
3.2.5 **ALPINE RUNOFF**

The Alps serve as a huge natural water storage site, where considerable precipitation in winter is shelved as snow and ice and released in the dry season through the melting of these reserves. This natural storage mechanism benefits many river systems throughout Europe, including the four major river basins, the Rhine, Danube, Po and Rhone, whose headwaters originate from the alpine region. The Figure 3-8 shows the major river basins originating in the Alps. The region possesses paramount importance due to its abundance of water resources. The increased precipitation rate and reduced evaporative loss due to low temperature with altitude is the main reason for surplus water availability in region.

![Figure 3-8: Major rivers originating in the European Alps- Rhine, Rhone, Po and Danube](image)

The large proportion of precipitation falls as snow at higher altitudes. The accumulation of snow at high altitudes may form a glacier - a prominent feature of alpine mountain hydrology. These glaciers occupy about 2900 km², approximately 1.5% of the total area of the Alps. During summer season, when precipitation and runoff is low, the glacier melt provides important services to low-lying areas (Liniger et al., 1998). The significance of the Alps, due to their disproportionately large supply contribution to lowland areas in these four river basins can be assessed through the catchment size and the actual discharge measured (Figure 3-9).
The Alp’s mean annual contribution varies from 26% (Danube) to 53% (Po) of the total discharge. The mountain part of Danube basin (around 10% of total basin area) provides 26% of total discharge, resulting in a disproportional influence of 2.6. Similarly, the mountain part of the Rhine, Rhone, and Po basin accounts 34%, 41%, and 53% of the total discharge, implying a disproportional influence of 2.3, 1.8, and 1.5 for each basin respectively (Weingartner et al., 2007). The contribution from Alpine part varies between seasons; the major contribution comes in summer and less in winter. Like in the Po basin, the mountain part contributes less than 40% of total discharge during winter months and more than 80% in summer months. The importance of the Alpine region can further be judged through specific discharge values. The alpine catchments produce high annual specific discharge (more than 30 l/s per km²) compared to lowland catchments (less than 12 l/s per km²) in central Europe (Liniger et al., 1998). However, due to the variation in the regional climatology (as varies at very short distances) and water usage, a significant difference in annual specific discharge does exist between various alpine rivers. Figure 3-10 & Table 3-1 shows mean annual specific discharge of various alpine rivers. The rivers Rhine, Rhone and Inn show stable and higher mean specific discharges (28–33 l/s per km²), while the rivers Po, Adige and Mur shows lower and variable mean specific discharges (17–24 l/s per km²).
Regardless of these differences, all alpine rivers provide reliable and sufficient supply for multiple purposes, not only for the up and down stream alpine region, but also for large parts of Europe in general. Since the hydrological cycle of the Alps is influenced by many factors e.g. meteorology, topography, climatic processes, and by the anthropogenic use of water, therefore, it could be altered under any changes in those parameters. As mountain regions are very sensitive to climate change, particularly the Alps, where the warming trend is almost 3 times higher than global average in recent past, any further change in temperatures will alter the hydrological cycle in the Alps. This would result in high evaporative loss, increased liquid to solid precipitation ratio, reduced snow cover days, and massive glacier retreats. Due to the increased warming trends over the past few decades, the alpine glaciers have already lost about two-third of its total volume till 2000, and additional 10 % of the remaining lost just in hot summer 2003 (Haeberli, 2003). If warming continues with same pace, the snow line may be raised 650 m by the end of this century (Jacob, 2001), the small
glaciers will be disappeared and large glaciers will lose about 30-70% of its remaining volume by the middle of century (Bogataj, 2007; Paul et al., 2004). Thus, the role of glaciers providing stable and sufficient supply of water in long dry seasons to low-lying areas may not be fulfilled in future. The impact of climate change on each alpine basin runoffs over past decades is further discussed below.

3.2.5.1 Danube flows

The Danube is the second longest river in Europe; which rises in Black Forest Mountains of Germany, and empties through deltaic region into Black Sea. After leaving Germany, the Danube passes through Austria, the Slovak Republic, Hungary, Croatia, Serbia, Romania, Bulgaria, the Ukraine and Moldova (Figure 3-11).

![Geographical map of Danube River from source to sea with both up & downstream gauge stations Achleiten and Ceatal Izmail respectively.](image)

Figure 3-11: Geographical map of Danube River from source to sea with both up & downstream gauge stations Achleiten and Ceatal Izmail respectively.

About 81 million people live within the catchment boundary. It is approximately 2900 km long and drains an area of about 817000 km². About one-third of the Danube river basin is mountainous, while the remainder consists of hills and plains. With an average discharge of about 6500 m³/sec, the Danube is the largest tributary of Black Sea. The basin altitude varies from over 3000 m a.s.l to few hundred meters at lowlands with a mean altitude of about 475m a.s.l. Due to its large surface area and diverse relief, the climate varies significantly from mountains to plain areas: Atlantic climate in the western part of the upper basin with high precipitation; Mediterranean climate through the Drava and Sava river basins, and continental climate with lower precipitation and cold winters. The Alpine part receives about 2000 mm annual precipitation, while plain areas receive about 500 mm per year. The highest average annual temperature (+11 to +12 °C) occurs in the middle and lower Danube, while lowest (+5 to +6 °C) observed in the upper Danube. The seasonal difference increases from west to east. The area above an elevation of 1500 m a.s.l remains under snow cover during November to March (Belz et al., 2004). The spatial and seasonal differences in precipitation have significant influence to surface runoff and discharge levels of Dan-
The Danube consists of total 26 major tributaries, of which tributary Inn, Drava, Sava, Tisza, and Morava are most important ones by volume.

![Danube tributaries mean annual flow & specific discharge](image)

Figure 3-12: The hydrological characteristics (mean annual flow & discharge per unit area) of various streams of Danube River. The alpine streams monitored at gauging stations (i.e. Hofkirchen, Passau, Wien) shows higher specific discharges compared to low land streams monitored at gauging stations (i.e. Tisza, Silistra, Ceatal Izmail). Source: (Klement T. et al., 2008).

![Danube tributaries mean monthly flows](image)

Figure 3-13: Mean monthly flow of various Danube tributaries. The contribution of Alpine tributaries is more than 25% in total mean annual flow and particularly in summer months its average contribution is around 40-45%, and may even reach to 80% in dry years like in the hot summer 2003. Source: (Klement T. et al., 2008)

The Sava River is the largest tributary by mean annual discharge volume (49.6 km$^3$) and second one in catchment area (95419 km$^2$), while River Inn is the third largest in volume (23.1 km$^3$), and seventh in size (26128 km$^2$). Figure 3-12 & Figure 3-13 shows the hydrological characteristics of various Danube tributaries. The upper Danube basin has high runoff rates per unit area due to the alpine tributaries, like the River Inn, while the regions of the middle and lower Danube have only small values...
The average annual specific discharge decreases from 25 to 30 l/s/km² in Alpine headwaters to 17.9 l/s/km² for the Sava, 6.03 l/s/km² for the Tisza and 3.8 l/s/km² for the rivers draining the eastern slopes of the Carpathians (Belz et al., 2004). Figure 3-13 demonstrates that the significant contribution in summer runoff comes from alpine tributaries (i.e. Inn), due to snow and ice melt in the season. The Austrian part of Danube basin lies mostly within the Alps and contributes about one-fifth to the total basin runoff with an average of 1448 m³/s (ICPDR, 2004).

Figure 3-14: The linear trends of mean seasonal flow series of Danube River at high alpine gauging station Achleiten over period (1900-2008). The linear trends indicate significant shift in seasonality: substantial increase in winter and decrease in summer. Station flow data was provided by GRDC, Germany.

Overall, the Danube flow regime is strongly influenced by various water infrastructures and intensive water use. There is some evidence for climate induced change in annual river flow series, as well as in the seasonality of flow during the 20th century. However, anthropogenic interventions in the catchment, such as groundwater abstraction, irrigation, river regulation, land use changes and urbanization, have considerably altered river flow regimes in large parts of the basin, confounding climate change detection studies. The analyses of monthly flow series of alpine station (Achleiten) indicates that the mean annual flow has slightly increased. The major impact has been observed over seasonal flows. The linear trends of mentioned alpine station clearly indicates that increases occurred mainly in winter and autumn probably caused by a general temperature increase during recent decades in combination with increased winter precipitation, while the major decrease is observed in summer (Figure 3-14). These seasonal trends indicate the glimpse of future scenario, when the water availability in summer might severely be reduced and also highlights the significance of Alps; like in summer draught 2003, the Alps partially compensated the water deficit through increased glacial melt in Alps. That was the most severe draught, with one of the lowest water level observed in summer over the century.

### 3.2.5.2 Rhine flows

The River Rhine is a major and most prominent cultural and commercial belt of central Europe (Belz, 2007; IKSR, 2005). The river originates in the Swiss Alps and flows around 1250 km through Northwest to the North Sea. The drainage basin occupies about 185260 km² with an average discharge of about 2300 m³/s, which makes the
Rhine 9th largest among Eurasian rivers. The basin ropes in overall nine national territories; of which, Germany, Switzerland, France and the Netherlands comprises more than 80% and the rest of the basin is spread over part of Belgium, Luxembourg, Austria, Lichtenstein and Italy. Figure 3-15 gives a geographic overview of the Rhine River basin along with its two gauging stations at up & downstream region.

![Geographical map of Rhine basin with its river from source to sea with both up & downstream gauge stations (Basel-Schifflaende and Rees).](image)

The main tributaries of the Rhine are the Aare (18000 km²), Neckar (14000 km²), Main (27000 km²), and Moselle (28000 km²). The drainage basin houses around 50-58 million people within its boundary. The basin altitude ranges from few meters at its deltaic region in the Netherlands to more than 4000 m a.s.l at its source in Swiss Alps. The mean altitude is about 472 m a.s.l. The basin comprises of three major hydrological areas; Swiss Alps, German Middle Mountain and Lowland. Based on these divisions, each area has typical climatological characteristics. The Alpine region shows a large spatio-temporal variation with altitude and local topography. The mean annual temperature of basin is about 8.3°C. It varies from 11°C in Valleys and low land areas to less than 0 °C at elevations >3000 m a.s.l. The average annual precipitation is about 945 mm. The upland receives high precipitation sums than low land region (Grabs et al., 1997; Hendl, 1995; Schwarb et al., 2001). Mountain regions exceeding 3000 m a.s.l typically have snow or ice covered summits.

The Rhine flow regime (Figure 3-16) is mainly dominated by combined snowmelt and precipitation runoff from Alpine region in summer, and precipitation from middle and lowland regions in winter (Belz, 2007). The snowmelt runoff in summer and precipitation runoff in winter complements each other in annual stream flow pulse, thus two peaks are observed in the annual hydrograph. However, high discharges are still observed during summer (Hirschfeld, 2003; Kempe and Krahe, 2005). The
glacial contribution in summer is very low due to very low percentage of glacier area (427 km$^2$) in Rhine basin. The alpine part, which constitutes only 15% of the total catchment area, contributes on average 34% of the total Rhine discharge. The alpine tributary Aare clearly dominates the total runoff in summer months. During the summer months, when the melting of snow and ice produces high and reliable discharge volumes, this discharge surpasses 50% (Viviroli and Weingartner, 2004a; Viviroli and Weingartner, 2004b). Not only this, the good quality of alpine water makes it a very precious supply source for domestic consumption throughout its course (IKSR, 2005; Viviroli and Weingartner, 2004a). With distance from the Alps, monthly hydrographs display increasingly stochastic variation that reflects the influence of the Oceanic climate and a less predictable rain-dominated precipitation. The importance of alpine contribution can further be seen in (Figure 3-17), where specific discharge of main tributaries declines from 34 l/s/ km$^2$ in the Alpine catchments of the Rhine (Aare), to 14 l/s/ km$^2$ in the Neckar catchment and less than 10 l/s/ km$^2$ in the Moselle catchment. Hence Alps, despite little glacier coverage, still dominate total summer flows. However, due to shift in climatic conditions (e.g. wet-warm winters and dry-warm summers) observed in last few decades, the hydrology of the Rhine basin may also affected.

![Rhine tributaries mean monthly flows](image)

Figure 3-16: Mean monthly flow of various Rhine tributaries. The contribution of Alpine tributaries is more than 33% in total mean annual flow and particularly in summer months its average contribution is over 50-55%. Source: (Klement T. et al., 2008).
Figure 3-17: The hydrological characteristics (mean annual flow & discharge per unit area) of various streams of Rhine River. The alpine streams (i.e. Aare) shows higher specific discharge compared to middle & low land streams (i.e. Neckar, Main). Source: (Klement T. et al., 2008).

Figure 3-18: The linear trends of mean seasonal flow series of Rhine River at high alpine gauging station (Basel) over period (1869-2001). The linear trends indicate significant shift in seasonality: substantial increase in winter, spring, autumn and decrease in summer. Station flow data was provided by GRDC, Germany.

In the southern region (Alpine part), where nivo-glacial regime dominates, the decrease in summer precipitation led to lower high-flow conditions in summer and higher low-flow conditions in winter, while in northern part, where pluvial regime dominates, higher low-flow conditions strengthened (Belz, 2007). The low-flow conditions in summer/autumn in middle Rhine is also slightly increased (BMVBS, 2007). In general, the total flow in Rhine River remains unaffected. The analyses of monthly flow series of alpine station (Basel) shows that the annual flow regime is slightly increased due to climate change. However it affects seasonal patterns (Figure 3-18). The linear trends of alpine station (Basel) clearly indicates the increased flows in winter, spring
and autumn due to increased temperature and precipitation rates in last few decades and significant decrease in summer flows as same observed in precipitation rates. If the warming trend continues in future, these effects will increase further in intensity.

3.2.5.3 Rhone flows

The Rhone is a major Western European river, which ranks as 48th largest by its average annual flow rate (1720 m³/s) and 16th by the wealth of specific volume (23.47 l/s km²) in the world’s river list. The river originates as an effluent of the Rhone glacier in Swiss Alps, at an altitude of approximately 2150 m a.s.l and flows west through Lake Geneva in Switzerland and then south-westward into France. It travels 260 km from its source to the Swiss border and then around 550 km through France before emptying in the Gulf of Lion, an arm of the Mediterranean Sea. The basin occupies about 98 000 km², out of which 8000 km² is in Switzerland and remaining all in France. Figure 3-19 shows a geographical view of the basin. The basin is surrounded by foothills of four major mountain ranges: the Alps with maximum height of (4807 m), the Jura (1718 m), the Cevennes (1699 m), and the Vosges (1424 m).

Figure 3-19: Geographical map of Rhone basin with its river from source to sea with both up & downstream gauge stations, Chancy (upland) and Beaucaire (mouth station).

Due to its geographical location and local topography, the basin is characterized by a variety of climatic conditions e.g. Atlantic, Mediterranean, and Continental. The diversity of climatic conditions brings contrasting temperature and precipitation regime. The precipitation regime varies over 2000 mm in the mountainous ranges to 500 mm at the edge of the Mediterranean Sea. The snowfall, which represents the major annual signal for discharge (Beniston, 2000) varies from 1500 mm/year (the Alps) to 600 mm/year (Jura) and 100 mm/year in the Cevennes and Vosges ranges. The Rhone comprises many small and large tributaries, out of which some major tributaries are; the Ain (123 m³/s), the Saone (410 m³/s), the Isere (350 m³/s), Durance
(188 m³/s), Doubs (176 m³/s) and Ardeche (65 m³/s). Each one shows different hydrological characteristics (Figure 3-20). The alpine part, which constitutes about 24% of the basin area, contributes about 40% of the total flow. This contribution is significantly increased in the summer season, when it jumps to more than 80%. The supply contribution from mountains is almost 1.8 times higher than if just the catchment size considered (Weingartner et al., 2007).

This can be seen in Figure 3-20, where alpine tributaries (i.e. Isere, Ain) produce high annual specific discharge (more than 30 l/s per km²) compared to middle & lowland tributaries i.e. Saone, Rhone (more than 12 l/s per km²) in the basin. The Isere and Ain, draining from the Alps, have a marked late spring-early summer peaks caused by the melting of snow and ice. The Ardeche is located in the south and produces heavy flash floods in spring and autumn due to heavy rainfall in these seasons. The Saone is the largest tributary of Rhone River and receives significant rainfall in winter, thus the largest flow contribution comes in winter. The Durance is a high altitude tributary, which receives heavy snowfall in winter and contributes significant flow in spring due to snowmelt. Overall, the flow regimes varies from glacio-nival influence at altitude to oceanic regime during the winter high waters north of the basin and a Mediterranean regime during the spring and autumn high waters in the southern portion. Historically, low waters occur in the Rhone’s alpine region in winter and in the Mediterranean region in summer (Habets et al., 1999). Typically, heavy rain events and snowmelt build up floods in spring and autumn.

![Figure 3-20: The hydrological characteristics (mean annual flow & discharge per unit area) of various streams of the Rhone River. The alpine streams (i.e. Ain) show higher specific discharge is compared to middle & low land streams (i.e. Saone, Rhone). Source: (Klement T. et al., 2008).]
Figure 3-21: The linear trends of mean seasonal flow series of Rhone River at upland gauging station (Chancy) over period (1904-2002). The linear trends indicate significant shift in seasonality: substantial increase in winter, autumn and decrease in spring, summer. Station flow data was provided by GRDC, Germany.

Due to warming trends over the past century, the basin average precipitation regime is changed significantly: increased in winter and decreased in summer. The flow regime is also affected the same way. The analyses of monthly flow series of alpine station (Chancy) shows that, due to the climate change, seasonal flow patterns have drastically altered (Figure 3-21): increasing in winter and decreasing in summer. The warmer winter temperatures and hot summers, coupled with seasonal precipitation shifts (more rainfall in winter and less in summer) may result in very distinct flow regimes in coming decades and even may resemble the 2003 hot summer conditions at the end of current century.

3.2.5.4 Po flows

The Po River is the largest Italian river with its length of 657 km and a catchment area of approximately 74,000 km². The catchment covers 24% of the total land of Italy. The major part of the basin (around 95%) lies in northern part of Italy, while the remaining 5% are stretched in Switzerland and France. The basin is surrounded by the foothills of Southern Alps in North-West and Northern Apennine Mountains in South. The river originates at an altitude of 2000 m a.s.l at Monviso Mountain in the Piedmont region near the French border and flows down Easterly into the Adriatic Sea. It houses about 16 million people within its boundaries. Geographically the basin can be divided in three parts: the Alps, the Apennines, and the Po valley. Figure 3-22 gives a geographic overview of the Po River basin. The basin comprises a number of natural lakes and artificial reservoirs, which makes the upper part a hub of hydropower plants and the valleys centres of commercial and agricultural activities.
The Basin experiences a complex weather system; the alpine climate in the mountain zone in North, continental-warm in the plain area and Mediterranean on the coast in South. The mean annual temperature of the basin is around 14°C, with a typical mean value of 3°C for winter and 25°C for summer. The mean annual temperature varies as a combination of topography and complex external weather system e.g. around 5°C on high Alps to 5-10°C in medium mountains and 10-15°C in plain areas. The precipitation also shows a large spatio-temporal variation with altitude and local topography. The Alpine range receives more than 2000 mm per year while Western Mountain including plain areas receives less than 900 mm per year. The average annual precipitation value is about 1200 mm. In winter, most of the precipitation over mountainous areas falls as snow. In spring, the melt water from the Alps and rainfall from Appenines range produce high stream flows. The Mediterranean warm climate results in large volumes of precipitation in autumn and spring, which even sometimes results in flooding conditions in both seasons. Thus the Po river experiences two peaks per year in late fall and spring (Figure 3-23). The average annual flow rate of Po River is about 1536 m³/s. On average, the contribution from Alps is about 53% to the total Po discharge and even increased to 80% in dry summer months (Viviroli and Weingartner, 2004). Figure 3-24 shows the mean annual hydrological characteristics of various tributaries of Po River. The specific discharge of alpine tributaries (e.g. Trebbia) is much higher (35 l/s.km²) than other tributaries (e.g. Oglio). The disproportional influence of mountain part is almost 1.5 times higher than if just the catchment size considered.
Since the last few decades, climate change has severely influenced the basin hydrology. The minimum temperature in the winter is increased by 0.4°C and maximum temperature in summer is increased by 0.6°C. The basin precipitation is also decreased by 20% of the annual value and by 35% for the months from January to August. The similar trends can be found in the Po river discharge; with 20% decrease in annual figure and a 40% dip in summer flows (Tibaldi et al., 2007). The reduced water availability worsens scarcity problems due to strategic storage in the upper areas (hub of many lakes and reservoirs), that may risk hydropower production during summer.
3.2.6 CONCLUSION

- The Alps are particularly sensitive to climate change and already experiencing higher increases in temperature than the European and/or global average. The temperature change in European Alps is approximately 3 times higher than the global average. Precipitation patterns observed during past century shows mixed signals: increasing during winter months and decreasing during summer months. Regional differences are also observed, particularly between NW and SE part of Alps.

- Snow cover is clearly declining at all elevations and melts much earlier. Glaciers are vanishing at faster rate than before (since 1850 to 2000, glaciers have lost more than 2/3 of their volume)

- All climate models show consistent warming trends by the end of the 21st century: temperature in winter may increase by 4 to 6°C and summers by 3 to 5°C. The climate models are also predicting change in the precipitation regime, increasing about 20-30% in winter and decreasing about 30-40% in summer.

- If current trends of warming (e.g. change in temperature & precipitation) continue, the current regions of snow precipitation will experience precipitation in the form of rain, the duration of snow cover will decrease by several weeks for each °C of temperature increase, the snowline is projected to shift 150 m/°C upward direction (at lower elevations by more than this average), the small glaciers will disappear, and larger glaciers will suffer a huge volume reduction till the end of the current century.

- Due to the observed changes in the Alpine temperature & precipitation during the past century, the Alpine flow regime is also altered: increased in winter and decreased in summer. The trend is projected to be intensified under enhanced climate change during the 21st century. The average flow of alpine rivers will increase in winter and significantly decrease in summer. The typical low flow period during winter will shift to a low flow period during late summer and autumn.
4 HYDROLOGICAL MODELLING AND MODEL DEVELOPMENT

4.1 OVERVIEW OF HYDROLOGICAL MODELLING

The hydrological modelling concept is entrenched in the interrelationships of soil, water, climate and land-use and represented through hydrological processes involved by means of mathematical abstractions. The predominant hydrologic processes involved in this interrelationship include rainfall, snowmelt, interception, evapotranspiration, in-filtration, surface runoff, percolation and subsurface flow. The utmost challenge in hydrological modelling is the variability of the parameters in space and time controlling these processes (Porter and McMahon, 1971). Traditionally, this has been dealt by assuming uniform properties for the hydrological processes over the entire catchment areas (Moore et al., 1993a). With the emergence of remote sensing techniques as potential sources of data of the hydrological processes and the improved capabilities of generating and processing DEM data, GIS techniques have acquired a crucial position in hydrological modelling (Ashour, 2000). Since last few decades, due to introduction of these techniques, the role of hydrological models completely shifted from generating simple streamflow hydrographs to simulating the effects of land use changes or climate changes on water resources. This has been become possible due to better description of the catchment topography and the distributed properties of the hydrological processes acting on it (Abott et al., 1986; Moore et al., 1993a; Ashour, 2000). Today a wide variety of hydrological models developed over past century are successfully being used around the world. Singh (1995) provides a comprehensive overview of the most popular ones. All these models can be classified as either black-box models, deterministic models or conceptual models. Still, this classification cannot be strictly applied since there is substantial overlap between various classes of models. As, the focus of this study is revolving around the hydrological analyses of mountainous catchments, therefore the discussion about hydrological models is limited to the category of conceptual models only, as this category of models are widely used nowadays in mountain catchment analyses. The conceptual models act as a trade-off between the deterministic approach and black box approach. These types of models are formulated by a number of conceptual elements; each element is a simplified representation of one process of the system being modelled. The model can be characterized into event models and continuous models. Event models represent only single events occurring over a period of time ranging from an hour or less to several days. For example, how a basin responds to an individual rainfall event (e.g., quantity of surface runoff, peak, timing of the peak etc.). On the contrary, continuous modelling synthesizes hydrologic processes and phenomena (i.e., synthetic responses of the basin to a number of rain events and their cumulative effects) over a longer time period that includes both wet and dry conditions. The functioning of the model is controlled by the parameters of various processes. Thus, assigning proper values to these parameters is vital for getting accurate model results. Based on the parameters representation, conceptual models are further categorized into lumped models, distributed models, and semi-distributed models (Juraj M, 2003).

4.1.1 LUMPED MODELS

The lumped models are the one, which explicitly don’t account for the spatial variability of catchment characteristics. Instead, the response is evaluated with average values of watershed characteristics i.e. vegetation, soils, geology or topography at the
catchment outlet. Thus, results produced by these models exhibits only the averaged watershed conditions. These models are based on the continuity equation, through which water balance is calculated. These models are widely used for generation of missing data; extension of historic flow records, production of synthetic data for water resource assessment etc. These models, with varying complexity ranges from the Stream flow Synthesis and Reservoir Regulation Model (Rockwood 1958; Anderson 1967) to the Stanford Watershed model (Crawford and Linsley, 1966), the Simple Lumped Reservoir Parametric (SLURP) model (Kite, 1978), HBV model (Bergström, 1995), LARSIM model (Bremicker, 2000) and many other examples are available in literature. The in-depth analysis by Franchini and Pacciani (1991) highlights some limitations of the lumped parametric models as given below:

- To represent the various hydrological processes, the lumped models explicitly utilizes the average values of watershed characteristics, thus the model compromises the spatial heterogeneity of the watershed. By averaging the value of various parameters means averaging the whole process. Therefore, due to the non-linearity and threshold values, this can lead to significant errors which in turn affect simulation accuracy.

- Any bias in the available data on which model is calibrated is transferred to the set of optimized parameters values. This confines the model applicability in other catchments.

- The data required for reliable calibration is often not available. Hence, lumped models are not suitable for un-gauged catchments.

4.1.2 DISTRIBUTED MODELS

Contrary to lumped models, distributed models account for spatial variability of catchment characteristics. The spatial variability is accounted by discretising the catchment into a number of hydrologically similar zones. This could be done by the Hydrological Response Unit (HRU) or Grouped Response Unit (GRU) concept. This is normally done on the basis of uniform topography, vegetative cover, soil type, and climatology of basin etc. The hydrological processes i.e. snowmelt, infiltration, surface/subsurface flow processes are modelled separately for each similar unit and then the output from each unit/zone is routed from one zone to another to attain the entire catchment yield. These types of models are widely used for analysing the effect of spatially variable inputs and outputs and effect of climate change or land-use patterns on catchment hydrology. The applicability may vary from model to model depending on the processes included in the developed models i.e. infiltration, surface/subsurface flow processes, snowmelt/accumulation processes. The distributed models that are widely cited in literature are: The Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) model (Beasley et. al., 1980); Systeme Hydrologique European (SHE) model (Abbott et al. (1986a, b); Kinematic Run-off and Erosion (KINEROS) model (Woolhiser et. al., 1990); The University of British Columbia (UBC) model (Quick, 1995) etc. Regardless of their suitability for certain purposes, these models are also prone to a number of limitations as discussed in recent publications like:

- The large quantity of input data and huge computational power required to run the models often renders them inefficient for everyday operational hydrology.
• The information (data) required about physical characteristics of the watershed is often too limited to assess the model parameters at desired scale (Loague and Freeze, 1985).

• The limited understanding of runoff generation processes at catchment scale also inhibits to develop truly physical base models.

4.1.3 SEMI-DISTRIBUTED MODELS

To offset the limitations of both approaches mentioned, the semi-distributed model approach is the best trade-off (Williams et. al., 1985; Arnolds et. al., 1993). The model approach is based on distribution functions, which allows parameters to partially vary in space by dividing the basin into a number of zones and finally provide correct approximation of spatial variability of system state at catchment scale. There are two main types of semi-distributed models: the probability distributed models (i.e. TOPMODEL) and kinematic wave theory models (i.e. HEC-HMS), which are based on surface/subsurface flow equations of physically based hydrologic models (Beven, 2000). The spatial heterogeneity of input parameters is represented by means of observable physical characteristics such as land use, soils and topography etc. Today a number of semi-distributed models are widely cited in literature: TOPMODEL by Beven and Kirkby, (1979); the Chemicals-Runoff-Erosion from Agricultural Management Systems (CREAMS) model by Knisel (1980); the Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) model by Leonard et al., (1987); Hydrological Model Application System (HYMAS) by Hughes and Sami (1994); the Soil Water Assessment Tool (SWAT) by Arnold et al., (1998) and PREVAH by (Viviroli et al., 2009) etc. Nowadays, the semi-distributed models are the ones that are widely being used in mountainous catchments. However, the selection of a specific model has always been a tricky job. The wide ranging application of the PREVAH model highlights that the model is a very flexible and robust tool to simulate a complete hydrological cycle at catchment scale. The process of configuring a PREVAH model for a given catchment has also been greatly facilitated by the development of a GIS-based inter-face with a number of pre & post-processing tools, which provide straightforward means of translating meteorological data, digital land use, topographic, and soil data into model inputs. The built-in option to simulate the climate change impact has also improved the usability of the model. The description of the model is given separately in the next section.

4.2 MODEL SELECTION CRITERIA

There are several criterions that can be employed to select the right and proper hydrologic model. The decisive factors in choosing the right model are mainly project-dependent, as every project has its certain prerequisites. Additionally, it also depends on the person’s choice, mostly based on expertise and familiarity. However, there are some basic criteria that must be satisfied at all the times (Juraj M, 2003); like:

• Is the model capable of simulating all the hydrologic processes that need to be modelled to calculate the desired outputs adequately?

• Does the model simulate the desired variables such as low flows, peak flows, long-term sequence of flows, etc.?

• Is the model flexible enough to be developed with a minimum set of input parameters?
• Is the price of the model (software) and data required comes within the project budget?

4.3 REASONS FOR SELECTING PREVAH MODEL SYSTEM

The reasons to choose the PREVAH model for this study are;

• The model was successfully applied in numerous mountainous catchments for climate change impact studies in a number of countries (Zappa et al., 2003; Verbunt et al., 2006; Wöhling et al., 2006; Vanham et al., 2008; 2009 and Laghari et al., 2012).

• The model simulates all the major hydrological process in mountainous catchments (i.e. snow accumulation, snowmelt, snow cover days, glacier melt, evapotranspiration, baseflow, interflow, surface flow);

• Due to its semi-distributed nature, its structure is more physically-based and thus, it is less demanding on input data than fully distributed model.

• It can work with a minimum number of input parameters i.e. precipitation and temperature (depends on the choice of evapotranspiration scheme)

• The model can be developed within reasonable time (depends on required task) with average expertise

• Free and easy availability of the model

4.4 DESCRIPTION OF PREVAH MODEL

PREVAH (Precipitation- Runoff- Evapotranspiration HRU related Model) is a semi-distributed hydrological model originally developed to increase the insight of the spatial and temporal variability of hydrological processes in mountainous catchments. It serves as a complete hydrological modelling system, consisting of a number of software programs for various pre & post processing tasks, running the model and interpreting results. The system provides a well-structured framework to explore the relationships between climate and catchment hydrology. The hydrological system is composed of several sub-modules. Figure 4-1 shows the different sub-modules with relevant inputs and outputs including the sequence in which the modules are processed in the PREVAH model core. The PREVAH model uses physically-based algorithms for the majority of process descriptions. However, the formulation of the relevant processes is simplified and some algorithms are related to more conceptual approaches. Besides sub-models for interception, soil water storage and depletion by evapotranspiration, runoff and baseflow generation, as well as for discharge concentration and flood-routing, PREVAH also incorporates modules written specifically with a view to representation of hydrological processes in mountainous areas, i.e. for snow accumulation and snowmelt as well as for glacial melt (Viviroli et al. 2009). Two types of external input data are required: (1) physiographical information for the HRUs, and (2) meteorological input. More specifically, the following data are required: a digital elevation model (DEM), a land-use map, a soil map, precipitation and temperature data and river discharge data for calibration of the model. For the meteorological data, different interpolation methods are available in PREVAH (Viviroli et al. 2009): elevation-dependent regression (EDR), inverse distance weighting (IDW), kriging (KRG) and a simple elevation lapse rate (LPR, only for temperature data).
It is possible to combine EDR with kriging or IDW, resulting in a detrended interpolation. Extensive meteorological input (relative humidity or water vapour pressure, global radiation, wind speed and sunshine duration) data are required to calculate evapotranspiration according to the Penman-Monteith approach (Monteith 1975). However, this is not a limitation, since simpler evapotranspiration formulae are also available in the model and allow for application in regions where meteorological observations are scarce. Snow cover duration is not required as input for the model; however, it can function as verification for snow cover simulated by the snow module of the model. The PREVAH is always forced with internal time-steps of one hour, which is also the minimum temporary resolution. However, high resolution multiples are allowed for input and output. The PREVAH system contains an automatic calibration tool integrated of interactive global search algorithms. The manual calibration option is also available, which can be utilized through a control file containing the configuration of PREVAH’s tuneable model parameters. The control file run all the submodels and contains complete details about model settings and hydrological response units (HRUs). PREVAH also contains built-in dialog option for application of ‘delta change method’ (Hay et al., 2000). The delta approach alters meteorological series to assess the impact of climate change scenarios over catchment hydrology (Gurtz et al., 2005).
4.5 PREVAH CALIBRATION SCHEME

Calibration is the standard procedure used to compare the model results to field observations and, if required, to fine-tune parameters representing the system until model performance realistically harmonizes with measured system performance. In hydrological systems, this means the conformity between observed and simulated hydrographs. This could be achieved by choosing suitable values of hydrological parameters depending upon the prevailing conditions in a particular catchment. This is usually referred to as model calibration and is a fundamental practice in the application of hydrological models. Nowadays in hydrological modelling, two calibration approaches are widely being adopted; the manual and automatic calibration. The manual calibration is very complicated and time consuming and requires very trained and experienced users (Botterweg, 1995; Madsen et al., 2002), thus automatic calibration is widely being adopted in modelling exercises. In the beginning, local search iterative strategies used to locally improve an initial guess of parameter values. This was done either by direct search method like downhill simplex algorithms (Nelder and Mead, 1965), pattern search algorithms (Hooke and Jeeves, 1961), rotating direction algorithms (Rosenbrock, 1960) or by gradient search, e.g. the Gauss–Marquardt–Levenberg algorithm (Doherty, 2002). But these local search strategies failed to provide any reliable approximation of global optimum. Thanks to the availability of powerful computers and development of a variety of global search procedures; the problem of global optima has been solved to a great extent. The most popular algorithms are adaptive random sampling (Masri et al., 1980); simulated annealing (Aarts and Korst, 1989); controlled random search (Price, 1987) and the genetic algorithm (Goldberg, 1989). Soon after, through the combination of local and global approaches, a new algorithm called the shuffled complex evolution (SCE-UA) algorithm was developed (Duan et al., 1992). These algorithms consider the whole feasible parameter space and iteratively advance toward the regions exhibiting promising results. PREVAH’s automatic objective calibration procedure also employs a straightforward interactive global search algorithm (see Zappa and Kan, 2007; Viviroli et al, 2007). It simply depends on a straightforward reduction of a two-dimensional parameter space (Sonderegger, 2004). The procedure starts with first two parameters paired for calibration with user assigned maximum and minimum values, which defines a two dimensional parameter space. The procedure is represented in Figure 4-2.

Figure 4-2: The straightforward reduction of a chain of two-dimensional parameter spaces. Usually a group of 7 to 9 pairs of tuneable parameters are analysed (source: Viviroli et al., 2007).
The calibration scheme first divides the entire parameter space into nine sections and model runs for each of the four resulting intersection points. In this way, the point with best model performance (based on objective index ranging between zero and one) with four adjoining sections is retained and the remaining five sections are discarded. The objective index is a weighted expression of 9 scores. The process continues till the possible best results e.g. improvement above certain threshold, is achieved or the number of maximum iterations are reached. Once the process is completed for the first pair, the model uses the two calibrated parameter values and starts the new cycle for other paired parameters with defined parameter space. This way the total model run results also provide some indications on parameter sensitivity and related uncertainty (Pappenberger and Beven, 2006). In the PREVAH model calibration scheme, parameters are always treated pair-wise, not at once; therefore, to allow all parameters to adjust with each other, multiple sequential runs of the parameter search algorithms are recommended. The methodology is very simple, transparent, efficient and particularly good for calibration of a large number of catchments by a single user (Viviroli, 2007). The PREVAH model potentially requires plenty of model parameters to be specified during the model setup. Most of these parameters are derived from maps of topography, soil types, and land use, etc. Thus the variation in spatial pattern of parameter values are achieved through defining the parameter classes of above available data base. The number of other parameters to be calibrated mostly depend on module specifications e.g. evapotranspiration scheme or presence of glaciers within the investigated area. They typically range between 14 and 19. The parameters with common sensitivities from similar processes are first paired and later pair groupings proceeded with the model structure, from input treatment to melt processes over to runoff components. Table 4.1 shows the PREVAH’s highly recommended sequential grouping of most sensitive parameters.

Table 4.1: Recommended sequential parameter pairs with most common sensitivity for automatic calibration of PREVAH (Viviroli et al, 2007).

<table>
<thead>
<tr>
<th>Pair</th>
<th>Parameter 1</th>
<th>Parameter 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rain correction (%)</td>
<td>Snow correction (%)</td>
</tr>
<tr>
<td>2</td>
<td>Threshold Temperature Rain- Snow [°C]</td>
<td>Transition Temperature Rain-Snow [°C]</td>
</tr>
<tr>
<td>3</td>
<td>Maximum degree day factor [mm d⁻¹ K⁻¹]</td>
<td>Minimum degree day factor [mm d⁻¹ K⁻¹]</td>
</tr>
<tr>
<td>4</td>
<td>Refreezing factor [mm d⁻¹ K⁻¹]</td>
<td>Threshold temperature snowmelt [°C]</td>
</tr>
<tr>
<td>5</td>
<td>Exponent for soil moisture recharge</td>
<td>Percolation [mm h⁻¹]</td>
</tr>
<tr>
<td>6</td>
<td>Threshold storage for surface runoff [mm]</td>
<td>Storage coefficient for surface runoff [h]</td>
</tr>
<tr>
<td>7</td>
<td>Storage coefficient for interflow [h]</td>
<td>Percolation [mm h⁻¹]</td>
</tr>
<tr>
<td>8</td>
<td>Storage coefficient for fast baseflow [h]</td>
<td>Maximum storage for fast baseflow [mm]</td>
</tr>
<tr>
<td>9</td>
<td>Storage coefficient for delayed baseflow [h]</td>
<td>Percolation [mm h⁻¹]</td>
</tr>
</tbody>
</table>
According to the scheme, the tune-able parameters are broadly categorized into six major groups. Figure 4-3 illustrates the schematic scheme with broad categories including tune-able parameters from top to bottom. In this way the highly sensitive parameters are treated first and the entire process continues in a row till the end. The observed gauged data is used to compare and assess model efficiency with the help of an objective function. Generally objective functions are based on only single standard linear efficiency scores. However, this often results in loss of information (Wagener et al., 2001), thus many authors (e.g. Madsen, 2000; Seibert and McDonnell, 2002) recommend the application of multiple-objective functions.

Figure 4-3: Schematic of the PREVAH model structure with tune-able parameters, storage modules and hydrological fluxes (source: Viviroli et al., 2007).
The PREVAH’s calibration scheme is also based on combination of three standard efficiency scores i.e. Linear Nash efficiency (Nash and Sutcliffe, 1970), logarithmic Nash efficiency and volumetric deviation with three different temporal ranges i.e. full period, annual, and monthly. Thus, PREVAH’s total model efficiency is based on nine objective functions. The investigation by Viviroli (2007) reported that PREVAH’s calibration procedure results in very stable and representative values of parameters sets.

4.6 Objective Index

The PREVAH calibration performance is usually judged through an objective index scale based on weighted average of nine scores (Sonderegger, 2004; Verbunt et al., 2006). The nine scores are typically derived from three basic equations: the Nash and Sutcliffe efficiency (NSE) - Eq. 1, its logarithmic formulation \( \log(\text{NSE}) \) – Eq. 2 and the volume error (VOL) – Eq. 3.

\[
E = 1 - \frac{\sum_{i=1}^{n} \left( O_i - M_i \right)^2}{\sum_{i=1}^{n} \left( O_i - \left( \frac{1}{n} \sum_{i=1}^{n} O_i \right) \right)^2}
\]  
(Eq. 1)

Where \( M_i \) is the modelled (simulated) runoff at the time step \( i \), \( O_i \) is the observed runoff at the time step \( i \). \( n \) is the number of time steps. The linear efficiency score \( E \) (Nash and Sutcliffe 1970) determines the virtual improvement of the model compared with the mean of the observations. Any positive value corresponds to an improvement. \( E \) tends towards unity when \( M_i \) tends towards \( O_i \).

\[
\log( E ) = 1 - \frac{\sum_{i=1}^{n} \left( \log(O_i) - \log(M_i) \right)^2}{\sum_{i=1}^{n} \left( \log(O_i) - \left( \frac{1}{n} \sum_{i=1}^{n} \log(O_i) \right) \right)^2}
\]  
(Eq. 2)

The logarithmic efficiency score \( \log( E ) \) provides a useful signal on the model performance in low flow conditions e.g. winter periods (Gurtz et al. 2001).

\[
VOL = \left[ \sum_{i=1}^{n} \frac{M_i}{O_i} - 1 \right] \times 100
\]  
(Eq. 3)

The volume error (VOL) evaluates the quality of the model run with respect to the volumetric deviation between observed and modelled runoff in percent.

The first three scores are based on computing all three equations for full calibration periods. The remaining six scores, with each three are obtained by computing all above equations for yearly and monthly basis within entire calibration period. Figure 4-4 shows the composition of the total score from nine partial scores.
All computed nine scores are reduced to a dimensionless index ranging between zero and one. Finally the geometric mean of all nine indexes is combined as proposed in Seibert and McDonnell (2002).
4.7 PILOT STUDY AREA – KITZBÜHELER ACHE CATCHMENT

4.7.1 CATCHMENT DESCRIPTION

The study area Kitzbüheler Ache catchment is located in the North-eastern Alps in Austria. The catchment covers an area of about 323 km$^2$ and is characterized by a non-glacierized middle mountain range with altitudes ranging from 600 m to about 2400 m, with an average of 1291 m above sea level. The catchment location and topography with gauge flow station is shown in Figure 4-5.

Figure 4-5: Map of Alpine region including the location of Kitzbühle_Ache catchment, catchment boundary, topography, and gauging station at catchment outlet.
Due to its location, the influence of the Mediterranean Sea is minimal and the climate can be defined as continental. The long-term mean annual precipitation ranges from 1474 to 1784 mm with an average of 1555 mm. Mountain tops receive much more precipitation than Valley zones. Similarly, the mountain tops remain under snow cover for higher duration (5 to 7 months) than valley areas (2 to 4 months). Figure 4-6 shows the mean annual distribution of precipitation and snow cover duration in the study catchment. The mean annual runoff ranges from 790 to 1565 mm with an average of 1128 mm, while the average summer and winter runoff are respectively 132 and 392 mm. One-third of total annual precipitation evaporates, whereas, two-thirds are total runoff. Generally in mountain catchments, precipitation is much higher and evapotranspiration much lower due to the effect of temperature decrease with altitude. This results in a more effective runoff generation in the mountainous catchments as compared to in the lowlands. The hydrological regime of the selected catchment can be characterized with low flows in the winter caused by snow accumulation (ΔS in Figure 4-7 is positive) and high flows during snowmelt in spring or early summer.

Figure 4-6: The long term mean annual (1961-90) precipitation and snow cover distribution in Kitzbüheler Ache catchment.

Figure 4-7: Mean monthly water balance components (mm) for the period 1961–990 for the catchment of the Kitzbüheler Ache up to gauge “St Johann i.T”
Forest is by far the most important land use in the study area, encompassing almost 50% of the total area. Alpine meadows at higher elevations and pastures at lower elevations cover also large areas. Percentages of urbanized areas are small and constrained to the valleys. Bare rock can only be found at mountain tops. Figure 4-8 shows the hydrogeology and land use map of the study catchment.

![Hydrogeology and land use map](image)

**Legend**

**a) Hydrogeology map**

- Lime High Alps
- Lime Pre Alps
- Un glaciated Central Alps

- Aquifers in which flow is mainly granular
  - mainly gravel and sand
  - mainly gravel and sand, locally moraine

- Karstifiable aquifers
  - limestone
  - mainly carbonate rock
  - dolomite

- Aquifers (porous, fissured or karstified) with local and limited groundwater resources
  - mainly slate and sandstone
  - mainly phyllite and schist
  - mainly clay, marl and sand, locally gravel, sandstone and conglomerate
  - mainly marl and sand sandstone

**b) Land use map**

- Urbanized area
- Pastures and crops
- Bare rock and sparsely vegetated area
- Alpine meadows
- Forest

Figure 4-8: a) Hydrogeology and b) land use in the case study area. The hydro-geological dataset was obtained from the digital Hydrological Atlas of Austria. The land use dataset is the CORINE-dataset in a resolution of 250 m.
4.7.2 MODEL DEVELOPMENT

To study the projected climate change impacts on hydrological processes at catchment scale, the PREVAH model was developed and applied with the daily flow time series of the reference period 1961-1990 measured at the gauging station (St Johann i.T) located at the outlet of the Kitzbüheler Ache catchment. The meteorological and spatial data required for model development was acquired from different sources. The geodataset of measurement stations are provided by TIRIS. The daily temperature time series is retrieved from the ZAMG (www.zamg.ac.at), whereas, the daily time series of precipitation and gauge discharge is obtained from Hydrographical Service (Hydrographischer Dienst) of Austria. The spatial data, land use & soil geodatasets are retrieved from the data service webpage of the European Environment Agency (http://dataservice.eea.europa.eu/dataservice) and digital Hydrological Atlas of Austria (Peticzka and Kriz, 2003) respectively. The model was calibrated over the 1983-88 period and validated over the baseline period (1961-90). The water consumption in the catchment area is minimal. Thus, the measured gauge flow represents the natural flow and can therefore be used directly for model development. The simulation results are then compared to the observed hydrograph at gauge station (St Johann i.T) both graphically and statistically. Sensitive catchment parameters calibrated include parameters of the snowmelt module, storage coefficients which govern the process of runoff generation (surface runoff, interflow, delayed and fast baseflow) and the percolation rate. Figure 4-9 shows the graphic comparison between observed and simulated mean daily flow for the calibration period (1983-88). The volumetric deviation for the whole calibration period is about 4.7%, the linear (Elin) and logarithmic (Elog) Nash–Sutcliffe efficiencies are both 0.84. The values thus show good agreement between observed and simulated flows. The calibrated parameters given in Table 4-2 are then validated over the whole period of 1961 to 1990. Figure 4-10 shows graphical comparison between the observed and simulated mean daily hydrograph for the validation period (1961-90). For the validation period the volumetric deviation is about 6.4%, Elin is 0.80 and Elog is 0.83. Also the monthly variations given in Table 4-3 for both periods; calibration and validation period, the Elin and Elog values are high. Thus model simulates the seasonal hydrological behaviour also very well. The lowest values are in spring, during the period of snowmelt, and during summer (July-September), the period of typical heavy thunderstorms. But even the lowest values are above 75.
Table 4-2: Kitzbühl Ache catchment calibrated parameters within the PREVAH model. Default parameters values as from (Viviroli et al., 2007b).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model ID</th>
<th>Threshold value/default</th>
<th>Calibrated value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold temperature for rain/snow</td>
<td>$T_{GR}$</td>
<td>0</td>
<td>0.46</td>
<td>[°C]</td>
</tr>
<tr>
<td>Transition temperature for rain/snow</td>
<td>$T_{TRANS}$</td>
<td>0.75</td>
<td>1.22</td>
<td>[°C]</td>
</tr>
<tr>
<td>Threshold temperature snow-melt</td>
<td>$T_0$</td>
<td>0</td>
<td>0.7</td>
<td>[°C]</td>
</tr>
<tr>
<td>Min., Max. temperature-index melting factor</td>
<td>$T_{MF_{min}}$, $T_{MF_{max}}$</td>
<td>1, 2</td>
<td>0.53, 2.08</td>
<td>[mm d$^{-1}$, K]</td>
</tr>
<tr>
<td>Refreezing coefficient for snow</td>
<td>$C_{RFR}$</td>
<td>0.1</td>
<td>0.56</td>
<td>--</td>
</tr>
<tr>
<td>Radiation melt factor for snow</td>
<td>$RMF_{SNOW}$</td>
<td>0.0001</td>
<td>0.0003</td>
<td>[mm W$^{-1}$ m$^2$ K$^{-1}$ h$^{-1}$]</td>
</tr>
<tr>
<td>Translation time for snowmelt</td>
<td>$TRT_{SNOW}$</td>
<td>2</td>
<td>2</td>
<td>[h]</td>
</tr>
<tr>
<td>Storage coefficient for surface flow</td>
<td>$K_{OH}$</td>
<td>10</td>
<td>30</td>
<td>[h]</td>
</tr>
<tr>
<td>Storage coefficient for interflow</td>
<td>$K_{IH}$</td>
<td>75</td>
<td>147</td>
<td>[h]</td>
</tr>
<tr>
<td>Storage coefficient for fast base flow</td>
<td>$C_{G1H}$</td>
<td>750</td>
<td>992</td>
<td>[h]</td>
</tr>
<tr>
<td>Storage coeff.. for delayed base flow</td>
<td>$K_{2H}$</td>
<td>2500</td>
<td>3790</td>
<td>[h]</td>
</tr>
<tr>
<td>Percolation Rate</td>
<td>$C_{PERC}$</td>
<td>0.1</td>
<td>0.18</td>
<td>[mm h$^{-1}$]</td>
</tr>
</tbody>
</table>

Table 4-3: The mean monthly Elin and Elog values for calibration and validation period.

<table>
<thead>
<tr>
<th>Month</th>
<th>Calibration period (1983 - 88)</th>
<th>Validation period (1961 - 90)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lin (E)</td>
<td>Log (E)</td>
</tr>
<tr>
<td>Jan</td>
<td>0.89</td>
<td>0.91</td>
</tr>
<tr>
<td>Feb</td>
<td>0.96</td>
<td>0.92</td>
</tr>
<tr>
<td>Mar</td>
<td>0.81</td>
<td>0.77</td>
</tr>
<tr>
<td>Apr</td>
<td>0.84</td>
<td>0.83</td>
</tr>
<tr>
<td>May</td>
<td>0.88</td>
<td>0.93</td>
</tr>
<tr>
<td>Jun</td>
<td>0.85</td>
<td>0.87</td>
</tr>
<tr>
<td>Jul</td>
<td>0.76</td>
<td>0.79</td>
</tr>
<tr>
<td>Aug</td>
<td>0.82</td>
<td>0.77</td>
</tr>
<tr>
<td>Sep</td>
<td>0.79</td>
<td>0.78</td>
</tr>
<tr>
<td>Oct</td>
<td>0.84</td>
<td>0.79</td>
</tr>
<tr>
<td>Nov</td>
<td>0.90</td>
<td>0.87</td>
</tr>
<tr>
<td>Dec</td>
<td>0.80</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Additionally the significance of the model was tested by means of snow cover duration maps. Especially because snow accumulation and snowmelt is an important issue within this catchment, the hydrological model should be tested not only on discharge data but also on snow depth/cover. The simulated snow cover was compared with real time snow measurements obtained from different stations. For 12 stations in the valley and one at higher elevation (station Hahnenkamm) snow cover measurements were available. They were interpolated with the GRADGRID module (Buchner et al., 2004), through linear regression with altitude as well as weighting of the stations according to distance. Generally the Hahnenkamm station thus represents the snow cover at high elevations. This gives limitations within the realistic snow cover
presentation based on measurements, as differences in e.g. exposure (southern or northern slopes) are not accounted for. This is however a restriction typical to mountainous regions (also the Alps, although being the best documented mountain range in the world), as measurement stations at high altitudes are generally underrepresented. As snow depth measurements were not available for this study, the model was validated with snow cover duration maps. The snow cover comparison results are given in Figure 4-11 & Figure 4-12. Results prove that snow module produce very reliable results. The correlation between the observed and modelled snow cover masks is good. The developed model was then used to investigate the hydrological behaviour of the basin under a future warmed climate. The simulated model results are presented in chapter 5 and 6.

Figure 4-11: Comparisons of the average annual snow cover duration within the catchment for the period 1961-1990, with (left) the raster as registered at the 13 measurement stations and (right) the raster as modelled with PREVAH (Laghari et al., 2012). Interpolation of the measured snow cover was done through linear regression with altitude, by means of the interpolation algorithm GRADGRID (Bucher et al., 2004). Time series from 13 stations were used (of these 12 stations are located in the valleys and 1 on a higher elevation, i.e. station Hahnenkamm at an altitude of 1760m). Correlation between the measured and modelled snow cover duration geodata sets is very high (R²=0.97).
Figure 4-12: Comparisons of the measured and modelled average snow cover duration within the catchment for different winter periods (December to April) starting from the winter 1961-1962 up to the winter 1969-1970 (Laghari et al., 2012). For the measured snow cover, time series from 13 stations were used (of these 12 stations are located in the valleys and 1 on a higher elevation, i.e. station Hahnenkamm) and interpolated by means of GRADGRID (Bucher et al., 2004). The model gives generally very good results (high correlation values) except one in winter season 63-64 due to extreme dry winter.
4.8 Pilot study area – Hunza basin

4.8.1 Basin description

The Hunza tributary with a catchment area of about 13746 km$^2$ is located in Upper Indus Basin (UIB) within the central Karakorum ranges of Pakistan (Figure 4-13). It is an important tributary in the Indus River System. It is a high altitude basin with elevation ranges from 968 m to over 7500 m a.s.l. About one-third area lies above 5000 m a.s.l. The area distribution in the catchment is shown by the hypsometric curve in Figure 4-14, whereas, some key features of the basin are given in Table 4-4. Hundreds of peaks exceed 6000 m elevation. About 34% of the total basin area is perennial glacial ice field. There are hundreds of glaciers, but approximately the 15 largest ones - like the Hispar (521 km$^2$), Batura (336 km$^2$) and Khurdopin (205 km$^2$) - dominate the hydrological flow regime. Seasonal snow & ice melt is a large contributor in the total flow regime of Hunza River. In most of the winters, almost 80-85 percent of the area becomes snow covered and decreases to 34% in summer. The precipitation regime is heavily under clout of westerly weather disturbances and nearly all the precipitation deposited during the winter and spring months in the form of snow (Young and Hewitt, 1990). The monsoon rains have very little influence in this particular basin, as the high altitude southern ranges decreases the effect of the monsoon in the catchment area; therefore, the climatic records in Karakorum Range are different from the eastern Himalayas (Fowler and Archer, 2005a; Young and Hewitt, 1990). The maximum snow cover area exists in February and March and extends till the melting process starts in May and/ or June depending upon the prevailing climatic conditions over the basin. The flow regime is highly seasonal; with highest flows occurring between June and September, when ice and snowmelt on the mountains cause a combined peak discharge, while minimum flows occur during winter months, e.g., November to February, when the mean monthly flows are only about one-tenth of those in summer. Maurer et al. (2003) stated that the presence of snow in a catchment area strongly affects the moisture that is stored at the surface and available for runoff in summer. The summer runoff is highly correlated with the summer mean temperature in this high-altitude basin, mostly covered with permanent snow pack and glaciers (Archer, 2003). Thus, temperature controls the rate of glacier melt. Glaciers provide more water in warm years and less water in cool years. The Hunza River has a mean annual flow of 323 m3/sec (i.e. 742mm) gauged at Dainyor Bridge, according to the 40-year (1966–2008) flow record. Historically no meteorological station existed in the Hunza river basin, just few stations installed in last decade. Data from these stations are also not available so far for research purposes; therefore neighbouring Skardu and Bunji meteorological stations that are located at the outskirts of Hunza catchment boundary are used for this study. The annual catchment precipitation regime based on these stations data ranges between 200 to 250 mm while mean monthly temperature varies between (-20°C) in winters to (+25°C) in summers. The same data was used earlier by many authors for Hunza catchment studies (Akhtar et al., 2008, Archer et al., 2005). A similar precipitation regime is also published in the New Oxford Atlas for Pakistan (Khan, 2000). However, these precipitation records are not representative of the runoff at the outlet. As both stations (Skardu and Bunji) are located in valleys (below 2500m a.s.l), many authors (Hewitt, 2007; Winiger et al., 2005) reported that the valley values (precipitation) in the Hunza basin are not representative for high-elevated zones.
Figure 4-13: Map of greater Hindukush-Himalaya region including the location of Hunza basin, catchment boundary, topography, and gauging station at catchment outlet.
Figure 4-14: Hunza basin hypsometric curve with area distribution under each 500m elevation band.

Table 4-4: Study area characteristics- Hunza basin.

<table>
<thead>
<tr>
<th>River gauge station</th>
<th>Dainyor Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>35 56 N</td>
</tr>
<tr>
<td>Longitude</td>
<td>74 23 E</td>
</tr>
<tr>
<td>Elevation of gauge station</td>
<td>1450 m</td>
</tr>
<tr>
<td>Drainage area</td>
<td>13746 km²</td>
</tr>
<tr>
<td>Glacier area</td>
<td>4688 km²</td>
</tr>
<tr>
<td>Glacier area percentage</td>
<td>34%</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>4631</td>
</tr>
<tr>
<td>Area above 5000 m</td>
<td>32.5%</td>
</tr>
<tr>
<td>Meteorological station</td>
<td>Skardu, Bunji</td>
</tr>
</tbody>
</table>
Young and Hewitt (1990) reported that the most active hydrological zone in the Hunza basin lies above 5000 m a.s.l. where maximum snowfall and accumulation occurs. Hewitt (2005, 2007) further concluded that the area above 5000 m a.s.l. elevation receives 5 to 10 time’s higher precipitation. 90% of the total glaciated area lies above 5000 m a.s.l. The investigations by Winiger et al., 2005 reported that the middle and upper part of the catchment receives about 1000 to 2000 mm precipitation respectively, whereas in the lower elevations, the average annual precipitation is as low as 150-300mm. Thus, valleys receive less than one-fifth of total annual precipitation, while most of precipitation is deposited between middle and upper part of the basin. Through the combination of physical data, field work, satellite derived snow data, and statistical approaches; Winiger et al., 2005 estimated the total precipitation regime across different zones in Hunza basin (Figure 4-15). However, these estimates depend on the site and time of investigation, as well as on the method applied. To get
the truly representative precipitation regime of this high altitude basin, the two hypothetical stations at higher elevations (e.g. 3500 m and 5000 m) are generated in the catchment and the daily data from Skardu station is modified as per precipitation gradient developed by (Winiger et al., 2005) for both hypothetical stations. Figure 4-16 shows the average monthly distribution of temperature, precipitation (original & modified) and discharge of the watershed based on the 10 years measured data. The model was later developed with modified data.

4.8.2 MODEL DEVELOPMENT

To analyse the hydrological regime of the catchment, the PREVAH model was developed with spatial (topography, soil & land-use) and meteorological data of neighbouring stations (Skardu & Bunji) including data from two hypothetically generated stations. The spatial data (Soil & land-use map with resolution of 1 km and topographic data with resolution of 10 m) was provided by the Global Climate Change Study Centre (GCSC), Islamabad. These data sets are aggregated to a common raster resolution of 500 m. The topographical map is shown in Figure 4-13, while the soil and land use map are shown in Figure 4-17 & Figure 4-18 respectively. The meteorological data (precipitation, temperature) is provided by the Pakistan meteorological department, Karachi, whereas the gauge data (observed discharge) is provided by the Water & Power Development Authority (WAPDA), Lahore. The precipitation data for model input was interpolated using IDW technique, while temperature data was interpolated with detrended IDW as recommended in model manual (Viviroli, 2009). The total 6 year (1990-1995) series of daily precipitation, temperature, and discharge data are used for model calibration and validation purposes. The first 3 years (1990-1992) are used for model calibration, while the remaining 3 years (1993-1995) for model validation. The calibration process is performed with the built-in automatic calibration scheme for the global model parameters; while the spatial model parameters are to remain constant. The constant parameters are derived from digital topography, soil and land-use maps. Global model parameters are paired sequentially following the model process diagram. The initial parameter values are assigned according to the basin characteristics as recommended in the PREVAH model manual (Viviroli, 20099). The simulation results are then compared to the observed hydrograph at gauge station Dainyor-bridge both graphically and statistically. Figure 4-19 shows a graphical comparison between observed and simulated daily flow for calibration (1990-1992) period. The calibrated model parameters are shown in Table 4-5. For model validation, the same calibrated parameters are used to simulate the daily stream flow for the second part of the data, i.e. from 1993 to 1995. Figure 4-20 shows a graphical comparison between observed and simulated daily flow for validation period. The hydrograph of both calibration and validation periods show that the model reproduced low flows as well high flows very well. The model performance is satisfactory for both calibration and validation periods. The mean annual efficiency for the calibration and validation period is above 80%, while the measured and simulated mean annual stream flow difference amounts to less than 5%.
Figure 4-17: Soil texture of the Hunza catchment. The glacier and rocks are the dominating soil textures in the catchment.

Figure 4-18: Spatial land use distribution in the Hunza catchment (2000). The catchment consists of 4 different types of land cover: 34% is covered by glaciers, 46% bare land, 7% shrub land and 13% grassland and pasture including less than 1% agriculture areas.
Table 4-5: Hunza Catchment calibrated parameters within the PREVAH model. Default parameters values as from (Viviroli et al., 2007b).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model ID</th>
<th>Threshold value/default</th>
<th>Calibrated value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold temperature for rain/snow</td>
<td>$T_{GR}$</td>
<td>0</td>
<td>1.10</td>
<td>[°C]</td>
</tr>
<tr>
<td>Transition temperature for rain/snow</td>
<td>$T_{TRANS}$</td>
<td>0.75</td>
<td>1.30</td>
<td>[°C]</td>
</tr>
<tr>
<td>Threshold temperature snow-melt</td>
<td>$T_0$</td>
<td>0</td>
<td>2.1</td>
<td>[°C]</td>
</tr>
<tr>
<td>Min., Max. temperature-index melting factor</td>
<td>$T_{MF_{min}}$, $T_{MF_{max}}$</td>
<td>1, 2</td>
<td>0.85, 1.55</td>
<td>[mm d$^{-1}$ K$^{-1}$]</td>
</tr>
<tr>
<td>Temperature melt factor for ice</td>
<td>CICEMF</td>
<td></td>
<td>1.62</td>
<td>[mm d$^{-1}$ K$^{-1}$]</td>
</tr>
<tr>
<td>Storage coefficient for surface flow</td>
<td>$K_{0H}$</td>
<td>10</td>
<td>25</td>
<td>[h]</td>
</tr>
<tr>
<td>Storage coefficient for interflow</td>
<td>$K_{1H}$</td>
<td>75</td>
<td>133</td>
<td>[h]</td>
</tr>
<tr>
<td>Storage coefficient for fast base flow</td>
<td>$C_{G1H}$</td>
<td>750</td>
<td>720</td>
<td>[h]</td>
</tr>
<tr>
<td>Storage coeff. for delayed base flow</td>
<td>$K_{2H}$</td>
<td>2500</td>
<td>4628</td>
<td>[h]</td>
</tr>
<tr>
<td>Percolation Rate</td>
<td>$C_{PERC}$</td>
<td>0.1</td>
<td>0.16</td>
<td>[mm h$^{-1}$]</td>
</tr>
</tbody>
</table>

Figure 4-19: Graphical comparison between observed and modelled daily flow for Hunza catchment at outlet station (Dainyor Bridge) for calibration period (1990-92).
Additionally the model was tested by means of snow cover maps of different dates during depletion period April-July, 1991. Particularly due to significant snow accumulation and melt contribution (snow & ice) in total catchment discharge; the hydrological model should be tested not only on discharge data but also on snow depth/cover. The modelled snow cover maps are then compared with observed snow cover maps. The observed snow cover maps are taken from Winiger et al., (2005), and digitized & geo-referenced for comparison purposes. Results prove that snow and ice module produce very reliable results. The correlation between the observed and modelled snow cover maps is very good (R2 => 0.77).
Figure 4-21: Comparison of observed and modelled snow covered areas for Hunza catchment on different days during the depletion period April-July, 1991. The sky blue colour shows the snow free area in the catchment. The observed snow cover maps are taken from Winiger et al., 2005 and digitized for comparison purposes.

The model is then run for the full period. The simulated mean annual water balance components for whole period (1990-1995) are shown in Table 4-6. The change in water storage could be explained by an increase in glacier mass. The mass balance measurements are not available. Therefore the calculated change in glacier mass cannot be checked against measurements. However, the positive change in mass balance is in good agreement with the conclusion of earlier studies (Hewitt 2005, 2007; Fowler and Archer 2006), which indicated substantial glacier surges particularly in this Hunza basin.
Table 4-6: Mean simulated annual water balance of the Hunza basin for the period 1990-1995 (mm year-1).

<table>
<thead>
<tr>
<th>Water Balance Components</th>
<th>PREVAH Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed runoff (mm)</td>
<td>687</td>
</tr>
<tr>
<td>Simulated runoff (mm)</td>
<td>659</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
<td>1234</td>
</tr>
<tr>
<td>Evapotranspiration (mm)</td>
<td>148</td>
</tr>
<tr>
<td>E (Linear)</td>
<td>0.88</td>
</tr>
<tr>
<td>E (Log)</td>
<td>0.84</td>
</tr>
<tr>
<td>Volume deviation (mm)</td>
<td>-28</td>
</tr>
<tr>
<td>Storage change (mm)</td>
<td>+427</td>
</tr>
</tbody>
</table>

The calibrated model was then used to investigate the hydrological behaviour of the basin under projected climate change scenarios.
5 MODEL APPLICATION AND ANALYSES

This chapter is structured as summarizing results of four papers attached in appendix A. These papers are focused on the application of the developed model (PREVAH) for the analyses of climate change effect over mountain catchment hydrology & water resources in two selected sampling areas i.e. Kitzbühl Ache and Hunza catchment. The catchment hydrological components (processes) are considered very prone to climatic changes i.e. precipitation and temperature (Beniston, 2003). Therefore, the quantification of the effect of climate change on the hydrological water balance components within a catchment is very useful for future planning and management within the water sector. In this respect, the first two papers (A & B) analyse the projected climate change impacts on the hydrological processes in the Kitzbühl Ache catchment, whereas the other two on Hunza catchment. The detailed description of study areas together with model development (calibration & validation processes) are given in section 4.3 to 4.6 (chapter 4). The developed model was then applied to simulate the climate change effect over catchment hydrology in both catchments. The analysing results of both catchments are discussed below.

5.1 KITZBÜHL ACHE CATCHMENT

5.1.1 PAPER- A

This paper is focused on analyses of catchment hydrological components and related uncertainty bands. The analyses of the catchment hydrological components under influence of climate change effects are complicated by a range of uncertainties related to the unknown future evolution of climate-forcing agents (emissions) and the limitations of the global to regional climate models used to project possible regional climate future (Jasper et al., 2004). This means that a wide uncertainty band for the future evolution of the Alpine climate is a fact. As the regional effect of global warming is somewhat uncertain, the provision of quantitative estimates with error bands is essential for a future planning & management in the water sector. In this context, paper A investigates the various hydrological responses in Kitzbühl Ache catchment to a number of regional climate change model scenarios for the end of the 21st century by means of a distributed hydrological model PREVAH. The map of Kitzbühl Ache catchment is shown in Figure 4-1 (chapter 4). The catchment climate change scenarios used are derived from various RCM model simulations taken from the EU PRUDENCE project (Christensen and Christensen, 2007), representing the period 2071–2100 with respect to the baseline period 1961-1990. These scenarios are based on different SRES A2 and B2 emission scenarios and different AO-GCMs (HadAM3H and ECHAM4/OPYC3) models.

A description of SRES emission scenarios and listing of the different used combinations of SRES emission scenario/model/resolution can be found in section 2.2 & appendix-A (paper 1) respectively. The hydrological components analysed are: evapotranspiration (ETR), snowmelt and total runoff. Additionally the snow water equivalent (SWE) is also analysed. All climate scenario simulations produce the same tendency in changes in the hydrological regime of the catchment. The monthly changes analysed are shown in Figure 5-1 and Figure 5-2, while annual changes are shown in Figure 5-3. Regardless of different boundary conditions, emission scenarios and resolution (50km and 25km), all scenario simulations show a drastic reduction in
SWE. Although all regional model scenarios (but one) show an increased winter precipitation (about +5% to +25%) trend, the increase in winter temperature (about 2°C to 5.5°C) results in a massive reduction in snow storage. As the winter temperature in the study area often remains below the freezing point, therefore, much of precipitation shifts from snow to rainfall, resulting in a dramatic reduction in SWE, snow cover duration and snow melt. The average snow free period in the catchment changes from June to September for the reference period, to minimum May to October (RCAO_Had) and maximum March to November (RCAO_ECH) Figure 5-1 and Figure 5-2.

Figure 5-1: Comparison of the projected (2071-2100) SRES-A2-based scenario mean monthly snow water equivalent (SWE), snowmelt, actual evapotranspiration and runoff with their corresponding base period (1961-1990) values.
Figure 5-2: Comparison of the projected (2071-2100) SRES-B2-based scenario mean monthly snow water equivalent (SWE), snowmelt, actual evapotranspiration and run-off with their corresponding base period (1961-1990) values.

Figure 5-3: The projected relative mean annual changes in precipitation, snow water equivalent (SWE), actual evapotranspiration (ETR), snowmelt, and total runoff in (%) from their corresponding base period (1961-1990) values under various climate change scenarios.
However, the significant reduction in average monthly SWE values observed at lower elevations, while SWE values at the higher elevations of the catchment are slightly reduced. Figure 5-3 shows catchment accumulated daily SWE reduction values as an annual average ranging from minimum 50% to maximum 96%. B2 emission based RCM scenarios have more moderate effects as compared to A2 emission based RCM scenarios. Generally ECHAM4/OPYC based boundary condition RCM scenarios have a stronger effect as compared to HadAM3H based boundary condition RCM scenarios. This is mainly due to more temperature and less precipitation increase for the projections in winter by ECHAM4/OPYC driven simulations in this particular Alpine catchment. This is in agreement with earlier findings of e.g. (Déqué et al., 2007) that the choice of GCM is more important for simulated seasonal temperature and precipitation changes than the choice of RCMs. In accordance to change in SWE, a significant decrease & shift in snowmelt is observed. Snowmelt volume in winter increases by about 100% to 150%, and decrease in spring, summer and autumn months. The large existing snowmelt peak from March to June decreases substantially. March and April become the future important snowmelt months. The decreased snow pack volume and earlier snow melting with reduced time span resulted in an overall decrease in spring snowmelt volume. On an annual average basis a snowmelt reduction from 31% to 81% occurs. Warmer scenarios (A2) have a relatively shorter snowmelt time span than B2 based scenarios.

The catchment average actual evapotranspiration (ETR) represents about 28% of average annual precipitation (1555mm). The model predictions in terms of monthly, seasonal and mean annual variations all conclude that the effect of the scenarios will be moderate for actual evapotranspiration. The projected warmer and more humid conditions in winter and spring result in an overall increase in monthly actual evapotranspiration values during both seasons. During summer and autumn the amount of evapotranspiration remains relatively unaffected, although temperatures increase. This can be explained by the projected reduction in precipitation. Despite these substantial seasonal changes, mean annual changes are relatively small, ranging from +6% to +20%.

As a result of these observed changes, a shift from a rainfall-snowmelt dominated flow regime to a rainfall dominated flow regime is projected for all scenarios. There will be an increase in winter flow and a decrease in spring, summer and autumn flow. Generally, the large snowmelt peak in spring is flattened out, and the typical low flow period during winter shifts to a low flow period during late summer and autumn. The uncertainty band between the different RCMs in average monthly flow is the largest during spring and summer. On an annual basis, total catchment flow is reduced by 6% to 33%, due to an annual increase in evapotranspiration and decrease in precipitation. A2 emission based scenario results show an almost double flow increase in winter, while all models show a decreasing pattern for the remaining seasons. B2 emission based models show the same identical patterns as A2 emission based models. In nutshell, even with uncertainty stemming from the climate change scenarios, the signal of change in alpine hydrology i.e. is very visible and pronounced.
5.1.2 PAPER- B

This paper is focused on prediction of the future water availability for Kitzbühler Ache catchment. So far most of the studies devoted to the evaluation of climate change impact on hydrological resources, generally investigated on changes in average flow conditions. Nevertheless, it is possible that variation in climatic parameters i.e. precipitation and temperature can lead to no change in mean flow, but may result in reduced low flows. The changing magnitude may alter the reliability of water supply sources. Therefore, the future discharge regime is assessed through quantifying changes in both indexes, mean flow as well low flow (Q95) conditions. In this study area catchment (Kitzbühler Ache), the major contribution in mean annual flow comes from baseflow component. In such conditions, understanding the likely consequences of climate change on total flow regime or on total water availability, the most important component to understand is baseflow volume. The contribution of baseflow is over 50% in total mean annual flow. The analyses of this component would help in long-term water resource planning and management, not only in protecting the underlying groundwater resources, but also in the context of land use allocation and development. The investigation of flow regime and total water availability is carried out through the application of the hydrological model PREVAH. The details about model development, climate scenarios and methodology used (delta change approach) to incorporate climate change scenarios into model simulations are given in Appendix A, (Paper 2). The analysis of flow regime and water availability during mid-century to end of 21st century is based on a comparison between the “present” condition (1961-90) and the “future” condition (2041-1970 & 2071-2100) simulations

The parameters analysed are baseflow, total flow, environmental flow and total water availability. The monthly simulated result of baseflow with seasonal shift (percentage change) in volume is shown in Figure 5-4, whereas annual change is given in Figure 5-8. In present conditions, the baseflow is generated during the late spring and early summer, corresponding to snowmelt. The volume of baseflow generated, is therefore, dependent upon the amount of winter precipitation and the amount and length of spring snowmelt season. Relative to the reference period, mean annual baseflow volume decreases by around 5-9% (Figure 5-8). Seasonally, as expected, baseflow volume is greater in winter than in other three seasons. Relative to reference condition (1961-90), the baseflow in winter is increased, whereas, in all other remaining seasons decreased (Figure 5-4). In winter season, warmer temperatures allow precipitation to fall as rain rather than snow, thereby resulting in massive increase in baseflow volume.
However, the change in baseflow volume is irregular across the watershed. For example, this could be seen in figure 5-5, which shows that baseflow varies considerably across the watershed, responding directly to variations in hydraulic characteristics of the underlying soils. The finding are in good agreement to the earlier conclusions made by several authors (Vanham et al. 2008, Jyrkama et al. 2002) that spatial variation in baseflow (recharge) is directly controlled by the soil and other subsurface properties. This latter point is important, as it highlights the fact that the impact of climate change is non-uniform across a basin. The important factor for changed baseflow patterns can be attributed to snowfall trends. The snowfall decreasing trends are observed in all model scenario simulated snow cover maps given in figure 5-6. A temperature rise results in an earlier onset of the snowmelt season, hence reduces the total snow cover days. The significant impact was observed over end of 21st century scenario snow cover maps, due to higher projected increase in temperature. This could have caused the total snow disappearance, but an increase in winter precipitation have compensated for the latter effect. The increasing winter rain to
snow ratio, rising temperatures coinciding with decreasing precipitation trends in fall and early onset of spring melt can all be attributed towards increasing snow free days.

Figure 5-5: The projected relative seasonal change in baseflow volume in (%) from corresponding base period (1961-1990) volume under A2-emission scenario.

The other major contributing factor in seasonal changes in baseflow is an increasing evaporative loss due to higher temperatures and seasonal shift in precipitation patterns. Fig 5-3 & 5-8 shows that simulated evaporative losses increased in all seasons, with relative mean annual losses increased about 6-20%. The change in total precipitation, snowfall and evapotranspiration, all results in change of magnitude and seasonality of total flow regime. Fig 5-4 shows the total mean flow, where summer discharge is found to reduce significantly, winter discharge increases, and the snowmelt-induced flow peak in May is shifted to March-April and decreases in most cases. Warmer winter temperatures resulted in a greater proportion of precipitation falling as rain. This potentially lead to higher winter flows by more than 100%. A significant reduction in the average runoff in the spring is also witnessed as the expected increase in spring runoff due to additional precipitation would be offset due to early snow melting, hence shifting of spring melting to winter months and somewhat by greater evapotranspiration due to warmer temperatures. In summer, both enhanced evapotranspiration together with decreased precipitation reduce streamflow by more than one-third. Whereas, due to decreased precipitation and higher moisture deficit in summer, results in reduced runoff throughout fall.
Figure 5-6: The comparison of projected mean annual snow duration maps with their corresponding base period (1996-1990) snow duration map.

The similar identical changes are also observed in projected environmental flow regime. This could be seen in Figure 5-4. The volume of change in environmental flow is much dependent upon the changes in precipitation and temperature together; therefore, decreasing patterns observed from April to September due to lower precipitation and higher evaporative losses. By considering the present-day water availability, the decrease in total mean discharge particularly from May to August with increasing low environmental flow conditions during same flow period may affect the water quality and supply during these months. The projected change in total flow and environmental flow results in change of water availability. Fig 5-7 shows the changes in available water, where the future water availability is assessed through the difference b/w total flow and environmental flow regime. The changes in projected total flows seem most critical from May to September, where all the projected total flows are just close to present environmental flow regime but in new statuesque of flow regime seasonality, the environmental flow regime is too reduced, hence not so much critical effect on maintaining present available water volume during these low flow seasons. All climate scenarios project higher water availability trends from December to March and decreasing water availability trends from May to August. However, at mean annual scale, most of the scenarios show slightly higher available water (Fig 5-8) due to significant increase in winter flows. The annual water availability is much less influenced by changes in temperature than by precipitation changes. Nevertheless, the rising temperatures have significant influence on changed seasonality.
In general, the catchment’s hydrological regime shows mild to moderate vulnerability to a changed climate. The projected monthly and seasonal baseflow, environmental flow, total flow, and available water have changed in great extent from observed trends. The increased temperature rates in winter have significantly changed the form of precipitation, from snow to rain and also resulted in early and faster depletion of snowpack volume. The increased precipitation amount (rain) in winter, decreased precipitation amount in summer, increased evaporative losses and early & faster depletion of snowpack volume, all this results in a change of seasonality of stream flow and water availability. However mid-century scenarios have more moderate effects as compared to end century scenarios. Despite the monthly or seasonal changes in mean available water, the water availability at mean annual scale is slightly increased.
5.2 Hunza Catchment

5.2.1 Paper-C

This paper is focused on analyses of the most important hydrological components e.g. snowmelt, glacier melt and total flow of Hunza catchment. The sensitivity of these components is simulated through PREVAH model under hypothetically generated climate change scenarios. The hypothetically developed scenarios are a combination of changes in temperature and precipitation, ranging from 1 to 4°C and -10 to +10% respectively. The detail about model development and generated scenarios can be found in appendix- A (paper C). The model results are shown in figures given below. Figure 9 & 12 shows the sensitivity of monthly and mean annual snowmelt volume towards projected scenarios. Under all adopted scenarios, monthly snowmelt runoff increased in April & May and decreased in June & July (except one, +10% precipitation scenarios).

![Figure 5-9: Effect of selected temperature and precipitation scenarios on the monthly (April to July) snowmelt runoff for the different years of 1990-1992.](image)

The maximum variation in monthly snowmelt runoff has been observed under maximum increase in temperature (4°C) combined with changes in precipitation. The maximum increase of about 25-30 mm in April & May and decrease of about 45-60 mm in June & July has been observed under (T+4°C, P+10%) and (T+4°C, P-10%) scenarios respectively. However, the timing of peak snowmelt runoff remains the same, but the magnitude of peak discharge is changed as per precipitation scenarios- runoff increased under high precipitation scenario (+10%) & decreased with decreased precipitation scenario (-10%). Due to increase of precipitation, snow water equivalent values also increase and accordingly the snowmelt runoff. This could be seen in mean annual values shown in Figure 5-12, where increase of precipitation (+10%) without temperature change, results in an increased annual snowmelt volume and vice versa with decreased precipitation scenario (-10%). The maximum effect over snowmelt volume is observed with increasing temperature scenarios. The increase in temperature results in an early & faster depletion of snowpack volume. Thus snowmelt runoff increased in early months and decreased in later months due to an early depletion of snowpack volume. This is apparent in monthly values as shown in Fig 5-9. The increased temperatures have also negative impact over annual snow melt runoffs. Figure 5-12 shows that with each degree of temperature increases, annual snowmelt volume decreases accordingly, as much of the precipitation shifts from
snow to rain. In the case where both temperature and precipitation increase, the temperature will cause a faster melt, but precipitation will enhance the snowpack volume. The likely compound effect could be seen in monthly values, e.g. under dry (P-10%) and wet (P+10%) scenarios (with or without temperature increase), monthly values vary between 5 to 10 mm between wet and dry scenarios. Although the difference is not significant at monthly scale, the mix scenarios (combination of temperature & precipitation) results in significant shift in annual volumes. Table 1 indicates that under scenario (T+4°C, P-10%), the snowmelt contribution in total stream flow reduced 8.7% from current reference contribution, while under scenario (T+4°C, P+10%), the snowmelt contribution just reduced 1.5% from current reference contribution. Generally, increasing temperature scenarios are the main cause behind annual snowmelt volume reduction, due to change in form of precipitation (snow to rain).

Due to low precipitation and high glacier coverage (about 34% of total catchment area), the contribution of glacier melt in total flow is much higher than that of snowmelt runoff. In the existing environment, the glacier melt contribution to the stream flow varies from late May to early September. Figure 5-10 shows the monthly glacier melt runoff under different warming scenarios. It is clearly seen that monthly glacier melt volume increased significantly under all warming scenarios. However, the timing of peak runoffs is not affected at all under any scenario, but the magnitude is changed significantly. The glacier sensitivity increased with increasing temperature scenarios.

Figure 5-10: Effect of selected temperature and precipitation scenarios on the monthly (May to September) glacier-melt runoff for the different years of 1990-1992.

The monthly values are higher under (T+4°C) scenario, and vice versa under condition (T+2°C). The trend is opposite in the case of precipitation scenarios. Under humid conditions, the snowpack volume is increased, thus snow cover remains a bit longer over glaciated area, resulting in late start of glacier melting, which comparatively produces lower glacier runoff than dry condition scenarios. Figure 5-10 clearly supports this fact, where the monthly glaciers melt runoff under humid conditions (+10% increase in precipitation) are comparatively lower than dry condition scenarios (-10% decrease in precipitation). However, due to low basin precipitation regime (mean annual 200-250 mm), the projected changes in precipitation (-10% to +10%) have no significant effect over monthly glacier melt runoffs. In general, due to increased temperatures, the monthly glacier melt trends under all adopted scenarios will significantly change annual glacier melt volume. The significant change is observed with increasing warm and dry scenario, e.g. (T+4°C, P-10%). Figure 5-12 illustrates this effect. The observed change in mean annual glacier melt volume will al-
so increase its contribution in total stream flow volume. Table 1 indicates that under all adopted scenarios (except one); the glacier melt contribution is increased from current glacier melt contribution. The maximum contribution observed under warm and dry scenario (T+4°C, P-10%). Accordingly, the changes observed in snowmelt & glacier melt volume are collectively reflected in streamflow patterns. Figure 5-11 & 5-12 shows the effect of all adopted scenarios on mean monthly & mean annual stream flows respectively. As Hunza basin is highly glacierized and precipitation regime is very low (ranges between 200 to 250 mm annually), thus changes in precipitation volume (-10 to +10%) have very low effect on monthly or annual stream flow volumes. However, the increased temperature scenarios have a significant effect on monthly glacier melt runoff- the major part of total stream flow in this basin; therefore the change in glacier melt runoffs under different climatic scenarios are reflected in the monthly flow volumes and subsequently total stream flow volumes. This could be seen in Fig 5-11 where increase in temperature or temperature combined scenarios systematically increased monthly flows.

**Figure 5-11:** Effects of temperature, precipitation and combined scenarios on mean monthly stream flows.

The maximum changes observed are in May, June July and August flows. In general, the timing of peak flow is not affected; however, there is a change in the magnitude of peak flows. A large increase in these months is due to the combined effect of snow melt runoff and enhanced glacier melt contribution due to warmer climate. The resulting increase in monthly flows has a significant effect on seasonality of flow regime. Table 5-1 & Figure 5-12 show the effect of adopted scenarios on mean seasonal & mean annual stream flow volumes respectively. The increase in temperature from 2 to 4°C will change the seasonal flows from current reference flows (154 mm) to (220-291 m) and from (433 mm) to (478-521 mm) respectively for spring and summer. The autumn and winter flows are not affected significantly. The increase in mean annual flow varies between (+18.5%) to (+37.7%). Seasonal flow change shows that the climatic sensitivity is limited to only in spring & summer seasons. The earlier study by Cayan and Riddle (1993) also reported that the temperature sensitivity seems to be confined to spring and early summer. This is a bit contradicting to some studies conducted in other mountain watersheds, which shows an increase in winter discharge due to a warmer climate caused by increased temperatures (Vanham et al., 2008a; Vanham et al., 2008b; Laghari et al., 2012).
Figure 5-12: Effect of variation in temperature and precipitation on mean annual snowmelt runoff, glacier melt runoff and stream flow over 3 years period (1990-1992).

However, for this specific basin, the temperature remains below freezing point in these months; the increasing of 2 to 4°C still be much lower than melting point, therefore have no important effect on autumn and winter flow season. The maximum increase of about (+40%) in mean annual total stream flow runoff is produced under a (T+4°C, P+10%) scenario. In nutshell, the maximum effect observed is on glacier melt runoff and accordingly on stream flow volume. Increase in air temperature for a longer time will therefore reduce the size of glacier due to higher melting rate.

Table 5-1: Effect of variation in temperature and precipitation on mean seasonal stream flow over 3 year's period (1990-1992)

<table>
<thead>
<tr>
<th>Climatic Scenario</th>
<th>Winter (Jan-Mar) Ref. flow (11mm)</th>
<th>Spring (Apr-Jun) Ref. flow (153 mm)</th>
<th>Summer (Jul-Sep) Ref. flow (433 mm)</th>
<th>Autumn (Oct-Dec) Ref. flow (42 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prec. Scenarios</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-10%</td>
<td>09.3</td>
<td>160.2</td>
<td>422.6</td>
<td>37.9</td>
</tr>
<tr>
<td>P+10%</td>
<td>12.0</td>
<td>147.3</td>
<td>444.0</td>
<td>46.5</td>
</tr>
<tr>
<td>Temp. Scenarios</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T+2°C</td>
<td>11.9</td>
<td>220.1</td>
<td>478.3</td>
<td>47.3</td>
</tr>
<tr>
<td>T+3°C</td>
<td>13.8</td>
<td>256.0</td>
<td>500.1</td>
<td>49.6</td>
</tr>
<tr>
<td>T+4°C</td>
<td>16.0</td>
<td>291.5</td>
<td>521.4</td>
<td>51.8</td>
</tr>
<tr>
<td>Combined Scenarios</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T+2°C, P-10%</td>
<td>10.5</td>
<td>224.4</td>
<td>468.0</td>
<td>43.0</td>
</tr>
<tr>
<td>T+2°C, P+10%</td>
<td>13.4</td>
<td>215.9</td>
<td>489.3</td>
<td>51.4</td>
</tr>
<tr>
<td>T+3°C, P-10%</td>
<td>12.2</td>
<td>258.6</td>
<td>490.0</td>
<td>45.4</td>
</tr>
<tr>
<td>T+3°C, P+10%</td>
<td>15.4</td>
<td>253.0</td>
<td>510.6</td>
<td>53.7</td>
</tr>
<tr>
<td>T+4°C, P-10%</td>
<td>14.2</td>
<td>293.3</td>
<td>511.8</td>
<td>47.5</td>
</tr>
<tr>
<td>T+4°C, P+10%</td>
<td>17.7</td>
<td>290.2</td>
<td>531.5</td>
<td>56.0</td>
</tr>
</tbody>
</table>

Similar effects are expected under the scenario of less precipitation. The glaciers will retreat because of their faster depletion under these conditions. Moreover, a combi-
nation of these two scenarios, increase in temperature and decrease in precipitation, for a longer time will have the compound effect of reducing them in size. On the other hand, the glaciers may grow in size and chances of their advancement will be higher if precipitation increases and temperature does not.

5.2.2 Paper D

In context of current water shortages in Indus basin, future water needs, food security as well as hydropower and flood control requirements, the Pakistan Water and Power Development Authority (WAPDA) have devised a 25 year gigantic National Water Resources and Hydropower Development Program—Vision 2025. The vision encompasses the development of additional reservoirs, introduction of water efficient techniques, reduction in conveyance losses, lining of water canals and distributaries and institutional strengthening etc. However, the prominent feature of this report is its focuses on development of 23 BCM (Billion cubic metres) new storage reservoirs in next 25 years. However, many experts and organizations have raised serious concerns and doubts over future water availability for proposed reservoirs on Indus River and its tributaries. The latest IPCC assessment report (2014) clearly indicated that the mountain river basins are inherently the most sensitive to climate change, and this sensitivity will particularly be crucial for snow/ice melt dominated runoffs. Due to substantial contribution from snow and glaciers, the flow regime of Indus river system is expected to be extremely vulnerable to climate change and can have serious implications on downstream water resources development and management programs. In such uncertainties, a review of historical flow data analysis and understanding of possible changes in future water resources are the key before successful commissioning of such mega projects. Therefore, Paper D analyses the viability of this project—current water availability for proposed large reservoirs through available historical data analysis and prediction of future water availability scene under different warmer climate change scenarios. The future water availability scene for proposed reservoirs is investigated through the potential impacts of climate change on hydrological regime of Hunza basin— a major tributary of the Indus River located in the western Karakorum ranges, and consequent impact upon flow regime of main Indus River. The current and future water availability analyses are discussed below.

5.2.2.1 Current water availability analyses for proposed large reservoirs

The flow regime of Indus river system i.e. the Indus river and its tributaries are highly seasonal and erratic; with the highest flows occurring between June and September, when ice and snowmelt on the mountains cause a combined peak discharge, while minimum flows occur during winter months, e.g. November to February. Based on 78 years (1931-2008) annual data (Fig 5-13); 172 BCM average annual water is available in river system, of which 130 BCM is diverted into irrigation systems and 42 BCM escapages to the Arabian Sea. This escapages level exceeds 110 BCM in wet years. Out of the total annual flow; about 84% are in summer season and 16% in winter season. More than 65% of the annual water flow in the Indus is available over a very short span of 8-10 weeks from June to August, while the remaining nine months period only constitutes 34% of total flow. The variability in river flow is a major limitation in the development of run of river type irrigated agriculture, particularly to meet crop irrigation requirements in low flow period of winter season and early and late summer season.
The construction of three reservoirs, Chashma (0.89 BCM) in 1967, Mangla (6.59 BCM) in 1967 and Tarbela (11.9 BCM) in 1976 have provided a great control and capability to store surplus water available in flood season and utilize in low flow periods i.e. low periods of winter from October to March, and the sowing summer period in April and May. After construction of these dams, the severe shortages in winter season have been eased to great extent and the area under cultivation is increased from 23 million acres in mid 60s to 36 million acres today. The annual canal diversion of 91.3 BCM in 1966 now has been reached to 130 BCM today. The water supply contribution in critical winter season is jumped from 27 BCM of pre dam period to 39 BCM of post dam period (Fig 5-14). The river contribution in summer period is also increased from 64 BCM in pre dam period to 83 BCM of post dam period.

**Figure 5-13**: Mean annual & seasonal flow in Indus river system for period of 1931-2008 and present seasonal crop water requirements.

**Figure 5-14**: Pre & post dam impact over canal water diversions and escapages to Sea.
The average post dam discharge has been increased by 44% in winter and 30% in summer, whereas annual withdrawals have been improved by 30%. Since development of last reservoir in 1976, three reservoirs have lost almost about 26% of their storage capacity due to siltation (Fig 5-15). It is estimated that by the year 2025, this loss would increase almost 75% of the original combined storage capacity of three reservoirs. With a large arable land, Pakistan still has the potential of bringing several million acres of virgin land under irrigation. Although river flows are fully utilized, large chunk of flood water in summer period is still unexploited and escapages to Arabian Sea. After adjustment of current 95 BCM summer crop water requirements and 12 BCM release for Indus deltaic region allocated under Indus water distribution accord 1991, still 30 BCM water remain unexploited in summer. Therefore, as per historical data analysis, sufficient amount of water is available for the proposed reservoirs. Our existing live storage capacity is hardly 14 BCM or less than 10 per cent of average annual flows, while the world’s average storage capacity for appropriate control is 25-40 per cent. Our grossly inadequate regulatory storage capacity does not enable us to make optimum use of surpluses river resources. Even a modest target level of 20 per cent would indicate need of over 30 BCM new storages. All above mentioned facts and figures clearly support the additional water availability in river system and favours the construction of proposed dams. The additional storage capacity will provide the flexibility in system to shift from a supply-based operation towards a demand-based system. Due to improved regulatory capability, reservoirs will provide great flexibility in controlled inter seasonal and inter-year transfer of river flows to substantially increase water supply for agricultural production, generate cheap hydro-power and reduce flood losses.

5.2.2.2 Future water availability analyses for proposed large reservoirs

The future water availability scenario for proposed reservoirs is investigated through the potential impacts of climate change on the hydrological regime of Hunza river- a major tributary of the Indus River and consequent impact on the flow regime of main Indus River. The Hunza River has a mean annual flow of 323 m$^3$/sec (i.e. 742mm) gauged at Dainyor Bridge. The annual catchment precipitation regime ranges between 200 to 250 mm. The mean monthly temperature varies between -20 °C in winters to +25 °C in summers. However, these precipitation records are not representa-
tive of the runoff at the outlet. As both stations (Skardu and Bunji) are located in valleys (below 2500m a.s.l.), many authors (i.e. Winiger et al., 2005) reported that the valley values (precipitation) in Hunza basin are not representative for high-elevated zones. The investigations by Winiger et al., 2005 reported that the middle and upper part of the catchment receives about 1000 to 2000 mm precipitation respectively where as in the lower elevations the average annual precipitation is as low as 150-300mm. Therefore, to get the truly representative precipitation regime of this high altitude basin, the two new hypothetical stations at higher elevations (e.g. 3500 m and 5000m) are generated in the catchment and the daily data from Skardu station is modified as per precipitation gradient developed by (Winiger et al., 2005) for both hypothetical stations. The model was then developed with available daily time series of temperature (e.g. Bunji and Skardu) and precipitation data (Skardu and two hypothetical stations). The details about modified precipitation regime and model development can be found in annexure A- (paper D). The temperature increase of 1 to 4°C have resulted in an increase of about 16%, 33%, 49% and 68% respectively in current mean annual total flow volume. Figure 5-16 illustrates particularly the effect of temperature on monthly stream flow volume. It is clearly seen that the increase in temperature systematically increased monthly flows. The findings are quite in contrast to earlier findings that mean annual water availability in general and summer in particular, will be reduced under warmer climate (Singh and Bengtsson, 2004). However, for this specific very low temperature regime basin, where 34% of the total basin area remains under ice cover and more than 85% precipitation falls as snow, the increase of 1 to 4 °C results in more melting runoff in summer. The timing of peak stream flow is not affected; however, the magnitude of peak stream flow is changed as temperature increases. The maximum change in monthly flows is observed from May to August. A large increase in these months is due to higher amounts of snow melt runoff and increased glacier melt contribution due to warmer climate. The resulting shift in monthly flows has a significant effect on the magnitude of seasonal and annual flow regime of basin.

![Monthly runoff contribution - Hunza river](image)

Figure 5-16: Effect of selected temperature scenarios on mean monthly total flow volume for period of 1990-1995.

The observed percentage change in projected monthly total flow regime of Hunza catchment is transferred with similar percentage increase in main Indus flow regime. The Indus River has its pivotal offshoot called as Hunza. It is the major part of Indus River System. The bulge amount of water received by both the rivers is via the snow
and glacier melt runoffs because the identical percentage changes have been observed in both of them as per their monthly volumes. The 25 year (1976-2000) flow data (monthly percent of annual flow) of these rivers explicitly reveal this direct relationship and proportionality. The regression equation shown below proves this relationship of both the rivers.

\[ Y = 0.7805X + 2.0743 \]

\[ R^2 = 0.9315 \]

The \( R^2 \), that is the coefficient of determination, shows with agreement the dependence and relationship of Hunza with the main Indus River in terms of monthly percent flows. With the above given regression equation, the percent value of water availability in Hunza can be exploited and subsequently the future percent water availability in the main Indus River.

Table 5-2: Main Indus River water availability scene under adopted warmer scenarios

<table>
<thead>
<tr>
<th>Climate scenarios</th>
<th>Water availability (BCM-Billion cubic meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter season (Oct–Mar)</td>
</tr>
<tr>
<td>1 °C</td>
<td>18.77</td>
</tr>
<tr>
<td>2 °C</td>
<td>21.55</td>
</tr>
<tr>
<td>3 °C</td>
<td>25.10</td>
</tr>
<tr>
<td>4 °C</td>
<td>28.26</td>
</tr>
</tbody>
</table>

The increase in temperature from 1 to 4 °C is shown to have a significant impact on annual and seasonal water by increasing its flows as the temperature proceeds (Table 5-2). A significant rise of winter flows from 2.35 to 70.56 BCM has been observed with the temperature increase of 1 to 4 °C. An increase of 1 to 4°C have resulted in an increase of about 2.35 to 11.84 BCM in winter flows, 15.51 to 58.71 BCM as per summer flows and 17.86 to 70.56 BCM in mean annual flows respectively. Even after all this, water availability is insufficient to cope up with the water demand for winter crops and therefore this additional demand can only be filled through reservoirs. It has become a high time therefore to construct new reservoirs as the snow and glacier melt runoffs during summer are for a very brief amount of time which results in higher water demand for crops irrigation especially in low flow periods of winter and early summer. The new reservoirs may not only help in the provision of needed water but can reduce the flood threats as well.
6 INDUS BASIN WATER RESOURCES MANAGEMENT & DEVELOPMENT: CHALLENGES AND WAY FORWARD

The mountainous system of Hindu Kush Himalaya region plays a major contributing role in provision of water supplies to regional and lowland. The Himalayan region is truly considered to be the earth’s “Third Pole” due to the ice reserves of nearly 6000 km$^3$. It is the Himalayan mountain system that is responsible for feeding water to one of the largest irrigation systems (Indus Basin Irrigation System- IBIS). Not only does it satisfy the water demand of the surrounding lowlands but it also is pivotal for energy production. Rainfall, melt water from snow covers and ice reservoirs, all together function to secure the resource system. Such a highland-lowland resource system is getting vulnerable due to the impact of climate change. Such apparent impacts of climate change are observed in mountains, specially the glacier retreat, as was also revealed in the current report by the Intergovernmental Panel on Climate Change (IPCC). The 70% of the total flow in Indus is contributed by the snow and ice melts, which normally last for 8-10 weeks only. Therefore the eco system and the human well-being depend upon is impacted by the snow and ice melts. Similarly, the socio-economic pressure is also on the rise, especially at downstream region. More and more water is being required for irrigation, energy production, industrial production, tourism, and drinking. This situation raises critical question: How should water management be modified in the face of climate change / how does Pakistan manages its water resources. These opposing trends can be bridged by means of adaptive and mitigation measures at the basin scale (Figure 6-1).

Figure 6-1: Interaction of mountain waters with water availability and water use at basin scale (Source: Kohler et al 2014).

In this context, paper- E gives the thorough assessment of the existing resources of water in Pakistan, the challenges that the Indus basin is encountered by, and a realistic approach of dealing with those challenges and safeguard the sustainability of irrigated agriculture in Pakistan. Paper F & G highlights the issues of industrial effluent disposal in canals and deteriorating health of Indus deltaic region respectively. Pakistan has been gifted with several river basins- namely the Indus, Karan and Makran. Yet major contribution of surface water resources about 172 BCM comes from Indus Basin, which occupies 71% of Pakistan’s total geographical area and fulfills water...
supply needs of 77% of total population and more than 95% of irrigation demand. The remaining two basins originate along the plains of Baluchistan, occupy 29% of total territory and contribute less than 5 BCM. The area under cultivation in Indus basin is about 28% of total geographical area (79.61 million hectares), of which 87% is under irrigation (Agricultural Statistics of Pakistan 2005-06). Irrigated agriculture is the main stay of Pakistan’s economy and Indus Basin Irrigation System (IBIS), the world’s largest contiguous irrigation systems is the backbone of this sector and subsequently it’s agro-based economy. The Indus River is major supply source of this contiguous irrigation system. Agriculture alone contributes more than one-fourth in total GDP, employs around 45% of labour force, provides support to 75% of the overall population and is responsible for more than 60% of earnings by foreign exchange. Irrigated agriculture is the main consumer of water and will continue to dominate water requirements in foreseen future; consequently the sustainability of this sector will totally depend on timely and adequate availability of water in Indus river system. Since last few decades, Pakistan observing severe water shortages; thus its irrigated agriculture and economy is likely to get worse. Since the last few decades, the water demand has amplified remarkably due to increasing food requirements owing to burgeoning population growth, urbanisation, industrialization, and improving living standards etc. in the country. Yet, proper management and development of the Indus Basin Irrigation System (IBIS) is far from the increased water demand. The most important management & development issues IBIS confronted today are enlisted below:

- Highly erratic nature of seasonal river flows,
- limited and dwindling storage capacity due to siltation
- Overexploitation of groundwater resources
- Inefficient water usage (flood irrigation system)
- High canal conveyance and field evaporative losses
- Inconvenient operational system at canal levels
- supply rather than demand driven system
- Untitled water rights & disparity in water allocation at tail-end levels
- Lack of modernization in irrigation systems (sprinkler and drip irrigation)
- Poor monitoring, maintenance and Operation
- Poor drainage facilities (increasing water logging and salinity hazard)
- Deteriorated water quality due to direct effluent discharge in irrigation system
- Less allocation of freshwater for deltaic region
- Poor participation of private sector
- fast fading institutional capacity of related institutions; and
- Lack of coordination among various departments in policies and strategies

Similarly, the emerging threat of climate change is further exaggerating the challenges IBIS is confronted today. IBIS largely relies on melting water from HKH region. The region known as “water towers of Asia” acts as reservoir, seizing snow and rain, storing and releasing it into the rivers, and subsequently nourishing the canals and recharge the groundwater aquifer (16.2 million hectare). The recent studies suggest that the river flows will augment in next few decades as the glaciers of HKH region
will get depleted faster than today. However once glacial reservoirs are empty, there is going to be a dramatic decrease in river flows. Due to looming threat of climate change and other factors given above, it is projected that in next 10 to 15 years, Pakistan could face 30-35% shortage in its total water requirements, which may result in shortage of 70 million tons of food requirements. In fact the depleting water resource will endanger the provision to irrigated agriculture and consequently may cause the food deprivation to 170 million Pakistani People. Many authors identified water shortage as the most critical challenge in 21st century, because water is the key engine for agriculture growth, thus the catalyst in economic development, wellbeing & prosperity of people of Pakistan.

6.1 General Description of Indus Basin Irrigation System

Pakistan is an agrarian country and its agro-based economy is largely dependent on mountain water resource base and the way these can be utilized and managed. The Himalayan watershed with numerous glaciers forms the critical water resource base of Indus River System, which consists of Indus River and its offshoots i.e. Jhelum, Chenab to the east and Kabul River to the west. The rivers of Indus Basin start from Hindukush-Himalaya Mountain chain and flows through Indus Plain of Pakistan, after descending from northern hills before emptying into the Arabian Sea. The Indus Plain is rich of highly fertile alluvium deposits and has become the heartland of agricultural activities. The agriculture practices in the Indus Plain are heavily dependent on regular supplies from Indus River System, because of skimpy and erratic nature of rainfall along with high evaporation rate in Indus Plain. Before partition, the agriculture activities were limited to very narrow strip of irrigated land along with Indus River and its tributaries. The partition of Indian subcontinent in 1947 has defined a new international boundary between India and Pakistan, which divided Indus River system unevenly between two countries. After years of hostility, both countries signed Indus Basin Water Treaty in September 1960. Under the agreement, the sole right of three eastern rivers were exclusively given to India, while the rights on three western rivers were apportioned to Pakistan. Since then, with the help of World Bank, a number of water projects in Indus Basin have been completed to divert flows from western rivers to eastern river fed command areas. As such a vast irrigation system called Indus Basin Irrigation System has been developed, which considered as the bread basket of Pakistan. Since the agreement, around 3 major reservoirs (Mangla, Chashma, and Tarbela), 19 barrages and 43 canal heads, 12 link canals, 61152 km long irrigations canals and 1.61 million km water courses as shown in (Fig 6-2) have been built by Pakistan. This system provides water supply to around 16 Mha culturable command area, out of that around 14 Mha are irrigated through perennial canal supplies. At present, around 142 BCM surface water supplies from the Indus River System are being diverted at canal heads for irrigating 14 Mha command area. Besides, around 0.3 million tube wells (in public and private sector) installed to tape groundwater resources, provide additional supply of around 52 BCM for domestic, industrial and agricultural sectors. The increasing salinity concentration and declining groundwater levels have dimmed the further exploitation of remaining 11 BCM potential yields from Indus aquifer.
6.2 THE CHALLENGES CONFRONTED

6.2.1 AGEING WATER INFRASTRUCTURE & LOW STORAGE CAPACITY

After historic water sharing agreement “Indus Basin Water Treaty” in 1960, Pakistan has developed World’s largest contiguous water infrastructure system called “Indus Basin Irrigation System”. The massive water infrastructure developments in 60’s & 70’s have brought a green revolution and boom in its agro-based economy. But since the last two decades, the sheer negligence of precedent governments and policy makers have left the water infrastructure, worth of about 300 billion US$, mostly owned and managed by regional departments in crumbling conditions. For instance the dwindling conditions of major structures such as Sukkar & Taunsa barrages,
which serve millions of hectares, would be calamitous. This puts the livelihood and well-being of millions of people at risk. The state agencies need to change the philosophy and practice of “build/neglect/rebuild” into culture of asset “rehabilitation and management”. The irrigation departments should develop asset management plans and go through regular checks and maintenance time by time. The governments also need to rethink and reprioritize the agenda. The water and agriculture sector development must be given top priority and to be the core of Pakistan’s long-term development plan. The last two decades witnessed negligible investment in water sector development, one of the major factors limiting growth of agricultural production and subsequent contribution in overall GDP growth and poverty reduction. The new storage facilities should be the centrepiece of long term development plans. Due to highly erratic and seasonal nature of Indus runoff, where 86% of annual flows available during 8-12 weeks of summer season and 14% in remaining months, it is paramount to develop new storage facilities at Indus. The Indus still have great storage potential to be tapped. Even with huge distribution network, its current storage capacity is very low, just 15% of annual flow and hardly store for 30 days (Fig 6-3).

![Water storage capacity/capita in selected countries (m^3) and storage capacity in days in various river basins](image)

Figure 6-3: water storage capacity/capita in different countries (left) and storage capacity in days in various river basins (right).

This is 4-7 times less than India, 16 times less than Orange River of South Africa and 30 times less than Murray Darling and Colorado Basins of USA. The per capita water storage facility in Pakistan is around 150 m^3; 15 times less than Australia and 40 times less than USA. Due to high siltation load of the Indus, with its origins in the young Himalayan Mountains, the 3 existing dams have already lost 22% of its designed capacity (23 BCM) and it is further projected that the reservoirs will lose 75% of its original capacity till 2025. Decreasing storage capacity puts serious constraint on reducing supply-demand gap, particularly in winter sowing season and early months of summer sowing season. It also limits the flexibility of sustained minimum flow essential to maintain a healthy ecosystem at deltaic region. The construction of additional storage facility would provide a great flexibility desired to shift from a supply-based system towards a demand-based system.

**6.2.2 GROWING IMBALANCE BETWEEN SUPPLY AND DEMAND**

Water is a vital source for existence of life on earth. This precious resource influences almost all segments of society and its development. The social, agricultural and economic systems of world’s greatest civilizations (i.e. Harappa, Mohenjo Daro and Gandhara) have been flourished in surroundings of Indus River and its tributaries. In
Pakistan, whose agro-based economy is largely dependent on irrigation, water is a key driver for its economic development and food security of 180 million people. Pakistan relies on water from Hindukush-Himalaya region that release about 170 billion m³ water each year into the Indus River and its tributaries. 96% of the 170 billion m³ inhibited water is used for irrigation purposes, remaining 2% for domestic and another 2% for Industrial use. The figure particularly highlights the importance of agriculture in the country. Since last 2 decades, Pakistan is observing severe water shortages. Burgeoning population, rapid urbanisation, industrialization, and rising agricultural needs - all put pressure on water supplies.

The gap between water supply and demand is sharply increasing in Pakistan; both in total amount of water and the per capita water availability. Figure 6-4 shows that in 1961, when population was 50 million, per capita water availability was 4000 m³, which now in 2013 reached to water scarcity level of 1000 m³. With the current rate of 2.9% population increase, it is projected that in 2020, the per capita availability will fall to 877 m³ with the population at 204 million and in 2025 water availability would be at 800 m³ with 225 million populations. As per Falkenmark Water Stress Indicator, a country becomes “water stressed” when annual per capita water availability falls below 1,700 m³. When annual per capita water availability drops below 1,000 m³, the country faces “water scarcity”. In this way around 2025, the country will be around at the levels of absolute water scarcity. Available, surface and groundwater resources, have almost fully being utilized to its potential, hence entirely depleted within the basin. It is projected that the irrigation water requirements will be around 250 billion m³ in 2025 against the current potential availability of 180-190 billion m³. The demand for other sectors i.e. domestic, industries and other non-agricultural purposes is increasing at the rate of 8% per annum. The demand for these sectors will reach to 10% of total available water resources till 2025. Similarly the percent of urban population will jump from current 35% to 52% by 2025. This would all mean a shortfall of about 33% in 2025, and subsequent shortage of 70 million tons in food requirements by year 2025 (Fig 6-5).
The shortages have already increased competition among various sectors, transferring water out of agriculture sector. Besides, lacking drainage facilities multiply the water logging and salinity hazard in basin. This would all severely hurt economy and livelihood of millions of people.

6.2.3 LOW SYSTEM EFFICIENCY AND CROP-WATER PRODUCTIVITY

The existing water infrastructure in IBIS is in crumbling conditions. The aged infrastructure, poor maintenance and repair are the major cause of depleted carrying capacity of irrigation system. As a result the overall irrigation efficiency is limited to just 30-40% (Archer et al., 2010). The canal losses are at 25%, conveyance losses at 30%, and field application losses reached to 25% (Archer et al., 2010). All these result in shortage of water. Additionally poor irrigation practices, lack of inputs, and salinization all together resulting in reduced crop yield. The crop yield both in terms of per hectare and per cubic meter of water are much below than world levels (Laghari et al., 2012b). The current average yields for rice as well as wheat are just at 2500kg/ha and 2000 kg/ha respectively. For both crops, the average yield in neighbouring India are about 3000 kg/ha and 2000 kg/ha respectively. Similarly water productivity is too at lowest level in the world. The water productivity for wheat is 0.76kg/m$^3$, 24% less than India and the global average and 50% less than California. Similarly water productivity of rice (0.45kg/m$^3$) is just one-half of the average value for rice in Asia. The water productivity for maize is around 0.3kg/m$^3$, lowest in the world-9 times lowest to Argentina (2.7kg/m$^3$). Contrary to current status of low productivity, a huge potential lies for major improvements for increased crop yield per hectare and per drop of water- that may fetch huge foreign exchange, create a large number of jobs and improve living standard of people.

6.2.4 OVEREXPLOITATION OF GROUNDWATER

Sugarcane and rice are the most dominant cash crops cultivated over 70% of fertile plains of Indus Basin. Due to the erratic nature of flows and surface water scarcity (still to meet crop irrigation requirements) more than 40% short fall is made up from groundwater pumping. Since last few decades country’s water economy is largely dependent on unmanaged groundwater pumping by sinking thousands tube wells in
public and private sector. The investment in tube wells have almost tripled earnings (2.3 billion US$) in form of production (Shah et al 2003). However, unsustainable mushroom growths of tube wells have created an era of productive anarchy in most of the fertile plains. The tube wells augmented in number from 0.01 million in 1960 to 0.6 million in 2002 where as the year 2007 accounted for more than 1 million (Qureshi et al 2003, World Bank 2007). The expanded growth of tube wells have destabilised balance of aquifer abstraction (52 BCM) against recharge (40-60 BCM). The continued over-tapping of ground water has critically dropped water table level (1.5m/year) in most areas of Indus basin.

6.2.5 Disposal of Drainage Effluent

There is a significant deficiency of properly shaped natural drainage in Indus Plain. Indus Basin’s flat surface also constrains the drainage water to flow down valley in to the groundwater. Such conditions have become the cause of frequent flood after intense rainstorms and crop and property damage in several regions of Indus Plain. Even after the construction of 15000 km of surface drains, the crop losses due to rain flooding remain high in Punjab and Sindh (Afzal 1992). One of the economics ways to dispose the saline effluent to the sea is possible only when the drainage system is designed and regulated just like canal system. The overall saline drainage requirements are around 13.5 BCM, out of which 3.63 BCM are from Punjab whereas 9.82 BCM come from Sindh and Baluchistan Provinces. It is more needed in Sindh to drain the saline effluents because of saline groundwater and the high water allowances for crops such as rice.

6.2.6 Disposal of Industrial Effluent

Untreated effluent discharge from urban centres and/ industrial zones into Indus River or its canal network has emerged as a major challenge for Pakistan. The irrigation network (i.e. canals, distributaries, water courses) taking off from Indus River are the major source of drinking supply of more than 90% population settled in urban centres and/ rural areas. The Irrigation network is often contaminated by the activities of the adjoining populations and industrial units. Waste entering into canal system either in form of solid or liquid is mostly derived from industrial, agricultural and domestic activities. As a result, the supply network becomes highly polluted. That polluted canal network causes an increase in biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS), toxic metals and Faecal coliform and hence make such water unsuitable for drinking, irrigation and aquatic life. Paper-G particularly takes Pinyari canal as a case study to analyse the above water quality parameters. Pinyari canal off-takes from Kotri Barrage which is last structure constructed at Indus River located nearby Hyderabad city, Sindh Pakistan. This is non-perennial canal, which provide supply in wet season for agriculture, industrial and domestic purposes but in dry season only for industrial and drinking purposes to three surrounding districts i.e. Hyderabad, Tando Muhammad Khan and Sajawal. About 319 industrial units have been installed in SITE Hyderabad area that are operating without any in-house treatment facility and their effluent about 60 MGD (million gallons per day) is discharged directly into the canal. Water quality of canal water is thus deteriorated at alarming pace, with most of water quality parameters do not meet national environmental quality standards (NEQS). For detail about parameters analysed can be found in Appendix- A (paper G). This polluted water is being consumed for drinking by millions of people without any treatment.
Ground water of canal command area is highly saline which is not fit for drinking purposes. Hence, contaminated water is not only spoiling aquatic life and damaging agricultural land and crops but also of public health concerns. It is high time for all government agencies, public bodies, NGOs, to strictly emphasize and put pressure on all industrial administration to install treatment facilities and treat effluent before disposing-off into water canal system.

6.2.7 LESS WATER ALLOCATION FOR DELTAIC REGION

The Indus River, after its long journey of about 3000 km from north to south, finally spill out into a deltaic region- covering an approximate area of 5000 km$^2$ where, over the centuries, it has developed a 263,000 hectares thick mangrove forest which sustains exotic and colourful life in plants, reptiles and mammals. The fan-shaped Indus Delta, the sixth largest in the world supports a population of over 130,000 people, whose livelihoods are directly or indirectly depends on fresh water availability in Indus River. Therefore, integrity and lavishness of delta is directly linked with increased fluvial sediment supply and minimal human interference. Paper-F analyses the effect of upstream water infrastructure development schemes on Indus water flux and sediment discharge to Indus deltaic region and subsequent impact on mangroves cover, and shrinking of agricultural land. The extensive use of fresh water for irrigation purposes and construction of vast network of dams, barrages and associated upstream structures have severely reduced the total flow days and downstream discharge of the River Indus below Kotri barrage. The construction of irrigation network has almost doubled the agricultural activity, once limited to 12 million hectares to 22 million hectares now. However, it diverted Indus water from once 80 BCM to 125BCM for irrigation needs. The developed network is siphoning off 74% water before it reaches last barrage point (Kotri) on Indus River in the southern part of the country. After development of irrigation network; the water with sediment discharge, once 108 BCM and 225 BT (billion tons) reduced to 48 BCM and 50 BT discharge to deltaic region (Figure 6-6).

![Figure 6-6: The changes in average annual canal water diversions, downstream Kotri barrage flow, and sediment discharge below Kotri barrage after every mega development project (modified from Govt. of Pakistan Report, 2006).](image-url)
The effect of development schemes can further be measured by number of flowing days at downstream Kotri barrage. After construction of Kotri barrage, the flowing days reduced to maximum 250 days—once flowing throughout the year. During post Mangla period, the flow days further dropped to 100 days. Since the signing of Water Accord 1994, the river bed is constantly showing deserted look (no flow condition at downstream Kotri) (Figure 6-7). The available flow is mostly used for extensive irrigation needs by upper riparian.

![Indus River flow below Kotri Barrage](image)

Figure 6-7: Variation in Water / sediment discharge with no. of flow days / year below Kotri Barrage.

Since last few years water released into deltaic region only in case of flood situations. As a result, there is a pronounced sea water intrusion in the deltaic region. The twin menace of almost total absence of silt laden fresh water supply and sea water intrusion into delta have turned the whole ecosystem of deltaic region into a dying state. The deltaic region, once occupying an area of about 5000 km² consisting of creeks, mudflats and mangrove forest is now condensed to 1,192 km². While the mangroves cover, once an approximate area of 250,000 to 283,000 hectares till early 1980s drastically declined to 73,000 hectares in 2006. The resulting destruction of delta is not a problem of its own but death of fishing culture, ecology and destruction of livelihoods of local fishers and peasants. The health of Indus Delta demands a sensible evaluation of the smallest amount of fresh water and sediments necessary to avoid total vanishing of the delta. The analysis provides invaluable information for future water management within the whole Indus River basin and specifically the quantum of possible available fresh water for deltaic region. The study concluded with clear indication of cause-effect relationship between silt-laden water flux and various environmental impacts.

### 6.2.8 Climate change threat

There are numerous mountain series in the upper Indus Basin covering an area of 16300 km² and most of the mountains there exceed elevation of as high as 6000 m above sea level. The Indus Basin is unique in its spatial inconsistency due to variable elevation which is caused by seasonal cycles and temperature variations. Pakistan’s economy and agriculture majorly depend on water resources of the Indus water sys-
tems. Therefore, variation in water flow triggered by climate pattern change and human activities may have a terrifying impact on food security and sustenance of the people dependent on the Indus water system. Not much of research work has been done on effects of climate change on availability of water and pattern of water flow of the Indus waters. Due to current trends of climate it is predictable that there will be irreversible and dangerous effects of climate change on agriculture, economy and lives of the people of Pakistan.

Climate change will melt glacier at a higher rate resulting in increase in water flow by 50% initially, the flow will increase exponentially due to rapid increase in ice-melt and eventually, the rate of deposition of ice will be lower than the rate of melting of ice on glaciers (Rees and Collins 2005). As a consequent of it, availability and flow of water will decline over the period of decades of the 21st century. Monsoon in south Asia is predicted to be affected by the on-going rapid change in the climate. It was predicted in the Third Assessment Report by the International Panel on Climate Change that monsoon in South Asia will rise to 8–24% in future bringing an extra quantity of water, which will cause mega floods resulting in destruction and damages. Therefore, Pakistan needs to be ready for effects of climate changes in future and devise better policies in advance and take necessary steps for saving water and for enhanced water management. An improvement in water management would be a viable strategy to get by to minimize risks and damages of climate change to economy and agriculture of Pakistan.

6.3 WAY FORWARD

To increase output and sustainability of Indus basin irrigation systems, following key solutions are recommended. Comprehensive listing of options to manage Indus basin water resources is given in paper- E. However, the most important recommendations (adaptive and mitigation measures) in context of above mentioned problems are given below:

6.3.1 REHABILITATION AND MODERNIZATION OF EXISTING INFRASTRUCTURE

There is a need to rehabilitate and modernize the present infrastructure for domestic, industrial and agricultural water supply. It is also required to address the leakage reduction in domestic water. The main goal is to adapt the irrigation system to fulfill the tomorrow’s needs. Modernization, a mix of technological and managerial upgrading to improve responsiveness to stake holder needs, will facilitate more productive and sustainable irrigation. The efficiencies in the IBIS on average are very low as well (Archer et al., 2010). Approximately 72% of the available 175 km$^3$ surface water resources are withdrawn in IBIS, of which 25% quantifies as a conveyance loss in canals. Even after such losses, only 69 km$^3$ provides the availability for agricultural irrigation (Kreutzmann, 2011). Such a low value is the reason behind the water supply shortage for irrigation in Pakistan, especially in Sindh province. The present surface irrigation techniques and methods are a failure and wasteful because the doses of flood irrigation with fresh water only add to the poor quality saline water. As such irrigation infrastructure should enable farmers to apply just the right amount of water in small and frequent quantities (e.g.by installation of drip or sprinkler irrigation). Reducing the canal leakages may also augment the irrigation efficiencies.
6.3.2 Development of New Reservoirs

The data analysis of the Indus River (paper-C) vividly shows the availability of additional water in river and therefore supports the need of new dams to be built. Our existing storage capacity is less than 10 percent of the average annual flows where as that of the world is 25-40 percent. Such an insufficient storage capacity deprives us of making the optimum use of our river resources. Even a modest target level of 20 percent would indicate need of over 34 BCM new storages. The large quantity of water still remains unexploited and falls in to the Arabian Sea even after making summer and winter crop water adjustments and allocated necessary release under Indus water distribution accord 1991. This unexploited water can efficiently help in making the system more flexible and can shift it from supply based to the demand based. The reservoirs will substantially augment the water supply for agriculture and hydropower due to enhanced regulatory capability and controlled river flows.

6.3.3 Water Quality Conservation and Investment in Wastewater Infrastructure

In order to maintain the limited availability of water supply, it is required to conserve the water and invest on waste water infrastructure. The waste water from municipalities, cities and industries need to be purified before being discharged in to their respective collecting bodies. The production of waste water in Pakistan is estimated to be 12.33 km3 whereas treated waste water is 0.135 km3; which is only 1% (Laghari et al 2012b). The total quantity of water withdrawn from Indus Basin for domestic and industrial purposes is 8.8 km3. Out of this quantity, only a small fraction of the waste water is purified whereas the remaining 7.9 km3 goes back in to the system. It is also highly recommended to maintain the quality standards of the receiving bodies for which huge investments must be made. Water quality conservation includes the implementation of water pollution prevention strategies (legislation, polluting taxes,...) for the different polluters (Kumar et al.,2005). Society and individuals in the riparian countries should possess knowledge and ability to bring about the much needed changes. One of the major issues related to Indus basin is the deteriorating quality of the ground water. It varies from fresh to saline. Salinity has become a core problem especially in irrigated regions of Sindh province due to ground water being the substitute for canal water. The ground water in this region is mostly saline in nature and therefore unsuitable for irrigation purposes. Therefore the joint management of surface and ground water is a key requirement and the farmers need to be educated about suitable crops that can be cultivated under the conjunctive management of surface water and ground water resources (Qureshi et al., 2009).

6.3.4 Aquifer Management

The explosion in ground water use has led to an unsustainable depletion of groundwater resources. The conjunctive use of surface and ground water by farmers should be managed as described by Qureshi et al. (2009). The unmanaged conjunctive use of surface and ground water at the head ends of the canals causes water tables to rise resulting in waterlogging whereas at the tail-ends salinity problems are increasing. Through the encouragement of planned conjunctive use this situation can be improved. Similarly, the plans ought to be established for replacing high water demanding crops (i.e. sugar cane, rice) with low water intensive and high market value crops. High value crops such as sunflower, pulses, vegetables and orchards can add significantly in to the farm earnings.
6.3.5 Salinity Management

There is a strong need for constructing and rehabilitating the new and the existing drainage systems so that the excess salts from the Indus Basin irrigated areas could be carried in to the sea. Though a variety of salt-tolerant crops, planting techniques and suitable fertilizers have been developed yet it remains pivotal for the government to promote gypsum and other physical methods as well. A number of salt-tolerant crops and salt scrubs, if used on salt-affected lands, have the potential to augment crop production as well as to reduce the land degradation. Biological approach suggests the use of salt-tolerant trees, bushes, trees and fodder grasses. They act as biological pumps in the hydrological cycle of the area. In Pakistan, the productive tree plantations can also be a valuable utensil for regulating the rising water tables and salinity as such plantations are capable of contacting groundwater with their deep roots.

6.3.6 Strengthening of Institutions

The emergence of progressive and commercial farmers is changing the agriculture sector as well as the water requirement. Therefore to cope up with this issue, water needs to be reallocated from less needy (Head-end farmers) to the ones who need it more (tail-end farmer). To do so, Pakistan needs to make investments on establishing the institutions for taking the challenges of water management. In Pakistan, head-end farmers get 32 and 11% more canal water than tail-end and middle end farmers (Haider et al. 1999). Therefore, the irrigation department should provide the tail-end users with more surface water where as the head-end users should be motivated to make more use of groundwater. Farmers should also be educated about the proper mixing ratios of both the waters and to grow high value crops than traditional ones to augment their income base.
7 SYNTHESIS AND SUMMARY

The call for climate change impact assessment modelling increases as the effects of climate warming are becoming more and more visible. The most significant effect observed is on the mountain water resources. Not only this, but the mountain hydrology will also be distressed significantly by the climate change, both in upstream and downstream river basin parts. The availability of global environmental datasets (i.e. DEM, landuse map, soil map), and the development of the highly sophisticated, flexible hydrological models in combination with GIS techniques provides an opportunity to quantify the possible futuristic change in hydrological parameters due to anticipated climate change. To achieve this, the dissertation focuses on the model development (and application) to explore the probable range (approximation) of hydrological change the mountain watersheds will experience due to climate warming. The evaluation of the climate change consequences, e.g. of the hydrological water balance components, is pivotal for economic as well as environmental interests, especially to scheme the future plans within the water sector (supply of municipal and industrial water, irrigation, hydropower, snowmaking etc.). In this context, the study is structured in a way that in first part (chapter 2 & 3), it provides general overview on the global change, significance of mountain areas and its contribution in global water resources, and anticipated changes in its hydrological cycle. Third chapter displays the importance of the European Alps – changes observed in hydrological processes i.e. precipitation, evapotranspiration, snow melt, glacier melt and runoff. In second part (chapter 4), the modelling approach was developed and applied for two catchments in two different regions. In the third part, the climate change scenarios for the future period are constructed and applied to developed model. The model results are then provided in chapter 5. The key findings of each chapter are highlighted below:

7.1 CONCLUSIONS

- Climate change is a reality toady, and most probably happening because of high levels of anthropogenic greenhouse gas (GHG) emissions. Due to increase of an anthropogenic GHG emissions, the average global temperature have risen up by 1°C over the last 100 years and the future changes in global average temperature are expected to be in the range of 1.5°C to 4.5°C over the 21st century. The variation in observed and projected temperature is large in mountain regions, e.g. temperature change in European Alps is approximately 3 times higher than the global average. Climate projections also show increases in globally averaged mean precipitation over the 21st century. It is complicated to represent the precipitation in mountainous areas except for some general trends that can be projected like the increase of precipitation in European Alps during winter and decrease in summer can be anticipated. Although regional differences do exist, particularly between NW and SE part of the Alps.

- The change in temperature and precipitation have significant influence over snow & ice parameters; like in European Alps, the duration of snow cover is clearly declining at all elevations and melts much earlier. Over the last century, glaciers throughout the world have also declined considerably in size. For example, the European Alps have lost one third of their area and one half of
their mass from 1850 to 1990. Like in other regions of world, the Himalayan glaciers are also reported declining at much faster rate. On the contrary, the glaciers on the Pakistani side (Karakoram) are mostly stable and surging. In spite of above findings, the available research on glacier retreat/surge is still limited at present; estimation of the glaciers’ conditions to be in future is challenging and can be subject to errors as well. This was confirmed by the controversy about the false IPCC statement (2007) that the Himalayan Glaciers could be disappeared in next few decades. The statement was later corrected in 2010, saying that the glaciers are retreating at high rates comparable to other regions of the world, but not disappearing in visible future.

- Mountain regions known as regional “water towers” of the world are the supply source of many world river basins and provide freshwater supply to more than half of the world’s population. But their expected role in global water resources can possibly be modified by the predicted changes in climate. Mountains are very sensitive to temperature and precipitation change. If current trends of warming (e.g. temperature increase) continue, the present snowy regions may experience the precipitation in the form of rain with the diminution of snow covers by several weeks for each °C of temperature increase. The snowline is projected to shift 150 m/°C upward direction (at lower elevations by more than this average); the small glaciers will completely vanish whereas the larger glaciers will reduce in their volume. Particularly in middle mountain ranges, the snowpack is near to its melting point, so it is very sensitive to temperature changes. The projected increase in temperature will result in shortening of winter season, increasing snow to rain ratio, and earlier peak flows in spring. This will all lead to changes in seasonality of Alpine rivers. In winter, the average flow of Alpine rivers will augment whereas it will reduce in spring, summer and autumn. There occurs a shift of typical low flow during winter to a low flow period in summer and autumn.

- The river basins located in semi-arid to arid regions, - where major contribution comes from snow & ice melt, water supply to demand is already critical, and their economies heavily dependent on intensive irrigated agriculture; the projected changes in temperature and precipitation will significantly affect the water availability at downstream regions, and subsequently the operation & management of existing water infrastructures. Due to projected temperature increase, the availability of water may increase in the short term, as glaciers recede, but decrease in the long term. The countries in region, i.e. Pakistan, India, may face up to 40% annual water shortages till end of current century. The situation will further exacerbated as a result of increased water demand due to increased population, energy & food requirements, urbanisation, industrialization and rise in living standards etc.

- Chapter 4 focuses on hydrological modelling and model development for two selected catchments. The hydrological regime of mountainous catchments is characterized by the complexity of topography, vegetation, soils, spatial and temporal differentiation in snow cover and high seasonal and annual climate variability. To represent these highly variable and heterogeneous conditions, a number of models have been developed in last few decades throughout the world. Most of these models have been successfully applied but a comparison of different models under the same conditions is widely missing. The few studies available so far concluded that the distributed models seem to be more
appropriate for mountainous regions. However, the extensive data requirements often hinder its applicability (Jain, M.K., 1990; Merz, J., 2004). The spatially distributed hydrological modelling system PREVAH (Precipitation-Runoff-Evapotranspiration Hydrotepe Model) has been one of those models developed for the mentioned conditions in mountainous catchments. Since it was first developed in mid 90s, the model has successfully been applied in number of catchments (Switzerland, Austria, China, Russia and Sweden). The model result shows that the PREVAH system simulated observed daily discharge in reasonably well manner for both catchments.

- Chapter 5 is based on model application and structured as summarizing results of various papers attached in appendix- A. Where, paper- A focuses on the quantification of uncertainty of future climate change projections. Many factors have made it difficult and complicated to anticipate the future changes in climatic and hydrological conditions, such as uncertainties regarding emissions of climate-forcing agents and the limitations of climate models used for climate projection. The wide uncertainty band for the future evolution of the Alpine climate is a fact. With the uncertainty of regional global warming effects, the quantitative estimates for future planning in water sector have been invaluable. In many studies, only a very limited sample of climate change scenarios is taken in to account whereas the present study analyses the hydrological response to a number of regional climate change scenarios within the catchment of the Kitzbüheler Ache. This allows for the incorporation of uncertainties in the hydrological projections within the catchment at the end of the 21st century. A general shift from a rainfall-snowmelt dominated flow regime to a rainfall dominated flow regime for all scenarios was observed. Both snow accumulation and snow cover duration are reduced substantially in the catchment, due to its topography of lower to middle mountain elevations. The effect of temperature increase is stronger on snow accumulation than the effect of precipitation increase. The results indicate a shift in hydrology. However, the extent of the shift is subject to the choice of the scenario. The applied scenario A2 and B2 considers the future aspect of climate system indifferent ways.

- Paper- B analyses the influence of different climate change scenarios on the hydrology and water availability in the case study area of Kitzbühel Ache catchment at mid and end of the 21st century. A differentiation in flow components e.g. surface flow, baseflow is made and flow regime including environmental flows and total flows are analysed, all on a seasonal and/or monthly basis. The catchment’s hydrological regime reveals a great vulnerability to an altered climate. The projected monthly and seasonal baseflow, environmental flow (Q95), total mean flow, available water, all have changed from observed trends. The study anticipates that there will be a shift of a rainfall-snowmelt dominated flow to merely a rainfall dominated flow regime in future for the case study area. A future decrease in snow accumulation and a curbing in snow cover duration are observed. Due to this a change in seasonality of river flows occurs. There will be an augmentation of winter flow whereas the reduction in spring, autumn and summer flows. There is going to be a shift of typical yearly low flow period in winter to a low flow period in late summer and autumn. At mean annual scale, evapotranspiration losses increases, snow cover duration decreases, the flow components- base flow, environmental flow and total flow also slightly decreases. Despite the monthly changes in mean avail-
able water, the mean annual changes in available water are negligible. All regional model scenarios applied, show more or less the same identical patterns of change in all hydrological parameters.

- In Paper- C, a modelling attempt has been made to quantify the sensitivity of snow and ice parameters and resulting change in future water budget under climate change conditions in Hunza basin. The sensitivity analyses are based on hypothetically developed climate change scenarios. The model results show that the magnitude of all hydrological parameters (snowmelt, glacier melt, and total stream flow) is significantly changed with increasing temperatures (without precipitation change). The most significant effect observed was on glacier melt volume. Increase in temperature systematically decreased mean annual snow melt volume and increased glacier melt volume. The seasonal analysis of total stream flow volume indicated that the increase in temperature produce significant increase in spring and summer flow volume. No significant change is observed in the winter and autumn flow volume. In nutshell, it can be concluded that the increase in air temperature or decrease in precipitation for a long time will reduce the size of glaciers due to higher melt runoff. There will be a process of glacier retreat, during which time river flows will increase. The projected increase in annual flow will certainly provide greater relief to lower riparian region of Indus basin. However afterwards the glacial reservoirs will be empty, and there are likely to be dramatic decreases in river flow in long future.

- Paper- D analyses the role of existing reservoirs & justification of new reservoirs to be constructed on main Indus River. The assessment is based on historical river data analyses. The flow in the Indus river system is unpredictable. It is difficult to envisage the flow of the Indus River and its offshoots; two-third of the water that flows annually in Indus River is only available for a very brief time of 8-10 weeks starting from June till August, whereas only one-third of the water is constituted by the remaining nine months. To cope up with the crop irrigation needs in a low flow periods, run of river type irrigated agriculture is developed which has a major limitation caused by the variability in river flows. The construction of existing three reservoirs- Chashma, Mangla, Tarbela has provided a great control and capability to store surplus water available in flood season and can be made available to be utilized for low flow periods from October to March for winter crops and in April and May for summer crops. After construction of these dams, the severe shortages in winter season have been eased to great extent and the area under cultivation is 56% increased today. The average post dam discharge has been increased by 44% in winter and 30% in summer, whereas annual withdrawals have been improved by 30%. Thus, the storage reservoirs facilitated to integrate wet season with the dry season and over 10 BCM water is now transferred through storage reservoirs from wet season to dry season, which greatly enhanced the agro production in addition to meeting the water requirement of other sectors such as industries, environment, water supplies and sanitation etc.

- The analytical data of the river suggests the availability of the additional water in the river system and prompts for the new dams to be constructed. In comparison to the world’s average water storage capacity, which is approximately 25-40 percent, our storage capacity is barely 14 BCM or just below 10 percent of the average annual flows. Due to this insufficient storage capacity, it has
become hard to make the optimum use of surplus river resources. Even to ful-
fil the target of 20 percent, 34 BCM of the new storages are required. After ad-
justment of current summer & winter crop water requirements and necessary
release for Indus deltaic region allocated under Indus water distribution ac-
cord 1991, still huge measure of water remains undiscovered, and escapades
to Arabian Sea (annual average of 42 BCM). The utilization of the chunk of
this unexploited quantity through additional storage reservoirs will certainly of-
fer the flexibility in system which can consequently be used for shifting from a
supply based operation to a demand-based system. The enhanced regulatory
capability will end up in the augmented supply of water for agriculture, cheap
hydropower generation and reduced flood losses because the reservoirs then
will have a great flexibility in control of the inter seasonal and inter year river
flows.

- Additionally Paper- D also focuses on hydrological modelling of the Hunza
catchment with modified precipitation regime, and subsequent water availabil-
ity in Hunza tributary and main Indus River under projected temperature in-
crease in 21st century. Contrary to Hunza modelling results (paper- C), where
model was developed with precipitation estimates recorded from valley sta-
tions (mean annual value ≈ 250-300 mm), in paper- D, model was developed
with precipitation estimates as per gradient curve (mean annual value ≈ 1200-
1300 mm) generated by Winiger et al., 2005. Through the combination of
physical data, field work, satellite derived snow data, and statistical approach-
es; Winiger et al., 2005 estimated the total precipitation regime across differ-
ent zones in Hunza basin. The model results reveal that as the temperature
rose, the volume of the mean annual snowpack condensed whereas the
snowmelt, glacier melt and the total stream flow volume increased. The major
effect has been observed on snowmelt volume (increased significantly) and
subsequently on mean annual stream flow volume. Particularly, flows in late
spring & summer have increased significantly. Flow regime in other seasons
slightly changed. Within projected temperature increase, the glacier volume
largely remains stable. However, due to decreased snowpack and increased
snowmelt volume, glaciers contrary to present situation may no more nourish
in future. In this high altitude basin (over 7500 m a.s.l), the climatic sensitivity
appears to be effective in late spring and the season of summer, specially to
lower and middle part of the basin, with no effect on upper portion of the ba-
sin. It is mostly the lower and middle parts of the basin that contribute to the
melt. Contrary to earlier findings in different regions of the world, the tempera-
ture regime of this particular basin in winter & early spring months is below
freezing point, therefore the increase of 1 to 4°C have no any significant influ-
ence over form of precipitation or melting process, and hence no significant
change is observed in seasonal flow volumes, except for late spring & sum-
mer.

- The future water availability for proposed reservoirs on Indus River will be de-
termined through the water availability changes predicted for Hunza tributary.
The snow and ice melt runoff seem to have a major influence over the Indus
River and its offshoot Hunza as they both show identical percentage change
in their respective total volumetric flow. From the data of these both rivers, it
can be concluded that the change in Hunza has a direct relationship with In-
dus River and therefore proportional. This co-relationship was used to esti-
mate the available water quantity in Indus River. The projected temperature
changes have resulted in significant increase in current mean annual flows. The increased water availability is mostly confined to massive increase in summer season. The increased quantity in winter is yet insufficient to fulfil the crop needs. Therefore this additional need can only be accomplished via the reservoirs during surplus season of summer. Even 1°C increase in projected temperature change will provide sufficient amount of melt water in summer. Therefore with augmented volume in summer due to snow and glacier melt runoff, the need for reservoir construction can be justified. More reservoirs can not only help in reducing the threat levels of flood but also can enhance the utilization of surplus water for crop irrigation when its highly needed, especially during low flow period. Generally, all water distribution in Indus basin is controlled and regulated through reservoirs. The projected future trends favours the sufficient water availability for construction of new reservoirs, and would also contribute in successful, forward-looking management of existing and proposed reservoirs on main stem of Indus River- and accordingly let a better, long-lasting control of water supply, for irrigation and power supplies.

- Chapter 6 (paper- E, F and G) focuses on the issues & challenges available in the Indus basin and recommends the solutions under current and future water resources management. Given the diversity of agro-climatic, socio-economic conditions, it is clearly one of the most complex river basin systems in the world. The basin is self-sufficient in terms of food security, and also meets the deficits of about nine other adjacent basins. But in the process, most of the available water resources are utilized within the basin leaving little scope for further development. Irrigated agriculture is no doubt the highest water consumer so far but industrial and domestic demands are not way back as well. The rise of population, more urbanization, industrialization and rising living standards are all contributing to more water use and thus more demand. Food and energy production also require water and will augment in their demand in future. So many of the challenges need to be addressed like unregulated use of resources, shift from surface to ground water, diminishing of reservoirs due to sedimentation, salinity, degradation and lesser production of an agricultural land, contamination of ground as well as surface water and modification in water availability due to climate. To sustain ecosystems in rivers and Indus delta, the environmental flows are needed to be increased; this may result in pressure on other demand stakeholders and can lead to a tension in between the riparian countries. For this, the water resource management has come up with formidable challenges with the steps towards resolving them by making recommendations of the supply and demand management. Some of them include: new water storages; rain water harvesting; artificial ground water recharge; reservoir management; rehabilitation & modernization of existing infrastructure; restriction of water uses during drought periods; improving productivity levels of crops; and moving towards high value diversified and precision agriculture etc.
7.2 RECOMMENDED FUTURE STEPS

1. Simplification of model simulations

The model simulations are based on simplifications. The range of climate change scenarios for example only included changes in precipitation and temperature, not in other meteorological variables like wind speed, relative humidity and radiation. Secondly, only mean (monthly) changed values (in precipitation and temperature) are considered. Possible shifts in the intensity and occurrence of extreme events are not taken into account. Thirdly, changes in vegetation due to climate change are not considered. The model simulations assumed a static description of the vegetation. However, in mountain regions with heterogeneity in vegetation zones, shifts are likely to occur. The tree line for example is expected to rise due to global warming to higher altitudes. Therefore, it is recommended that the projected changes in mentioned meteorological variables, vegetative cover and extreme events in face of projected climate change should also be considered for hydro-climatic studies.

2. Availability and accuracy of geo-spatial datasets

Recent developments and increased availability of geospatial datasets (e.g., topography, hydrology, climatology, soil, land use map, snow cover etc.) in the public domain has provided an opportunity for spatially distributed modelling of hydrological processes. However, the inconsistency of the spatial and temporal scales in different datasets and lack of information regarding the accuracy of the datasets increase the uncertainty of the model results based on these datasets. Like, information on soil depth, porosity, wilting point, field capacity and hydraulic capacity is used to parameterize hydrological model, but insufficient accuracy in these parameters results in an increased uncertainty. Therefore, it is highly recommended that the hydro-climatic models should be developed with high resolution fine scale geospatial data sets, which may truly represent information at catchment scale.

3. Availability of truly representative data

The high altitude Hunza basin precipitation estimates (only based on Valley Station) are subject to combination of considerable measurement errors (mainly associated with wind, especially with snow, and local-scale orographic effects). Therefore, a network of rain-gauge stations as per World Meteorological Organisation (WMO) recommendations should be installed and data should be made available in public domain. Dissemination of data is often prohibited for political reasons, especially in South Asia. Most of the Hunza basin precipitation regime is limited in winter months and falls as a snow. The flow regime of high altitude Hunza basin is highly dependent on melting of previous seasonal snow and/ or glacier melt in summer. Therefore, reliable estimates are required for both air temperature and the temporal & spatial distribution of precipitation for assessing the future behaviour of seasonal snow cover/ glaciers and their role in providing melt water during summer months.

4. Availability of field measurements for model validity

Model validation is extremely important for the reliability of predictions. In hydrological modelling, this generally requires a comparison between the measured and predicted flow values. But in mountain catchments, where the snow and ice are dominating hydrological processes, the additional validity with
snow water equivalent values and snow cover duration maps etc. increases the confidence & reliability in model results. Therefore, it is highly recommended that model may also be validated with maps of snow cover areas.

5. Water budget calculations for the entire mountain part

The present study is based on the two sampling catchments. Like one, Hunza catchment is just one part of upper Indus basin. Therefore, another possible step in this study is a water budget construction for the entire upper Indus basin. This would enormously help in understanding, planning & management, and operation of water infrastructure.

6. Application of more than one hydrological model

Calibration and validation processes proved that the PREVAH model gives a good representation of reality, but as any model it is not perfect. Therefore on top of the error bands resulting from uncertainties within the different climate change scenarios, uncertainties from the modelling itself have to be accounted for. Therefore, another study with more than one hydrological model should be carried out and compared, so as to account the uncertainty within models.

7. Collaboration across disciplines

The complexity of climate change issues e.g. impact on land use practices vegetation cover, hydrogeology and relative impact over hydrological parameters in mountain areas makes it nearly impossible for an individual to represent all of the relevant areas of expertise. This clearly requires for scientists to engage in interdisciplinary research and to pledge to acting on advisory boards and alike scientific bodies.
CHAPTER 8 - REFERENCES

8 REFERENCES


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To what extent does climate change result in a shift in Alpine hydrology? A case study in the Austrian Alps

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Water Availability Look in Snow Dominated Regions under projected climatic variability: A Case Study of Alpine Catchment, Austria

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Abstract

This study analyzes the response of various hydrological parameters and future water availability scene against anticipated climate variations in snow dominated alpine catchment, Austria. The parameters assessed are base flow, environmental flow, total flow, evapotranspiration, and snow cover duration. The distributed hydrological modeling system PREVAH is developed to assess the impacts through the combination of various climate change scenarios produced under the framework of the European project “PRUDENCE”. The model results clearly indicate an apparent shift from observed trends in monthly, seasonal and annual values. The mean annual changes observed by all model scenarios ranges between 45 to 60\% decrease in snow cover duration, 15 to 20\% increase in evapotranspiration, 5 to 15\% decrease in base flow, and 15 to 25\% decrease in total runoff values. However, mean annual changes observed in available water are marginal; just ranging from -3 to +2\%. All regional model projections show more or less the same identical pattern of changes in analyzed parameters.

Key words: climate change, Alpine catchment, hydrological response, water availability
Analyses Hydrological Response against Climatic Variability: A Case Study of Hunza Catchment

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Abstract

The hydrological response of mountainous catchment particularly dependent on melting runoff is very vulnerable to climatic variability. This study is an attempt to assess hydrological response towards climatic variability of the Hunza catchment located in the mountainous chain of greater Hindu Kush-Himalaya (HKH) region. The hydrological response is analyzed through changes in snowmelt, ice melt and total runoff simulated through the application of hydrological modeling system PREVAH under hypothetically developed climate change scenarios. The developed scenarios are based on changes in precipitation and temperature and combination of both parameters. Under all warmer scenarios, the increase in temperature systematically decrease mean annual snow melt and increase significantly glacier melt volume. The temperature change from 1 to 4°C produces a large increase in spring and summer runoff, while no significant change observed in the winter and autumn runoff. The maximum seasonal changes recorded under ((T+4°C, P+10%) scenario.

Keywords: Mountain region, Hunza catchment, melting contribution, water resources

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Abstract: The mountainous region of Upper Indus Basin is critical water supply source for Indus River System and thus for Pakistan. The future water availability scene for proposed reservoirs are investigated through the potential impacts of climatic change on flow regime of Hunza basin under hypothetically generated climate change scenarios simulated through the application of the semi-distributed hydrological model PREVAH over a period of 10 years and consequent impact upon flow regime of main Indus River. The adopted climate scenarios ranging from 1 to 4°C temperature change are based on ensemble of 9 global model predictions for the studied region in 21st century. Under all adopted scenarios, total stream flow produces an early response along with a change in their runoff distribution. The early and extended ablation period for snow and ice melt have significantly enhanced water availability in main Indus River. The flow pattern of Indus River and its tributary Hunza shows identical percentage change in their monthly contribution to respective annual flow volumes, as major contribution in both rivers comes from snow and ice melt runoff. The regression coefficient was above 90%. The relationship was used to estimate the water availability in main Indus River. An increase of 1 to 4°C have resulted in net increase of about 2.35 to 11.84 BCM in winter flows and 15.51 to 58.71 BCM in summer flows, while 17.86 to 70.56 BCM increase were recorded in mean annual flows. The mean annual figure of Indus River, even at 1°C shows sufficient water availability for proposed reservoirs. Based on current Indus River data analysis and future water availability scene under warmed scenarios, the government’s decision to develop new reservoirs as to meet future demands through tapping part of 42 BCM unutilized water flowing to Arabian Sea, seems justifiable and also viable in changing climate. In nutshell, the increased snow and glacier melt runoff and resulting massive increase in summer flows justifies the construction of new reservoirs, as it will not only reduce the threat of floods but enhance the present capacity of regulating and utilizing surpluses water for crop irrigation in much needed times particularly during low flow period of the winter and early and late summer season.

Keywords: Climate change; mountain hydrology, future water resources

1. INTRODUCTION

Irrigated agriculture is the backbone of Pakistan’s economy, which is heavily dependent on an annual influx of water from mighty Indus River and its tributaries originate in the northern and northwestern parts of the country commonly known as Hindu Kush- Himalaya (HKH) region. Therefore, the Indus water system is the lifeline for Pakistan’s agriculture economy. The flow regime is highly erratic and seasonal. The average annual water available in the river system is 172 BCM; of which 130 BCM is diverted into irrigation systems and 42 BCM escapages to the sea. Out of the total annual flows; about 84% are available in Khareef season and 16% in Rabi season. The crop water requirements in Khareef and Rabi season is about 95 and 35 BCM respectively. The additional Rabi crop water requirements are met through large reservoirs constructed over Indus River and its tributaries. The three reservoirs with total capacity of 19 BCM, provides continuous supply in low flow periods (Rabi season). Since, development of last reservoir in 1976, three reservoirs have lost 26% of their total storage capacity due to siltation. It is estimated that by the year 2025, this loss would increase to almost 75% of the original combined storage capacity of three reservoirs. The decreasing capacity of existing reservoirs due to siltation on one hand and lesser rainfall than the normal on other hand are all resulting in sever short falls in canal water supplies. Over recent years, water supply shortages are identical. Many authors have reported shortages of the order of 15 to 50 per cent in Rabi from October to March, and early Khareef in April and May (Javaid and Yamin 2003). Due to severe water shortages, Pakistan’s annual GDP growth rate, which is directly linked with agricultural development, has drastically fallen to 3.5%, once consistently growing at 5-7 % in last one decade. On the basis of current water shortages and rapidly increasing future demands, the experts have foreseen that this situation would simply be unsustainable for the agriculture, thus Pakistan could soon become one of the food deficit countries in the near future. The damming of unutilized Indus water; with sizeable surplus of about 42 BCM still going out to sea, and 30,000 MW of economically developable hydropower potential provides the only left over opportunity to bridge the widening inter-seasonal supply-demand gap and to harness and regulate all available river surpluses. Therefore, in context of
current water shortages, future water needs, food security as well as hydropower and flood control requirements, the Pakistan Water and Power Development Authority (WAPDA) have devised a 25 year gigantic National Water Resources and Hydropower Development Program—Vision 2025. The vision encompasses the development of additional reservoirs, introduction of water efficient techniques, reduction in conveyance losses, lining of water canals and distributaries and institutional strengthening etc. However, the prominent feature of this report is its focuses on development of 23 BCM new storage reservoirs in next 25 years. However, many experts and organizations have raised serious concerns and doubts over future water availability for proposed reservoirs on Indus River and its tributaries. The latest IPCC assessment report (2007) clearly indicated that the mountain river basins are inherently the most sensitive to climate change, and this sensitivity will particularly be crucial for snow/ice melt dominated runoffs. Due to substantial contribution from snow and glaciers, the flow regime of Indus river system is expected to be extremely vulnerable to climate change and can have serious implications on downstream water resources development and management programs. In such uncertainty, a review of historical flow data analysis and understanding of possible changes in future water resources are the key before successful commissioning of such mega projects. The objective of this study is to assess the viability of this project- current water availability for proposed large reservoirs through available historical data analysis and to scrutinize the future water availability scene under different warmer climate change scenarios. This study will provide analysis to make informed, robust decisions on adaptation and mitigation strategies to cope with any expected future changes in water availability scenarios for proposed project.

2. MATERIAL AND METHODS

Current Water Availability Scene for Proposed New Reservoirs

The flow regime of Indus river system i.e. the Indus river and its tributaries are highly seasonal and erratic (Fig 1 and 2); with the highest flows occurring between June and September, when ice and snowmelt on the mountains cause a combined peak discharge, while minimum flows occur during winter months, e.g., November to February, when the mean monthly flows are less than one fifth of those in summer. Based on 78 years (1931-2008) annual data; 172 BCM average annual water is available in river system, of which 130 BCM is diverted into irrigation systems and 42 BCM escapages to the Arabian Sea. This escapages level exceeds 110 BCM in wet years (Fig 2). The highest maximum flow in the recorded 78 years history was 231 BCM in 1959-60 as against the minimum of 120 BCM in the year 2001-02. The recorded average Kharif flow is about 144 BCM, while in Rabi season it is around 28 BCM. Out of the total annual flows; about 84% are in Kharif season and 16% in Rabi season. During Kharif season the maximum flow of 191 BCM was recorded in the year 1959-60 as against minimum of 98.6 BCM in the year 2001-02, while in Rabi season the highest flow was about 43.4 BCM in 1990-91 as against minimum of 19.43 BCM in 1971-72 (Fig. 2). The monthly figure shows that more than 65% of annual water flows in Indus, is available over very short span of 8-10 weeks from June to August, while the remaining nine months period only constitutes 34% of total flow. The variability in river flows is a major limitation in the development of run of river type irrigated agriculture, particularly to meet crop irrigation requirements in low flow period of Rabi season and early and late Kharif season. The construction of three reservoirs, Chashma (0.89 BCM) in 1967, Mangla (6.59 BCM) in 1967 and Tarbela (11.9 BCM) in 1976 have provided a great control and capability to store surplus water available in flood season and utilize in low flow periods i.e. low periods of Rabi from October to March, and the sowing Kharif period in April and May. After construction of these dams, the severe shortages in Rabi season have been eased to great extent and the area under cultivation is increased from 23 million acres in mid 60s to 36 million acres today. The annual canal diversion of 91.3
BCM in 1966 now has been reached to 130 BCM today. The water supply contribution in critical Rabi season is jumped from 27.3 BCM of pre dam period (1931-67) to 39.3 BCM of post dam period (1976-08) (Fig 3, 4). The river contribution in Kharif period is also increased from 64 BCM in pre dam period to 83 BCM of 34 year post dam period. The average post dam (1976-08) discharge has been increased by 44% in Rabi and 30% in Kharif, where as annual withdrawals have been improved by 30%. Since last 34 years, after development of last reservoir in 1976, three reservoirs have lost almost about 5.0 BCM or 26% of their storage capacity due to siltation (Fig 4).

It is estimated that by the year 2025, (Fig. 3) this loss would increase to 14.5 BCM, almost 75% of the original combined storage capacity of three reservoirs. With a large arable land, Pakistan still has the potential of bringing several million acres of virgin land under irrigation. Although river flows are fully utilized, large chunk of flood water in Kharif period is still unexploited and escapages to Arabian Sea. After adjustment of current 85 BCM Kharif crop water requirements, 45 BCM Rabi crop water requirements and 12 BCM release for Indus deltaic region allocated under Indus water distribution accord 1991, still 30 BCM water remain unexploited.

Due to improved regulatory capability, reservoirs will provide great flexibility in controlled inter seasonal and inter-year transfer of river flows to substantially increase water supply for agricultural production, generate cheap hydropower and reduce flood losses. All above facts and figures clearly supports the additional water availability in river system and favors’ the construction of proposed dams.

3. RESULTS

Study Area Characteristics

The Hunza tributary with catchment area of about 14746 km² is located in upper Indus basin within western Karakoram ranges of Pakistan. It is an important tributary of Indus River System. It is high altitude basin with elevation ranges from 968 m to over 7500 m a.s.l (Fig 5). The Hunza basin consists of alpine climatic conditions, where annual precipitation ranges between 1400 to 1500 mm while mean monthly temperature varies between -20°C in winters to +28°C in summers (Fig 6). The westerly weather disturbances deposit nearly all the precipitation during the winter months and most of precipitation falls in the form of snow in this season. The monsoon rains have very little influence in this particular basin, as compared to the main Himalayan ranges.

Valleys receives less than one fifth of total annual precipitation, while most of precipitation is deposited between middle and upper part of the basin. The maximum snow cover area exists in March and extends till the melting process starts in May/June. About 35% of the total basin area is perennial glacial ice field with about 808.79 km³ ice reserves (Fig 5,6). The flow regime is highly seasonal; with the highest flows occurring in Khareef season, e.g., between June and September, when snow and ice melt on the mountains cause a peak discharge, while minimum flows occur in Rabi season, e.g., November to February, when most of the precipitation falls in form of snow.
Model Application and Calibration

The quality of a hydrological simulation in mountainous regions depends on its ability to consider the very heterogeneous physical (topography, land use, land cover, soil) and meteorological variables typical of such a region. The distributed hydrological modeling system PREVAH (Precipitation-Runoff-Evapotranspiration Hydrotrope Model) has been developed to suit such conditions present in mountainous catchments (Viviroli et al., 2009). Since its development it has been successfully applied to various hydrological and/or climatological studies in mountainous catchments (Gurtz et al., 2003; Zappa et al., 2003; Verbunt et al., 2006; Vanham et al., 2008a; Vanham et al., 2008b). The details about model can be seen in (Viviroli et al., 2009). For this particular study, the 10 year time series of daily flow from the gauge station Dainyor Bridge on the Hunza River have been used for calibration and validation purposes. The first 3 years have been used for calibration, while the whole period (1990-1999) was used for validation processes. The mean annual efficiency for the calibration and validation period is above 80%, while the measured and simulated mean annual stream flow difference amounts to less than 5%. The calibration/validation results indicate that the basin characteristics are well reproduced by the model. The simulated mean annual water balance components (1990-1999) are shown in (Table 1) respectively.

Table 1 Mean simulated annual water balance of the Hunza basin for the period 1990-1999 (mm year^{-1})

<table>
<thead>
<tr>
<th>Water balance components</th>
<th>PREVAH Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed runoff (mm)</td>
<td>686</td>
</tr>
<tr>
<td>Simulated runoff (mm)</td>
<td>659</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
<td>1434</td>
</tr>
<tr>
<td>Evapotranspiration (mm)</td>
<td>117</td>
</tr>
<tr>
<td>Storage change (mm)</td>
<td>+652</td>
</tr>
<tr>
<td>Volume deviation (mm)</td>
<td>-27</td>
</tr>
</tbody>
</table>

The change in water storage could be explained by an increase in glacier mass. The mass balance measurements are not available. Therefore the calculated change in glacier mass can not be checked against measurements. However, the positive change in mass balance is in good agreement with the studies conducted by (Hewitt 2005 and Fowler and Archer 2006), which indicated glacier surges particularly in this Hunza basin. The calibrated model was then used to investigate the hydrological behavior of the basin under a future warmed climate. The detailed study about model structure, parameterization or calibration/validation processes can be referred to (Verbunt et al. 2006 and Viviroli et al. 2009).

Hydrological Modeling of Hunza basin

In this study attempts are made to investigate the climate change impact on total stream flow for a highly glacerized high altitude Hunza river catchment which is one of the major tributary of main Indus River. The adopted climate scenarios ranging from 1 to 4°C temperature change were based on ensemble of 9 global model predictions for the studied region in 21st century. (Fig 7) illustrates the effect of temperature on monthly stream flow volume. It is clearly seen that the increase in temperature systematically increased monthly flows. The findings are quite in contrast to earlier findings in high altitude basin that mean annual water availability in generally and summer in particularly will be reduced under warmer climate (Singh and Bengtsson, 2004).
However, for this specific very low temperature regime basin, where 31% of the total basin area remains under ice cover and more than 85% precipitation fall as in snow, the increase of 1 to 4 °C thus results in more melting runoff. The timing of peak stream flow is not affected; however, the magnitude of peak stream flow is changes as temperature increases. The maximum change in monthly flows is observed from May to August. A large increase in these months is due to higher amounts of snow melt runoff and earlier glacier melt contribution due to warmer climate. The resulting shift in monthly flows has significant effect on magnitude of seasonal and annual flow regime of basin. The increase in temperature from 1 to 4 °C will change seasonal flow from current reference contribution (24%) to (34.4-45.6%) and (67.7%) to (74.8-81.5%) in total flow for winter (Oct-Mar) and summer (Apr-Sep) flows respectively. As contrary to some hypothesis (Vanham et al., 2008b and 2009), that increases in temperature result in a conversion of much of the winter precipitation to rainfall and early snowpack decline produce higher winter flows, the winter flow regime of this specific basin is not affected significantly. As the temperature regime of this particular basin in winter months is below freezing point, therefore the increase of 1 to 4°C have no any influence over form of precipitation or melting process. However, the higher increase in monthly flows from April to August are in good agreement of an earlier findings (Laghari et al., 2009) that temperature sensitivity seems to be confined to spring and summer months. The maximum effect of increased temperature is found on glacier melt runoff as compared to snow melt runoff. However, snow melt contribution in total flow is still dominating than to ice melt contribution. This high altitude basin, which contains snow fields/glaciers throughout the ablation period, more melt is generated under a warmer climate. On a basin scale, reduction in snowmelt from lower part is compensated through the increase in from middle part i.e. 3500-5500 m a.s.l. The glacier melt contribution comes only through middle zone. However, the increase in air temperature for a longer time will reduce snow cover in shorter time, thus expose glacier area early to warmer climate and hence glaciers will retreat because of their depletion under these conditions.

**Future Water Availability Scene for Main Indus River**

The Hunza River is a major tributary of main Indus River which forms an important part of the Indus river system. Both rivers receive substantial contributions from snow and glacier melt runoff to annual stream flows. The flow pattern of both rivers shows identical percentage changes in their monthly volumes. The 25 year (1976-2000) monthly flow (percent of annual flow) data of both rivers clearly indicates that any changes observed in Hunza tributary is proportionally reflected in main Indus River. This could be seen in Fig 8, which shows co-relationship between Main Indus River and its tributary Hunza River. The value of coefficient of determination $R^2$ shows good agreement between monthly flows and thus any % changes in future water availability in Hunza tributary could be adopted for main Indus River. The value of (%) change in water availability in Hunza River is therefore applied to regression equation given in (Fig 8) to quantify the % change in future water availability in main Indus River. Under all adopted scenarios, the rise in temperature from 1 to 4 °C have substantially increased mean annual and seasonal water availability in main Indus River. The mean annual figure of Indus River, even at 1°C shows sufficient water availability for proposed reservoirs (Table 2).
reservoirs, as it will not only reduce the threat of floods but enhance the present capacity of regulating and utilizing surpluses water for crop irrigation in much needed times particularly during low flow period of the winter season and early and late summer season.

Table 2 Main Indus River water availability scene under adopted warmer scenarios

<table>
<thead>
<tr>
<th>Climate scenarios</th>
<th>Water availability (BCM)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Winter (Oct–Mar)</td>
<td>Summer (Apr–Sep)</td>
<td>Mean annual</td>
</tr>
<tr>
<td>1 °C</td>
<td>18.77</td>
<td>114.22</td>
<td>132.99</td>
</tr>
<tr>
<td>2 °C</td>
<td>21.55</td>
<td>127.85</td>
<td>149.40</td>
</tr>
<tr>
<td>3 °C</td>
<td>25.10</td>
<td>141.68</td>
<td>166.77</td>
</tr>
<tr>
<td>4 °C</td>
<td>28.26</td>
<td>157.42</td>
<td>185.69</td>
</tr>
</tbody>
</table>

4. CONCLUSION

The objective of this study is to provide an overview of potential implications of climatic variability on the flow regime of the Hunza basin and consequent changes upon flow regime of main Indus River and subsequent future water availability for proposed reservoirs. The temperature increase of 1 to 4°C have resulted in an increase of about 16.6%, 33.08%, 49.66% and 68.57% respectively in current mean annual total flow volume of Hunza basin. The major contribution comes from summer months, while flow situation in other months remain same. In this high altitude basin, the climatic sensitivity is seems limited to summer season, particularly to lower and middle part of the basin, while upper part of the basin remains unaffected. The other main finding of this study is identical percentage change in monthly contribution to total flow volumes of Indus River and its tributary Hunza, as major contribution in both rivers comes from snow and ice melt runoff. The regression coefficient was above 90%. The relationship was used to estimate the water availability in main Indus River. An increase of 1 to 4°C have resulted in an increase of about 2.35 to 11.84 BCM in winter flows and 15.51 to 58.71 BCM in summer flows, while 17.86 to 70.56 BCM increase were recorded in mean annual flows. It is quite clear that massive increase in annual flows justifies the construction of new reservoirs, as it will not only reduce the threat of floods but enhance the present capacity of regulating and utilizing surpluses water for crop irrigation in much needed times particularly during low flow period of the winter and early and late summer season. However, the above conclusion is based on one basin study; it is therefore recommended that similar studies should be carried out in other catchments of Indus basin, having seasonal snow cover and permanent ice fields, so as to assess any influence over basin hydrology and water resources.

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

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Abstract. The Indus basin is one of the regions in the world that is faced with major challenges for its water sector, due to population growth, rapid urbanisation and industrialisation, environmental degradation, unregulated utilization of the resources, inefficient water use and poverty, all aggravated by climate change. The Indus Basin is shared by 4 countries – Pakistan, India, Afghanistan and China. With a current population of 237 million people which is projected to increase to 319 million in 2025 and 383 million in 2050, already today water resources are abstracted almost entirely (more than 95 % for irrigation). Climate change will result in increased water availability in the short term. However in the long term water availability will decrease. Some current aspects in the basin need to be re-evaluated. During the past decades water abstractions – and especially groundwater extractions – have augmented continuously to support a rice-wheat system where rice is grown during the kharif (wet, summer) season (as well as sugar cane, cotton, maize and other crops) and wheat during the rabi (dry, winter) season. However, the sustainability of this system in its current form is questionable. Additional water for domestic and industrial purposes is required for the future and should be made available by a reduction in irrigation requirements. This paper gives a comprehensive listing and description of available options for current and future sustainable water resources management (WRM) within the basin. Sustainable WRM practices include both water supply management and water demand management options. Water supply management options include: (1) reservoir management as the basin is characterised by a strong seasonal behaviour in water availability (monsoon and meltwater) and water demands; (2) water quality conservation and investment in wastewater infrastructure; (3) the use of alternative water resources like the recycling of wastewater and desalination; (4) land use planning and soil conservation as well as flood management, with a focus on the reduction of erosion and resulting sedimentation as well as the restoration of ecosystem services like wetlands and natural floodplains. Water demand management options include: (1) the management of conjunctive use of surface and groundwater; as well as (2) the rehabilitation and modernization of existing infrastructure. Other demand management options are: (3) the increase of water productivity for agriculture; (4) crop planning and diversification including the critical assessment of agricultural export, especially (basmati) rice; (5) economic instruments and (6) changing food demand patterns and limiting post-harvest losses.

1 Introduction

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

Different aspects of the water cycle in the Indus basin have been the subject of several studies, e.g. hydrology and available water resources (Winiger et al., 2005; Archer, 2003; Immerzeel et al., 2010; Kaser et al., 2010), the impact of climate change.
change on glaciers and the hydrological regime (Akhtar et al., 2008; Immerzeel et al., 2010; Tahir et al., 2011), agricultural water demands and productivity (Cai and Sharma, 2009, 2010), groundwater management (Kerr, 2009; Qureshi et al., 2009; Scott and Sharma, 2009; Shah et al., 2006), reservoir sedimentation (Khan and Tingsanchali, 2009), ecological flows and the Indus delta (Leichenko and Wescot, 1993), water policy (Biswa, 1992; Miner et al., 2009; Shah et al., 2006, 2009; Sharma et al., 2010) and water resources management (Archer et al., 2010; Qureshi et al., 2009).

Within the two latter publications the major challenges facing the Indus basin were described, as well as recommendations for sustainable water management. However, both papers have certain limitations. They both focused only on Pakistan, although 40 % of the basin’s surface area is located within 3 other countries. Qureshi et al. (2009) focused on groundwater. The recommendations for sustainable water management within Archer et al. (2010) were far from complete, as not all available options were accounted for. Within this latter paper the focus is on water supply management options. The part on “water resources management” is not sufficient, and water demand management options are not addressed. In a world with finite (water) resources the solution is not only in supply management but sustainable management options require the inclusion of demand management practices. The aim of this paper is to give an overview on all relevant recommendations for the whole Indus basin.

This paper gives a comprehensive listing and description of all available water resources management options and does not restrict itself to the Pakistani part of the Indus basin. Especially the Indian part of the basin is also included in the analysis. Also the topic of flooding and especially the massive floods of 2010 are discussed. The paper also gives a comprehensive overview on water balance quantities obtained from different sources, which is currently not available in the literature.

2 The Indus basin

2.1 General

The Indus basin is located in 4 countries, of which the largest part in Pakistan, and substantial upstream parts in India, China and Afghanistan (Fig. 1). More than 40 % is located at an elevation higher than 2000 m a.s.l. The total hydrographic basin – as defined by the International Water Management Institute (IWMI) – has an area of 1 137 819 km². Other authors (Babel and Wahid, 2008; Eastham et al., 2010; Harrington et al., 2009; Hoekstra and Mekonnen, 2011; Jain et al., 2009) indicate an area range from 1 080 000 to 1 218 500 km². Of a total population of about 237 million (Fig. 1), Pakistan accounts for 61 % (145 million) and India for 35 % (83 million). Another 4 % (9 million) live in the Afghani part of the basin, and the Chinese population is very little due to the rough Himalayan landscape character of this part of the basin. Of the irrigated area (228 694 km², 21 % of basin area) about 60.9 % is located in Pakistan, 37.2 % in India, 1.9 % in Afghanistan and 0 % in China. The Indus Basin Irrigation System (IBIS) is the largest irrigation system in the world. Water demands are thus by far the highest in Pakistan followed by India. The focus of this paper will therefore be on these two regions.

The wettest regions of the Indus basin are on the southern slopes of the Himalaya-Karakoram-Hindu Kush (HKH) mountain range (Fig. 2). The high mountain ranges in the north of the basin – like Ladakh in India – are very dry, as well as the lowlands. The aridity index within the basin ranges from humid to hyper-arid. The glacial area is very large, i.e. 37 134 km² according to the DCW database (Raup et al., 2000). Within the GLIMS-Database (Armstrong et al., 2005) glaciers from India and Pakistan are missing. The latter is definitely more accurate than the DCW database, which overestimates the glacial area for the region. Other sources that refer to the GLIMS-database indicate within the Indus basin a glacial area of about 22 000 km² (Immerzeel et al., 2010) or 20 325 km² (Kaser et al., 2010). These values are more realistic estimates.

2.2 Water balance

General water balance components have been quantified by different authors and are shown in Fig. 3. Based upon computations from the 2 datasets (GWSP, 2008; Hijmans et al., 2010) or 20 325 km² (Kaser et al., 2010) annual 0.3 m for the Upper Indus basin (Sharma et al., 2008; IUCN, 2010) or 252 mm (Eastham et al., 2010; Harrington et al., 2009). Especially for the mountainous part of the basin the latter authors state much higher precipitation values, e.g. annually 1130 mm for the entire Upper Indus basin. This is a very high value as compared to other sources, e.g. Bookhagen and Burbank (2010) state annually 0.3 m for the Upper Indus basin or Immerzeel et al. (2009) state 340 mm. These amounts are coherent with the precipitation map of Fig. 2b, where it is shown that the high mountain ranges in the north of the basin are very dry.

Total basin long term average water availability – renewable water resources – (surface and groundwater) adds up to 287 km³ (Sharma et al., 2008; IUCN, 2010) or 252 mm annually. The Indian part of the basin (including the Chinese upstream part) accounts for 97 km³ whereas the Pakistani part (including the Afghan upstream part) accounts for
Basin long term average surface water availability is in the order 239 km$^3$ (Hoekstra and Mekonnen, 2011) to 258 km$^3$ (Gupta and Deshpande, 2004; Kreutzmann, 2011; Sharma et al., 2008). In India, surface water availability is 73 km$^3$ (Gupta and Deshpande, 2004; Sharma et al., 2008) and the Pakistani part accounts for 175 km$^3$ (Briscoe and Qamar, 2007) or 185 km$^3$ (Kreutzmann, 2011). This includes 165 km$^3$ from the 3 western rivers (Indus, Chenab, and Jehlum) and 10 km$^3$ from the eastern rivers (Ravi, Beas, and Sutlej). Afghani surface water availability is 25 km$^3$ (Qureshi, 2011) and is included in the latter Pakistani volumes. Replenishable groundwater resources in India are 27 km$^3$ (Sharma et al., 2008) and in Pakistan 63 km$^3$ (Briscoe and Qamar, 2007; Qureshi, 2011). There is an overlap between available surface water resources (about 250 km$^3$) and replenishable groundwater resources (about 100 km$^3$). Especially in Pakistan, a substantial part of available water resources diverted in the IBIS canal system leads to the recharge of the groundwater reservoir. According to Van Steenbergen and Gohar (2005), only 21% (14 km$^3$) of the Pakistani replenishable groundwater resources (total 63 km$^3$) originate directly from rainfall. About 45% originate from recharge from the canal system, 26% from irrigation return flows and 6% from river recharge. The remaining 2% originate from other return flows. The Indus Basin is underlain by an extensive unconfined aquifer that covers 16 million ha of surface area, of which 6 million ha are fresh and the remaining 10 million ha are saline (Qureshi et al., 2008).

Irrigated agriculture currently accounts for more than 95% of blue water withdrawals in the Indus basin (Fig. 3). The major agricultural zones are located in the Pakistani and Indian provinces of Punjab (Fig. 4).
in Pakistan is an important agricultural area as well as the Indian province of Haryana; the major irrigation system is located in these regions. The harvested area of the three crops wheat, rice and cotton represent 77% of the area of all crops harvested under irrigation (33 million ha) (Fig. 4). Total water withdrawals in India add up to 98 km$^3$ (Saleth and Amarasinghe, 2009), of which 94 km$^3$ is for irrigated agriculture (55 km$^3$ or 59% as groundwater, 39 km$^3$ or 41% as surface water). Total water withdrawals in Pakistan add up to 180 km$^3$ (Briscoe and Qamar, 2007; Qureshi, 2011), of which 128 km$^3$ (71%) as surface water and 52 km$^3$ (29%) as groundwater. However, as indicated before the distinction between both is not absolute. A large fraction of the replenishable groundwater originates from surface water. In the Afghani part of the basin about 10 km$^3$ are withdrawn, of which 96% is for irrigated agriculture. Water abstractions in the Chinese part of the basin are neglectable.

Water consumption values (Fig. 3) show that only about 11% of domestic water in the basin is consumed, the remaining 89% returns to the system. Industrial water is returned at 91% back to the system. There is also a large gap between water withdrawals for irrigation and actual water consumed for crop production. Dependent on the source and the assessed period, water consumption by crops in the whole basin is estimated in the range 117 to 143 km$^3$ (GWSP, 2008; Immerzeel et al., 2010; Mekonnen and Hoekstra, 2010b). Harrington et al. (2009) estimate much higher values. Total crop consumption in India amounts to 35 km$^3$ (Saleth and Amarasinghe, 2009) for 94 km$^3$ withdrawn. The total consumption in the Pakistani part for irrigation ranges from 69 km$^3$ to 99 km$^3$ (GWSP, 2008; Kreutzmann, 2011). Irrigation efficiencies are low. Much of the surface water that enters the system is wasted (also to groundwater recharge). This is responsible for the continuous shortage of irrigation water in Pakistan and especially in tail-enders such as the Sindh province. Pakistan is close to using all its available water resources in most years in the current situation. Of the replenishable groundwater resources of 63 km$^3$, 52 km$^3$...
is used. Of the available surface water resources of 175 km$^3$, about 75%, is withdrawn. In a system with little storage and considerable variability, average values can however be deceptive. Summer or monsoon crops (kharif, autumn harvest) and winter crops (rabi, spring harvest) have different demands and water availability during these periods also differ.

Mekonnen and Hoekstra (2010b) calculated both the blue water consumption (irrigated consumption) and green water consumption of crops in the Indus basin. Large regions within the basin—with extensive agriculture—are rainfed. Irrigation of wheat, rice, cotton and sugarcane crops account for 90% of the total blue water consumption in the basin (Fig. 3). The same crops and maize account for 67% of total green water evapotranspiration in the basin.

The remaining river flow to the sea ranges from 35 to 64 km$^3$ (Briscoe and Qamar, 2007; Karim and Veizer, 2002; Kreutzmann, 2011).

3 Major challenges

3.1 Introduction

Major challenges are foreseen for the water sector in the Indus basin. The region is under extreme pressures of population and poverty, unregulated utilization of the resources and low levels of productivity (Sharma et al., 2010). Population within the basin is projected to increase—with resulting higher water demands—and changes in water availability are
predicted (Archer et al., 2010). On the short term climate change is expected to have a positive effect on available water resources, however, on the long term this effect will be negative. The following gives an overview of challenges for the Indus basin:

- Water resources changes due to climate change.
- Population increase and increased urbanisation and industrialisation, resulting in higher water demands for domestic and industrial purposes, food production and energy.
- A shift from surface water to groundwater use resulting in rapid depletion of groundwater resources – an observation made for both the Indus and Ganges basins.
- Flooding

Other challenges include the low water productivity in food production at particular locations; a declining reservoir storage due to sedimentation; water logging and salinity, loss of productive agricultural land, land degradation, contamination of surface and groundwater resources; an increase in environmental flows to sustain ecosystems within the rivers and the Indus delta, but also to prevent further salt water intrusion in the delta; and tension between riparian countries. The first 4 challenges are discussed more in detail within the following Sects. 3.2 to 3.5. The section with recommendations (Sect. 4) will however answer to all listed challenges.

### 3.2 Water resources changes due to climate change

Water from the sparsely inhabited upstream mountains in the Indus basin is essential for the densely inhabited semi-hyper-arid lowlands (Fig. 2) with its extensive irrigation system. In many basins with mountainous regions, the seasonal storage of water in snow and ice is very important for the lowlands, so that water resources management analyses need to be conducted on at least a seasonal level (Vanham et al., 2008). Also basins with monsoonal regimes like the Indus basin require water resources management analyses on at least a seasonal level (Vanham et al., 2011b), as both available water resources and water demands (Vanham et al., 2011a) fluctuate over time. Total surface water availability in the basin has its peak in the summer months (kharif) whereas water availability is generally lower during the winter months (rabi) (Fig. 3). During the winter months...
November to February, average monthly surface water availability is about 10 km$^3$ whereas during the summer months July to September this value is larger than 30 km$^3$. In systems with considerable water availability and demand variability, averages can therefore be deceptive.

Immerzeel et al. (2010) showed that meltwater is extremely important in the Indus basin. For the present day climate, discharge generated by snow and glacial melt is 151% of the total discharge naturally generated in the downstream areas. About 40% of the meltwater originates from glaciers, 60% from snowpack. Also Kaser et al. (2010) stress the importance of glacial melt water to the Indus flow, as well as Tahir et al. (2011). Bookhagen and Burbank (2010) calculated the meltwater contribution to annual discharge for the major southern Himalayan catchments where the rivers flow into the plains (at the foot of the Himalayas): 66% for the Indus, 25% for the Jhelum, 43% for the Chenab, 16% for the Ravi, 21% for the Beas and 57% for the Sutlej river. Further downstream these fractions become smaller. The regimes in the basin are (Archer, 2003):

- A nival regime at middle altitudes with flow dependent on the melting of seasonal snow. The greatest contribution to total flow comes from this regime.
- A glacial regime at very high altitudes with river flow closely dependent on summer temperatures.
- A rainfall regime dependent on runoff from rainfall mainly during the monsoon season. This regime dominates on the southern foothills of the Himalayas (Fig. 2) and also over the plains but with much reduced total amounts.

Climate change will definitely affect the temporal and spatial availability of water resources. A listing of potential effects and studies conducted on the three hydrological regimes is given in Archer et al. (2010). Also Immerzeel et al. (2010) indicate that upstream snow and ice reserves of the Indus basin, important in sustaining seasonal water availability, are likely to be affected substantially by climate change, but to what extent is yet unclear. A new study by Scherler et al. (2011) actually indicates that debris coverage may be a missing link in the understanding of the decline of glaciers in the HKH. Controversy about the current state and future evolution of Himalayan glaciers has been stirred up by erroneous statements in the fourth report by the IPCC. According to Scherler et al. (2011), glaciers in the Karakoram region are mostly stagnating. This anomaly was already described by Hewitt (2005). However, glaciers in the Western, Central, and Eastern Himalaya are retreating. Half of the studied glaciers in the Karakoram region are stable or even advancing, whereas about two-thirds are in retreat elsewhere throughout High Asia. Also Tahir et al. (2011) concluded a rather slight expansion of cryosphere during the period 2000–2009 in the Hunza basin in the Upper Indus. This is in contrast to the prevailing notion that all glaciers in the HKH are retreating. Basically glaciers in the Central Karakoram are stagnating or even expanding, whereas glaciers in the Afghani part and the western Himalayas part of the Indus basin are retreating. An overview on this situation is given in Fig. 5.

There is general consent that in the Indus basin climate change will result in increased water availability in the short term. However in the long term water availability will decrease. Immerzeel et al. (2010), for example, indicate a decrease in mean upstream water supply from the upper Indus ($-8.4\%$) by 2046–2065 with respect to the reference period 2000–2007. The authors indicate that these changes are considerable, but they are less than the decrease in meltwater production would suggest, because this reduction is partly compensated for by increased mean upstream rainfall (Indus +25%). Regardless of the compensating effects of increased rainfall, summer and late spring discharges are eventually expected to be reduced consistently and considerably around 2046 to 2065 after a period with increased flows due to accelerated glacial melt. The authors also analyzed an extreme scenario in which all glaciers are assumed to have disappeared, for which the Indus shows the largest reduction in water availability of all major Himalayan rivers. Mukhopadhyay (2012) states similar conclusions. According to the author, global warming is expected to dramatically alter the flow regime of the Upper Indus river. The predicted change in flow regime is an initial increase in summer flows in the early decades of 21st century followed by a sharp decline of the same during the latter parts of the century. Similar results were found for the Sutlej river (Singh and Bengtsson, 2004).

Although the effects of climate change will not be as visible in the short term, they will be prominent on the long term. Reduced water availability will be the most profound during the spring and summer months. Water from the snow and glacier melt will appear earlier than the main monsoon flows.

### 3.3 Increase in population

Water demand increases for domestic and industrial purposes, food production and energy relate primarily to the predicted population increase in the basin, associated with an increase in urbanisation and industrialisation but also an increase in living standards. The current population in the basin of 237 million is projected to grow to 319 million in 2025 and 383 million in 2050 (medium population estimates) or 336 million in 2025 and 438 million in 2050 (high population estimates) (Fig. 6). Substantial population increases are predicted in all Pakistani and Indian Indus basin regions. Kabul is located in the Indus basin, and its population has tripled in size since late 2001, to approximately 4.5 million people, making it perhaps the world’s fastest-growing city in the last eight years (Lashkaripour and Hussaini, 2008;
3.4 Shift from surface water to groundwater use

During the last decades there has been a shift from surface water resources to groundwater resources within the Indus basin, for irrigation but also for domestic and industrial purposes. On demand availability of groundwater has transformed the concept of low and uncertain crop yields (before predominantly fed with surface water) into more assured crop production (Qureshi et al., 2009). The availability of inexpensive drilling technologies allows even poor farmers to access groundwater. Over 80% of the groundwater exploitation in Pakistan takes place through small capacity private tube wells. During the last decades, the number of tube wells in the main agricultural zones of the Indus basin has increased dramatically. By the early 1960s, an estimated 23 % of Pakistan’s land suffered from waterlogging and crop root zone salinity. Initial response was through the SCARP-project, which aimed at lowering the groundwater table by means of the installment of 13 500 publicly owned and operated tubewells (Qureshi et al., 2008).

However, the main change came by the independent decision of farmers to use groundwater as a substitute or to supplement for direct surface water irrigation. The explosion in the installation of private tubewells within the Pakistani provinces in the Indus basin is shown in Fig. 7a. With a total of about 822 000, more than 85 % of private tubewells are currently located in the Punjab province. Especially after 1990 the increase in private tubewells went extremely fast. In 2005 the total amount was almost 1 million. The amount of public tubewells was only 20 000 (GOP, 2005). As a result, groundwater abstraction in Punjab from 1965 to 2002 has increased from 9 km$^3$ to 45 km$^3$ (Qureshi et al., 2009). The total groundwater withdrawal in the Pakistani part of the basin currently amounts to 52 km$^3$ (Fig. 3). In the Indian states of the Indus basin the same observation can be made. Figure 7b shows the changes in net irrigated area under surface water and groundwater from 1993–1994 to 2000–2001 in the main provinces of the Punjabs and Sindh. Over this period, for example, the net irrigated area under surface irrigation in Pakistani Punjab decreased from 4.2 to 3.7 million ha (decrease of 12 %) and the net irrigated area with groundwater increased from 8.8 to 10.3 million ha (increase of 18 %). The same observation is made in Sindh and Indian Punjab. In the latter the net irrigated area under surface irrigation...
between extraction and replenishment. Water tables are falling at alarming rates, both on the Pakistani (Qureshi et al., 2009; Tiwari et al., 2009) and Indian sides (Rodell et al., 2009; Sundarajan et al., 2008; Tiwari et al., 2009). For the Indus basin Tiwari et al. (2009) estimated a change (loss) of terrestrial water storage of about 10 km$^3$ yr$^{-1}$ between April 2002 and June 2008. The Indian Ministry of Water Resources (Indian M.W.R., 2011) lists for the Indian states of Punjab and Haryana an annual overdraft of 9.89 km$^3$ (stage of groundwater development 145 %) and 1 km$^3$ (stage of groundwater development 109 %), respectively. Excessive lowering of the groundwater table has made pumping more expensive. As a result, many wells have gone out of production, yet the water table continues to decline and salinity increases.

A factor which also contributed to the increase in groundwater withdrawals is simply the increase in cropped and irrigated areas during the past decades as well as the increased cultivation of more water intensive crops like rice, cotton and sugarcane. The harvested area of these crops accounted for 20 % 13 % and 3 %, respectively, of all harvested area under irrigation in the year 2000 (Fig. 4). The principal regions where these crops are grown are the both Punjabs and to a lesser extent Haryana and Sindh. The irrigation of these 3 crops accounts for 28 % 19 % and 13 %, respectively, of the total blue water consumption in the basin (Fig. 4). These values show their water intensive nature as compared to the harvested areas. Figure 8a shows the increase in both the area (million ha) and production (million t) of rice (basmati and other varieties) in Pakistani Punjab from 1987–1988 to 2004–2005. Note the increasing gap between area and production due to increased yields. Punjab accounts for more than 50 % of the total rice production and more than 90 % of the total basmati production in Pakistan. About 70–80 % of rice produced in the province is basmati. However, large quantities of rice produced in Pakistan are for export (Fig. 8b). From 2001 to 2005, about 40–60 % of all rice produced in Pakistan was exported. Basmati exports increased from 0.6 to 0.9 million t during that period.

3.5 Flooding

Flooding has always been an issue in the Indus basin (Tariq and van de Giesen, 2011). Monsoon rainfalls are the main source of floods in the basin. High flows are experienced in summer due to the increased rate of meltwater and monsoon rains. The nature of flooding varies according to geography. Fluvial floods in the Indus plain prove most devastating, as the terrain is flat, densely populated and economically developed. Hill torrents (flash floods) are the second most destructive type of flood.

The July–August 2010 floods in Pakistan were one of the greatest river disasters in recent history (Gaurav et al., 2011; Houze et al., 2011; Mustafa and Wrathall, 2011; Webster et al., 2011). More than 20 million people were affected.
almost 2000 lost their lives and financial damages were in the range of 40 billion dollars (Webster et al., 2011). Although excessive rainfall has been cited as the major causative factor for this disaster (Houze et al., 2011; Tariq and van de Giesen, 2011), the human interventions in the river system over the years made this disaster a catastrophe (Gaurav et al., 2011). Also its geomorphic character with a high sediment load, typical for many Himalayan rivers, adds to the extent of the catastrophe and the unpredictability of the river. As a matter of fact, Gaurav et al. (2011) compare the 2010 Indus floods to the Kosi disaster in 2008 in India because of many similarities. The average annual sediment load – originating from the relatively young Karakoram and Himalaya mountains ranges – of 291 million t per year (Gaurav et al., 2011), ranks the Indus as one of the highest sediment load carrying rivers in the world.

Geomorphic analysis suggests that the Indus River has had a very dynamic regime in the past. However, the river has now been constrained by embankments on both sides, cutting it off from its natural floodplains. Barrages and dams were built. Flood control strategies on Himalayan rivers are primarily embankment based. Therefore the river has been accumulating sediment and aggrading rapidly during the last decades, making it a “superelevated river” in several reaches, which is considered to be prone to avulsion. Deforestation in the basin has led to increased erosion and sedimentation (Da Silva and Koma, 2011; Ali et al., 2005), as well as faster flood runoffs. The draining of natural wetlands has increased flooding. The wetlands that once surrounded the Indus River tamed floods, by regularly taking up parts of flood waters during monsoonal seasons and slowly releasing them again.

Change in flow regimes due to low flows in eastern rivers after the Indus Water Treaty and enhanced flood protection measures have attracted economic activities and settlements in the floodplains, in a country with an increasing population and substantial poverty. Vulnerability on such locations has increased due to a false sense of safety. Due to increased settlements and constructions in the floodplains, water that enters the inundation zone has its drainage path back to the main river interrupted by levees, roads, railway lines and canal embankments. The result is that water does not drain back. The relationship between anthropogenic environmental degradation and catastrophic flooding is well documented (Mustafa and Wrathall, 2011). Conversely, we know there is an established link between healthy watersheds with flow capacity – wetlands, marshes, estuaries and mangroves – and flood mitigation. This disaster has stressed the urgent need to move from “river control” to “river management” strategies. The latter will be discussed in the following Sect. 4.1.4 “Land use planning and soil conservation; flood management”.

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

Literature on solutions and alternative policy options for future sustainable WRM in the Indus Basin and India in general include (Gupta and Deshpande, 2004; Kumar et al., 2005; Sharma et al., 2010; Thakkar, 2008). Sustainable WRM practices include the management of water supply and the
managing of water demands. Applicable practices for the Indus basin are discussed in the following sections. Section 4.1 discusses water supply or availability management, Sect. 4.2 water demand management and Sect. 4.3 discusses the topic of international collaboration.

4.1 Water supply-availability management

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

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

The 25 largest reservoirs in the basin represent a volume of 48.7 km$^3$ (Fig. 3) – based upon the dataset of Lehner et al. (2008). Of this volume 22.2 km$^3$ is located in India, especially in the reservoirs of the Pong Dam (8.6 km$^3$) on the Beas River, Bhakra Dam (9.6 km$^3$) on the Sutlej River and Thein Dam (3.7 km$^3$) on the Ravi River. In Afghanistan the two included dams represent a volume of 0.6 km$^3$. The remaining reservoir volume (26 km$^3$) is located in Pakistan, especially in the reservoirs of the Tarbela Dam (13.9 km$^3$) on the Indus River, Mangla Dam (7.3 km$^3$) on the Jhelum River and Kalkri Lake (2.5 km$^3$). However, a decline of reservoir storage due to sedimentation is observed in the Indus basin. The Indus River and its tributaries carry a very high sediment load which has seriously affected the storage capacity of these dams (Archer et al., 2010). The live storage capacity of the Indian dams is estimated to be 16.3 km$^3$ (CWC, 2010). Sedimentation resulted in a reduction of 28 % in the initial capacity of 13.9 km$^3$ of Tarbela – commissioned in 1978 – by 2000 and the useful life of the dam is now estimated to be 85 yr (Archer et al., 2010). Similarly, the capacity of Mangla – completed in 1967 – was reduced by 20 % by 2007, although a current project to raise Mangla will soon restore the capacity to an amount greater than when originally constructed (Archer et al., 2010). Of a total volume of 48.7 km$^3$ about 39 km$^3$ is currently available (when the Mangla volume is supposed to be 100 % active). Replenishable groundwater resources amount to a volume of 27 km$^3$ in India and 63 km$^3$ in Pakistan (Fig. 3). When the latter are regarded as natural buffer or reservoir, the total reservoir volume is 129 km$^3$. Nevertheless, unless new storage dams are built there will be a progressive reduction in active storage, which will seriously limit the capacity to transfer surplus summer flow to the winter (wheat) crop and downstream irrigation will return to run-of-river management. As described in the Sect. 3.2 “Water resources changes and climate change”, on the long term there will be a substantial reduction of water availability during spring and summer. To compensate this, an increase in water storage is required. The loss of existing storage volume due to sedimentation needs to be reduced to...
a minimum by means of land management measures as described in the following Sect. 4.1.4 “Land use planning and soil conservation; flood management”.

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

Apart from these multipurpose dams, decentralised rainwater harvesting can have a small impact in the Indus basin. Rainwater harvesting also prevents soil erosion, an essential matter in the basin. It can focus on (1) capturing water for domestic use (e.g. by rooftop rainfall collection); (2) replenishing green water (e.g. through stone bunds on the contour line); or (3) increasing blue water availability locally (e.g. through small check dams that increase recharge to the groundwater or store water in small reservoirs). Decentralised water harvesting is definitely an important factor for poor communities.

If suitable aquifers are accessible, AGWR has many benefits when compared to other storage options, e.g. low evaporation rates, natural treatment and storage capacity to buffer seasonal supply and demand variations. Basically the aquifers in the Indus basin have large reservoir capacities. The observed gradual depletion of the ground water table can be (partly) compensated by AGWR. It can compensate for the lack in reservoir storage which is highly vulnerable to sedimentation. This storage has to be conducted in the framework of IWRM. Also, Qureshi (2011) indicate that aquifer management is considered as the most effective way of establishing a balance between discharge and recharge components. In recent years, India has taken serious steps to use harvested rainwater to recharge its aquifers and recently allocated significant funds in the central government budget for further promotion of the practice.

Natural floodplains of the Indus and its tributaries should be maintained as much as possible. This topic is discussed in the Sect. 4.1.4 “Land use planning and soil conservation; flood management”. With sustainable floodplain management, large water quantities of monsoon floods could be temporarily stored and groundwater reservoirs thereby replenished.

4.1.2 Water quality conservation and investment in wastewater infrastructure

The conservation of water quality and investment in wastewater infrastructure are a necessity in order to maintain the already quantitative scarce water availability. Especially the wastewater generated by municipalities, cities and industries should be purified before discharging them again in the receiving water bodies. In 2000, total wastewater produced in Pakistan was estimated at 12.33 km$^3$ while treated wastewater was estimated at 0.135 km$^3$; this is only 1%. Total water withdrawn for domestic and industrial purposes in the Indus Basin is 8.8 km$^3$ (Fig. 3). Water consumption values show that only about 11% of domestic water in the basin is consumed, the remaining 89% returns to the system. Industrial water is returned for 91% back to the system. In other words, 7.9 km$^3$ of wastewater is returned to the system of which only a small fraction is purified. In order to maintain quality standards of the receiving water bodies, massive investments need to be made. Water quality conservation includes the implementation of water pollution prevention strategies (legislation, polluting taxes, ...) for the different polluters (Kumar et al., 2005). Society and individuals in the riparian countries should have a greater knowledge and ability to bring about the required changes and mentality.

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

4.1.3 Use of alternate water resources

Alternate water resources include the recycling of wastewater and desalination. Since both domestic and industrial water demands will increase substantially in the basin, so will the potential for recycled wastewater. As discussed in the previous section, about 90% of water withdrawn in the Indus basin for domestic and industrial purposes is returned to the water system (7.9 km$^3$ of wastewater), predominately without purification in a treatment plant. The present water withdrawals for municipal and industrial uses in the whole of Pakistan are 5.4 km$^3$. This demand is expected to increase to about 14 km$^3$ by the year 2025 (Qureshi, 2011). Also in the Indian and Afghani parts of the basin domestic and industrial withdrawals will increase. The potential for recycled
wastewater is therefore substantial. A general discussion on recycling of wastewater in India is given by Kumar (2009). A role model in sustainable urban water management and recycling of wastewater can be seen in Singapore (Vanham, 2011). The city state has invested and still is investing massively in a sustainable self-sufficient water supply system. Singapore aims at being self-sufficient in its water supply by effective measures like water recycling (NEWater) and desalination, amongst others. Water purification is 100 %. By 2060, the city plans to increase the current NEWater capacity so that NEWater can meet 50 % of future water demand. Already today citizens are drinking recycled wastewater. The water cycle of the city is becoming more and more closed. Singapore has, of course, the financial and technical means to implement such a system. Nevertheless, the city shows sustainable solutions, which could also be implemented in the future in cities throughout the Indus Basin.

The use of domestic and industrial wastewater for irrigation also creates possibilities for irrigating crops. Not only will greater benefits be generated per unit of water diverted from a freshwater source, but some of the nutrients required to produce crops also will be recycled at a cost that is smaller than continuously developing new supplies. However, wastewater irrigation also creates health risks for farmers, their families, and consumers. An overview on the different aspects of wastewater for irrigation is given by Wichelns and Drechsel (2011). With increasing water withdrawals for domestic and industrial purposes, this issue offers a lot of opportunities as generally 90 % of withdrawn water is returned to the system. When the bulk of this returned water is used for irrigation, a required reduction in irrigation requirements to meet other future demands will be not so substantial.

In the Sindh Province there are substantial deposits of brackish water in the underground. As the cost of desalinisation is falling (Kumar et al., 2005), the prospects of desalinating brackish water – and also seawater for the coastal communities – are becoming more attractive. Studies done in Pakistan and India have also shown that brackish water can be used for irrigating different crops under different soil types and environmental conditions (Qadir et al., 2001; Sharma and Rao, 1998).

4.1.4 Land use planning and soil conservation; flood management

These practices include a change of land use, reforestation and the reduced sealing of areas in order to prevent erosion and high surface flow coefficients. As discussed in the Sect. 3.5 “Flooding”, erosion and the resulting high sedimentation loads in the river system of the Indus basin lead to the rise of the river beds between their embankments as well as the level of floodplains, diminishing their buffer capacity. Additionally the capacity of reservoirs is reduced substantially due to sedimentation. An important cause of increased sedimentation is past deforestation (Da Silva and Koma, 2011). Current forests should be maintained and reforestation should be considered as an option to reduce erosion, especially in the mountainous regions of the basin to control flash floods. Erosion can also be reduced within agricultural zones by particular resource-conserving agricultural practices. For an overview on such practices refer to Bossio et al. (2010). These include agroforestry (the incorporation of trees into agricultural systems) or conservation agriculture (which combines non-inversion tillage (minimum or zero tillage in place of plowing) with mulching or cover cropping and crop rotation).

The 2010 floods in the Indus Basin stressed the urgent need to move from “river control” to “river management” strategies (Gaurav et al., 2011). Alternatives to embankments for flood management must be implemented with an emphasis on the “living with the flood” concept. Floodplain zoning and mapping projects need to be completed on priority basin (Tariq and van de Giesen, 2011; Gaurav et al., 2011). Basin-scale flood risk maps should be based on historical data as well as modelling approaches. They could be linked to an online database and flood warning system.

Where possible wetlands should be restored and inundation zones should be implemented. In the past, wetlands have generally been considered as wastelands, and have been used for drainage of water, reclaimed for agriculture, or treated as dumping grounds for all kind of refuse (Briscoe and Qumar, 2007). Both wetlands and inundation zones would have a large impact in moderating high flow peaks, in addition to providing important ecosystem services such as groundwater recharge and biodiversity benefits (Mustafa and Wrathall, 2011). People living in such inundation zones could be relocated after fair and just compensation. Water managers and engineers of the Indus basin need to be sensitised to the need for adapting to the rhythm of the Indus basin rivers instead of the urge for engineering to control the river. Especially in the wake of climate change, due to which the monsoons will become more unpredictable, the idea of controlling the rivers 100 % is an illusion.

4.2 Water demand management

4.2.1 Managing conjunctive use of surface and groundwater

The explosion in groundwater use has led to an unsustainable depletion of groundwater resources. Within Sect. 3.4 this phenomenon has been discussed in detail. It is identified as one of the major challenges for the Indus basin. Due to the enormous number of wells installed by small farmers, licensing is not the best option to resolve this, as observed in both Pakistan and India (Qureshi et al., 2009). The conjunctive use of surface and groundwater by farmers should be managed as described by Qureshi et al. (2009). The unmanaged conjunctive use of surface and groundwater at the head ends of the canals causes water tables to rise resulting
in waterlogging whereas at the tail-ends salinity problems are increasing. Through the encouragement of planned conjunctive use this situation can be improved. Upstream farmers should make better use of the surface supplies – more reliable to them – in the canals. For this purpose, the canal department needs to regulate the canal flows to match the requirements.

4.2.2 Rehabilitation and modernization of existing infrastructure

Existing infrastructure for domestic, industrial and agricultural water supply should be rehabilitated and modernised. Leakage reduction in domestic water use should be addressed. A major task is adapting yesterday’s irrigation systems to tomorrow’s needs. Modernization, a mix of technological and managerial upgrading to improve responsiveness to stakeholder needs, will enable more productive and sustainable irrigation. The average irrigation efficiency in India is about 40% for surface and 60% for groundwater irrigation (Singh, 2007). Total crop consumption in the Indian part of the Indus basin is 35 km$^3$ for 94 km$^3$ withdrawn (Fig. 3). Irrigation efficiencies in the IBIS are also very low (Archer et al., 2010). Of the 175 km$^3$ available surface water resources, about 125 km$^3$ (72%) is withdrawn in the IBIS (Fig. 3). About 25% of this amount (31 km$^3$) can be quantified as conveyance loss in the canal system. Due to water course conveyance losses and field application losses, 69 km$^3$ according to Kreutzmann (2011) or 99 km$^3$ according to the dataset (GWSP, 2008) are still available for irrigation agriculture as blue water consumption (Fig. 3). This low value is responsible for the continuous shortage of irrigation water in Pakistan as a whole and especially in tail-enders such as Sindh province. The present methods of surface irrigation are wasteful and larger doses of through flood irrigation with fresh water only add to the non-retrievable pool of poor quality saline groundwater. As such irrigation infrastructure should enable farmers to apply just the right amount of water in small and frequent quantities (e.g. by installation of drip or sprinkler irrigation). Irrigation efficiencies can also be increased by reducing irrigation canal leakage.

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

Basically the crop system in the Indus basin is a rice-wheat system. During kharif (summer months, wet season, autumn harvest) rice is grown. In Indian Punjab sowing occurs from Mai to July and harvest from September to October (CWC, 2010). Other kharif crops include cotton, sugarcane and maize. During rabi (winter months, dry season, spring harvest, water availability is generally lower) wheat is grown. In Indian Punjab sowing occurs from October to November and harvest from April to Mai (CWC, 2010).

An overview on crop areas and harvested areas is shown in Fig. 4. Dominant agricultural production regions are the two Punjabs, Indian Haryana and Pakistani Sindh. The crop area and harvested area under irrigation for the five main crops – wheat, rice, sugarcane, maize and cotton – are also displayed in Fig. 4. Figure 8 displays the area and production of rice (basmati and other varieties) in Pakistani Punjab from 1987–1988 to 2004–2005. This province accounts for more than 50% of the total rice production and more than 90% of the total basmati production in Pakistan.

An overview on yields in selected states/regions in the Indus basin and national averages (India and Pakistan) for the period 1950–1951 to 2008–2009 for the four major crops rice, wheat, cotton and sugarcane is displayed in Fig. 9. It is shown that average yields generally rose during the past decades. The average yield of rice, e.g. in India, rose from about 1000 kg per ha in 1960 to more than 2000 kg per ha currently. Similarly the average yield of rice in Pakistan rose from about 1500 kg per ha in the eighties to about 2000 kg per ha at the beginning of this century. The average yield of wheat in India rose from about 850 kg per ha in 1960 to almost 3000 kg per ha currently. Similarly, the average yield of wheat in Pakistan rose from about 1700 kg per ha in the eighties to about 2500 kg per ha at the beginning of this century. There is also an important difference in yields of a certain crop between different regions in the Indus basin and production method. Yields are very high in certain areas and low in other regions of the basin. In the Indian Punjab, for example the yield of irrigated rice is more than 3500 kg per ha, whereas the yield of rainfed rice in Himachal Pradesh is only about 1500 kg per ha. The average rice yield in India is about 2000 kg per ha. Average rice yields of basmati rice in Pakistan are only about 1500 kg per ha. The same observations are valid for wheat. As a country average in Pakistan and India, the yield of wheat increased to about 2500 kg per ha in 2005. In the Indian Punjab irrigated wheat has an average yield of more than 4000 kg per ha, although rainfed wheat in the same province only has an average yield half of this value. The figure also shows that average yields of cotton are much less than the yields of wheat and rice, which are in the same range. Especially rainfed cotton has low yields (e.g. about 250 kg per ha in Haryana) whereas irrigated cotton yields are higher. Cotton yields are lower in India as compared to Pakistan. Sugar cane has very high yields, ranging from about 25 000 kg per ha as rainfed sugarcane in Haryana up to 60 000 kg per ha in the same state.

Figure 5 displays the average annual blue and green water consumption of crops in the Indus basin for the period 1996–2005, based upon data from Mekonnen and Hoekstra (2010b). The authors estimate blue water crop consumption at 117 km$^3$ annually. Wheat blue water consumption is estimated as the highest fraction of total consumption, i.e. 41 km$^3$ (35%). Additionally the green water consumption of wheat is estimated at 23 km$^3$. The sum of green and blue water consumption is thus 64 km$^3$. During 1996–2005
the total annual production of wheat in the Pakistani part of the Indus Basin was about 18.5 million t (98 % of total Pakistani production) whereas in the Indian part of the basin this amount was 18.7 million t (27 % of total Indian production). For the total basin production, this results in an average WP of 0.6 kg km\(^{-3}\) for wheat. For the Indo-Gangetic basin, Cai et al. (2010) state an average value for wheat of 0.94 kg m\(^{-3}\). For the IBIS, Bastiaanssen et al., (2003) state a productivity per unit consumed of 0.64 kg m\(^{-3}\). The same authors list for the IBIS a WP of 0.42 kg m\(^{-3}\) for rice, 0.22 kg m\(^{-3}\) for cotton and 4.79 kg m\(^{-3}\) for sugarcane. For the Indo-Gangetic basin, Cai et al. (2010) state an average value for rice of 0.74 kg m\(^{-3}\). In Indian Punjab this value is 1.18 kg m\(^{-3}\), whereas in the Pakistani part of the basin it is 0.69 kg m\(^{-3}\). Cai et al. (2010) and Mahajan et al. (2009) give a value of 1.1–1.63 for rice in Indian Punjab. According to Mekonnen and Hoekstra (2010b), the blue water consumption of rice in the Indus basin is 29 km\(^3\) and the green water consumption is 18 km\(^3\). For a total annual production of 17.6 million t (of which 5.1 million t in Pakistan and 0.7 million t in India), the WP is 0.17 kg m\(^{-3}\). The latter is a very low value, and cotton is defined as a water intensive crop. Gaining more yield and value from less water can reduce future demands for water, limiting environmental degradation and easing competition for water. Specific irrigation techniques (drip irrigation, sprinkler irrigation) that can deliver water at the appropriate timing and quantification for the different growing stages of the plants, have large potential for increasing water productivity. The percentage of irrigated area under drip irrigation, e.g. in Indian Punjab and Haryana, was 0.5 % in 2000 whereas the potential for both states is estimated at 5.5 % of total irrigated area (Narayanamoorthy, 2009). In 2005 0.5 % of the irrigated area of Punjab was under sprinkler irrigation, whereas in Haryana this value was 30 %. For rice the system of SRI (System of Rice intensification) has a lot of potential. Average yields are considerably increased with this technique, with a reduction in water requirements up to 70%. An overview of this methodology is given by Sharif (2011).

Additional approaches to increase water productivity include: (1) providing appropriate quantum of fertiliser to the crop to realize yield potential; (2) cropping planning and diversification (which will be discussed in the next Sect. 4.2.4); (3) increasing the value per unit of water by integrating livestock and fisheries in irrigated systems; (4) in
situ soil and water management and water harvesting techniques (bunds, terracing, contour cultivation, land levelling, etc.). An overview on resource-conserving agricultural practices that increase water productivity is given by Bossio et al. (2010).

Not included in the WP values water withdrawals are lost in the system due to poor irrigation efficiencies. This topic was addressed in the previous Sect. 4.2.2 “Rehabilitation and modernization of existing infrastructure”.

4.2.4 Crop planning and diversification; concept virtual water import-export

Cropping planning and diversification includes the growing of crops in regions where or at times of the year when ET requirements are lower. An example of a policy acting on this, is the Punjab Preservation of Sub-Soil Water Act (2010) which prevents farmers from transplanting of paddy before 15 June to reduce ET (groundwater pumpage and energy) during the extremely hot summer months. Pakistani Punjab and other states may also emulate such regulations.

Certain crops produced in the Indus basin are partially exported out of the basin. Especially rice is exported from Pakistan and rice and wheat from Indian Punjab to other Indian states. Figure 8 shows the area and production of rice (basmati and other varieties) in Pakistani Punjab from 1987–1988 to 2004–2005 and was discussed in Sect. 3.4 “Shift from surface water to groundwater use”. Punjab province represents 90% of overall Basmati rice production and more than 50% of the total rice production in Pakistan. About 70–80% of rice produced here is basmati. However, from 2001 to 2005, about 40–60% of all rice produced in Pakistan was exported (Fig. 8b). Basmati exports increased from 0.6 to 0.9 million t during that period. As discussed in the previous Sect. 4.2.3 “Increasing water productivity (WP) for agriculture (irrigated and rainfed)”, rice is a water intensive crop with an average WP of 0.37 kg m$^{-3}$. Additionally, large quantities of water (percolation and soil moisture) are required in traditional rice production, which are not consumed by the plant. Especially basmati from Pakistan has low yields as displayed in Fig. 9. Therefore, it is to be re-evaluated whether the production of such a water intensive crop for export is defendable in the current and future situation of the Indus basin. Reducing areas under rice crop may be a long term policy by encouraging rice cultivation in wetter areas or growing water-efficient but high value crops. Also, Qureshi (2011) questions whether Pakistan should continue to grow rice for export or instead use this water for other crops that represent a comparative advantage for the country.

According to Verma et al. (2009), the state of Punjab is amongst the largest net virtual water exporters (total amount 20.9 km$^{3}$ per year) within India. Basically large amounts of crops produced are consumed elsewhere in the country, outside the Indus basin. Proponents of the virtual water trade argue that if certain policies – where farmers receive highly subsidized agricultural inputs (including water for irrigation) and are assured high prices for the wheat and rice they produce as in Punjab – were to be revisited in favour of the wetter Indian states, water rich states would no longer have to import virtual water from water scarce states (Verma et al., 2009). Since wheat is a low-value crop, one may question whether water allocation to wheat production for export in states such as Punjab is worth the cost (Mekonnen and Hoekstra, 2010a). Especially for products that are exported out of the Indus basin, an evaluation of benefits (economically and livelihoods) to costs (depletion of water resources) should be made.

4.2.5 Economic instruments (e.g. water pricing)

According to Singh (2007), part of the reason for the low irrigation efficiencies is the highly subsidized price of irrigation water that encourages the excessive application of water to crops. An overview of potentials, problems and prospects for water pricing for irrigation is given by Reddy (2009), and particularly for the Indus basin by Shah et al. (2006, 2009). However, Qureshi et al. (2009) argue that direct management of an economy with such a large number of farmers through enforcing laws, installing licensing and permit systems and establishing tradable property rights did not prove to be effective in Pakistan. In Pakistan, the use of electricity for groundwater pumping started in 1970s. During this period, all capital installation costs were borne by the government and electricity tariffs were based on a metering system. In the 1980s, the population of tube wells surged and due to increasing electricity costs, the government withdrew subsidies on electricity tariffs in the Punjab and the Sindh provinces. As a result, large numbers of electric tube wells were replaced with diesel tube wells. The massive increase in private tubewells, as displayed in Fig. 7a, is thus due to diesel pumps and not electric pumps (which amount has remained rather stable at about 100 000 since the 1980s). Diesel pumps however increased from about 200 000 in 1987 to 900 000 in 2005 (GOP, 2005). This clearly shows that changing energy prices only forces farmers to shift from one mode of energy to another but could not help resolve the real issue of groundwater overdraft. Therefore, changing electricity pricing policies, as the case in parts of India, would have a minor impact on controlling the groundwater overdraft. This clearly demonstrates the need to search for more innovative ways to solve the problem of groundwater over-exploitation while maintaining the current levels of agricultural production in view of the increasing population. In the wake of this paper these options are not further explored.

4.2.6 Changing food demand patterns and limiting post-harvest losses

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

Post-harvest losses can be reduced by improving transportation and storage infrastructure and systems. Estimates of agricultural produce lost in the steps between production and consumption are between 40 % and 50 % (Lundqvist et al., 2008). A study commissioned by the FAO (Gustavsson et al., 2011) has quantified the amount of global food losses and food waste. Roughly one third of the food produced in the world for human consumption every year – approximately 1.3 billion to – gets lost or wasted globally. Fruits and vegetables, plus roots and tubers have the highest wastage rates of any food. Food losses – occurring at the production, harvest, post-harvest and processing phases – are most important in developing countries. Food waste is more a problem in industrialized countries, most often caused by both retailers and consumers throwing perfectly edible foodstuffs into the trash. Per capita food loss in South Asia is about 125 kg a year, whereas per capita food waste is only 6–11 kg per year.

### 4.3 International collaboration

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

The Permanent Indus Commission (PIC) is responsible for resolving disputes between India and Pakistan over the implementation of the Indus Waters Treaty. Disputes are managed primarily through regular meetings of the engineers and officials that make up the two national sections of the commission (Zawahri, 2009b). Monitoring development projects in the Indus river system by PIC has eased fears of cheating between India and Pakistan (including the confirmation of accuracy of all exchanged data) and helped promote compliance with the 1960 Indus Waters Treaty (Zawahri, 2009a).

### 5 Conclusions

The Indus river basin – shared by Pakistan, India, China and Afghanistan – is one of the most depleted river basins in the world. The basin is confronted with a list of current and future challenges. Irrigated agriculture is by far the most important water demand stakeholder, but water demands for domestic and industrial purposes are increasing, due to population increase (from currently 237 million people to 319 million in 2025 and 383 million in 2050), increased urbanisation and industrialisation and the rise in living standards. Water availability will decrease on the long run due to climate change. A shift from surface water to groundwater use resulted in rapid depletion of groundwater resources in the past. There is a large gap between water withdrawals for irrigation and actual water consumed for crop production. Irrigation efficiencies are low. Much of the surface water that enters the system is wasted (also to groundwater recharge). Other challenges in the basin include water logging and salinity, loss of productive agricultural land, land degradation and the contamination of surface and groundwater resources.

This paper lists all challenges for the Indus basin, provides for a review on the different water balance components as quantified by different authors and own quantifications (presented in Fig. 3) and identifies all applicable sustainable WRM practices to meet these challenges. The latter include both water supply management and water demand management options. In this sense it differs from available literature regarding the Indus basin up to this date. Different papers have been written on the basin with recommendations to cope with current and future challenges (e.g. Archer et al., 2010; Qureshi et al., 2009; Qureshi, 2011; Sharma et al., 2010). However, none of them gives a comprehensive overview on all recommendable options for the entire basin (including all 4 countries). Because the challenges are so massive and because sustainable WRM requires the inclusion of all available options, it is essential for scientists and policy makers to have a holistic vision for the Indus basin. In the past the focus has always been on the increase in water availability, mostly implemented by technical measures. Even now traditionally trained engineers often tend to look only for solutions within water supply management options. However, water resources are not a finite resource. Sustainable water management also requires for the incorporation of water demand management options. This paper shows that the challenges of the Indus basin need to be taken upon by a list of measures within both options. This needs to be done within the concept of IWRM, regarding the Indus basin as a natural system, independent of political borders, where flooding needs to be tackled by means of “river management” measures, not merely “river control” strategies. The past vision to engineer the natural river system to a network of water providing canals has led to the physical cut-off of the river to its floodplains and the loss of natural buffer capacity due
to the drainage of wetlands. Due to both deforestation and one of the worldwide highest sediment loads, reservoirs in the Indus basin tend to lose their capacity rather fast. Only by accepting the natural character of the basin again, flooding can be addressed. Current forests should be maintained and reforestation should be considered as an option to reduce erosion. Floodplain zoning and mapping projects need to be completed on priority basin. Where possible wetlands should be restored and inundation zones should be implemented.

Water supply management options that need to be addressed to deal with the challenges of the Indus basin are: (1) reservoir management (an increase in reservoir storage and the implementation of artificial groundwater storage (AGWR)); (2) water quality conservation and investment in wastewater infrastructure; (3) the use of alternative water resources like the recycling of wastewater and desalination (with a substantial potential due to the future increase in domestic and industrial water demands in the basin); (4) land use planning and soil conservation as well as flood management.

In addition to the presented water supply management options, water demand management options are a necessity. Options that are applicable to the Indus basin and would have an important impact to deal with the basin’s challenges are: (1) the management of conjunctive use of surface and groundwater; (2) the rehabilitation and modernization of existing infrastructure; (3) the increase of water productivity for agriculture; (4) crop planning and diversification including the critical assessment of agricultural export, especially (basmati) rice; (5) economic instruments and (6) changing food demand patterns and limiting post-harvest losses.

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ABSTRACT

Pinyari canal off-takes from Kotri Barrage which is last structure constructed at Indus River located at latitude 25°20'36.99"N and longitude 68°24'36.17"E nearby Hyderabad city, Sindh Pakistan. This canal is non-perennial which supplies water in wet season for agriculture, industrial and domestic but in dry season only for industrial and drinking purposes to Hyderabad, Tando Muhammad Khan and Sajawal Districts. As the canal is passing across the Hyderabad city, therefore, large and small industrial enterprises, urban wastewater and solid waste are being disposed off into it. Due to the direct discharge of untreated effluent into the canal, the quality of canal water is degrading at an alarming rate and do not meet NEQS. Meanwhile, about 319 industrial units have been installed in SITE Hyderabad area that are operating without any in-house treatment plants and their effluent about 60 MGD is disposed off into the canal. Different types of highly toxic chemicals are used during manufacturing process of various items. For dyeing only leather, million tones of salts and other chemical are used. The solid waste of domestic, encroached area, hospitals and slaughterhouses, containing tissues, organs, blood, drugs and chemicals, are one of the biggest sources of pollutants and being discharged directly into canal. The contaminated water of this canal is being consumed for drinking by millions of people without any treatment because ground water of canal command is highly saline which is not fit for drinking. Hence, this situation has led to create of various water-borne diseases such as dysentery, cholera, hepatitis migraine, gastroenteritis, etc.

Keywords: Canal water, Domestic waste, Effluent, solid waste, NEQS, MGD
Impact Analyses of Upstream Water Infrastructure Development Schemes on Downstream Flow and Sediment Discharge and Subsequent Effect on Deltaic Region

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Abstract: The lavishness of delta and its ecosystem heavily depends on continuous supply of fresh water flow and sediment flux into deltaic region. Since last few decades, the mighty river contributing a portion of fresh water and deposit sediment into the Delta. The extensive use of fresh water for irrigation purposes and construction of vast network of dams, barrages and associated upstream structures have severely reduced downstream discharge of the Indus River to Sea. The reduced down stream flow has resulted in pronounced sea water intrusion into once the fertile and lush green land of Indus Delta. The decline in the inflow of fresh water has uncovered this composite bionetwork to a number of environmental and social stresses in the form of habitation and biodiversity; reduced in productive values of ecology. The Indus Deltaic region, once occupying an area of about 5000 km² consisting of creeks, mudflats and mangrove forest is now condensed to 1,192 km². While the mangroves cover, once an approximate area of 250,000 to 283,000 hectares till early 1980s drastically declined to 73, 000 hectares in 2006. The resulting destruction of delta is not a problem of its own but death of fishing culture, ecology and destruction of livelihoods of local fishers and peasants.

Keywords: River Indus, water and sediment discharge, Indus delta, environmental impacts

1. INTRODUCTION

Indus deltaic region is heavily dependent on water availability in Indus River and its tributaries, which originates from commonly known as greater Hindukush, Karakorum, and Himalaya (HKH) region. The River Indus, after its long journey of about 3000 km from north to south, finally spill out into a deltaic region-covering an approximately area of some 5000 km² where, more than the centuries, it has developed a 650,000 acre wide mangrove jungle which maintain alien and multicolored plant life, mammals and reptiles. The fan-shaped Delta Indus, the sixth biggest in the planet supports an inhabitants of over 130,000 communities, whose source of revenue are directly or not directly reliant on the water availability in tributary Indus. The integrity and lavishness of delta is directly linked with increased fluvial deposit provide and negligible human intervention (Sanchez-Arcilla, et al., 1998 and McManus, 2002). The storage and diversions of freshwater for any consumptive uses have usually resulted to decrease the net sediment load of rivers (Dynesius and Nilsson, 1994; Walling and Fang, 2003; Vörösmarty et al., 2003; Nilsson et al., 2005 and Syvitski et al., 2005). The Indus’s silt-laden fresh water sustained the life supporting system of deltaic tract along the coastlines of southern belt of Sindh province. The deltaic population by inborn understanding sensibly operated these capital and preserved sustainability of the structure for centuries. All of this and much more is under threat now. The extensive use of fresh water for irrigation purposes and construction of vast network of dams, barrages and associated upstream structures have severely reduced down stream discharge of the River Indus. The reduced silt-laden down stream flow has resulted in reduction of mangroves cover and consequently sea water intrusion devastated once the fertile and lush green land of Indus Delta (Meynell, and Qureshi, 1993). The decrease in the inflow of fresh water has uncovered this composite ecology to ecological and communal pressure in the form of habitat and biodiversity thrashing and a decline in prolific principles of flora and fauna. The destruction can be manifested in reduction of mangrove coverage, intrusion of sea, degraded groundwater, shrinking of agricultural land and vegetation and significant reduction in livestock grazing areas. In the context of global warming, the vulnerability of HKH region to climate change is of vital importance because of the impact on water resources at lower riparian areas and consequent effect on the Indus deltaic region. The present study will review the effect of past treaty and various water development schemes on water flux and sediment discharge to deltaic region and resulting impact on mangroves cover and shrinking of agricultural land. The analyses will provide invaluable information for future water management within the whole Indus River basin and specifically the quantum of possible available fresh water for deltaic region.
Description Of Indus Delta Region

The fan-shaped Indus Delta area scatter with 17 most important and many small stream covers an estimated region of 5000 km² (Fig. 1). The Deltaic mangroves-forest are exclusive in living being the biggest vicinity of bone-dry climate and 7th major obstruct in the earth, which ropes a inhabitants of above 130,000 people, whose livelihoods are directly or not directly reliant on Indus stream. The mangroves cover occupies around 600,000 ha extending from Korangi Creek in the north to Sir Creek in the south. Over last half of the century, the construction of new water infrastructures-barrages and dams due to development of cultivation, serious yield, power production, boost in residents etc, have resulted in continuous decrease in silt laden fresh water flow into Arabian Sea. The decreased flow have turned whole ecosystem of deltaic region into dying state, where fauna, flora, the livelihood of thousands people are in jeopardy.

![Fig. 1 The expanding view of Indus Delta and its creek system (Source: Inam et al., 2007).](image)

Development of Indus Basin Irrigation System (IBIS) And Its Impact on Water / Sediment Flux Below Downstream Kotri Barrage

After division of Asian subcontinent in 1947, the water distribution of the Indus River and its tributaries become a source of conflict b/w India and Pakistan. However, under arbitration of World Bank an accord was signed among India and Pakistan in September 1960. Under the accord, usually known as Indus basin water agreement, India was exclusively apportioned the use of three eastern rivers (Ravi, Beas and Sutlej), while Pakistan retained the sole rights for the three western rivers, namely Indus, Jehlum and Chenab. As a result, a set of major replacement works were built to redirect water from Pakistan’s western rivers to supply the irrigation systems formerly fed by water flowing from the eastern rivers. Since the agreement, around 19 barrages and 43 canal heads with 48 off-takes have been built up on Indus River system-consisting thousands of canals and water courses, irrigating around 42 million acres of land. As shown in (Fig. 2). These replacement works include the three major storage dams: Chashma, Mangla and Tarbela-supplying irrigation water to command area of an approximately 14 million hectares.

![Fig. 2 Indus Basin Irrigation Systems (IBIS) - Water infrastructure developments at Indus River and its tributaries](image)

The construction of these link canals and storage reservoirs has almost doubled the agricultural activity, once limited to 12 million hectares to 22 million hectares now. However, this agricultural sector development has diverted the River Indus water from once about 80 BCM to 125 BCM for irrigation needs. The said canals and reservoirs have resulted in the siphoning off 74 percent of Indus waters before it reaches Kotri Barrage, the last barrage point on the Indus River in the southern part of country. These anthropogenic changes have also resulted in five times reduction in sediment discharge to Deltaic region. Prior to development of Indus Basin Irrigation System, the sediment and water escapages to the Arabian Sea were about to 108 BCM and 225 BT respectively. After commissioning of barrages and dams, it further reduced to 48 BCM and 50 BT (Fig. 3). The most recent flow was determined by way of the Indus Water Accord in 1994, whereby the allocation of water between the Provinces of Pakistan was decided, based on historical record of available water. As per accord, 141 billion m³ allocated for irrigation purposes, while only 12 BCM were apportioned for Deltaic region. However, in last one and half decade the fresh water flows below downstream Kotri barrage have been inconsistent and mostly below the minimum required quantity as most of the available fresh water in Indus River is being used for upper plain irrigation needs. Therefore, the major decline in fresh water and sediment flux to the delta can be attributed to the development of Indus Basin Irrigation System. Since last 8 years, water and sediment discharges have declined at an alarming pace below Kotri Barrage-it have almost created a worst droughting like situation, where the flow and sediment load is dropped to the single digit (Fig. 4). The figure were also supported by conclusion of (Meynell, and Qureshi, 1993) study, that the delta which once receiving around 250-600 BT sediment in 1930s, just trickled down to less than double digit. The effect of the engineered structures on the Indus River water discharge can further be measured by the number of flowing days downstream Kotri Barrage. Before the construction of Kotri Barrage, the Indus was flowing...
throughout the year. However, after construction of Kotri Barrage, first intermittent breaks in flows were observed and the numbers of flow days were recorded to maximum figure of 250 days. During post Mangla period, the flow days further dropped to 100 days (Fig. 4). Since the signing of Water Accord 1994, the river bed is constantly showing deserted look, as most of the available water is used for extensive irrigation needs by upper riparians. The twin menace of almost total absence of silt laden fresh water in the river downstream of Kotri Barrage—the last barrage on Indus River and heavy sea water intrusion into the delta have turned whole ecosystem of deltaic region into dying state, where flora, fauna, the livelihood of thousands people are in jeopardy.

Fig. 3 The changes in average annual canal water diversions, downstream Kotri barrage flow, and sediment discharge below Kotri barrage after every mega development project (modified from Govt. of Pakistan Report, 2006).

Fig. 4 Variation in Water / sediment discharge with no. of flow days / year below Kotri Barrage

2. ENVIRONMENTAL EFFECTS

Since last two decades, water released below downstream Kotri barrage only in case of worst flood situations - subsequently the Indus River contributing hardly any water or sediment to deltaic region. As a result, there has been severe intrusion of sea water upstream of the delta - at places extending up to 80 km in the coastal areas. As per Government figures seawater intrusion has resulted in tidal infringement over 1.2 million acres of land in the Indus Delta (Ref, 2004). The twin menace of almost total absence of fresh water in the river downstream of Kotri and heavy sea water intrusion from the delta has destroyed large areas of prime agricultural land, including submersion of some villages in the coastal belt of these districts. The study by Wells and Coleman (1984) concluded that the highest wave energy due to the intense monsoonal winds transforming the Indus delta into a true wave dominated delta, which converting the ever lush green delta into sandy beaches and dunes. The above facts and figures can be verified in satellite view of the Indus Deltaic Region (Fig. 5), where large portion of deltaic region have been converted into sandy and saline area. The devastation of delta can further be observed in drastically reduced mangrove forest cover (Fig. 6). The mangrove cover once an approximate area of 250,000 to 283,000 hectares till early 1980s drastically declined to 73,000 hectares. The sandy area, once just about 30% of the active delta over the years increased around approximately 68% of the total deltaic area till early 90s and it is assumed that the figure should have been jumped to higher percentages in recent years.

Fig. 5 Satellite view of the Indus Deltaic Region

Fig. 6 Mangrove forest cover at different time intervals (Modified from WWF-Pakistan, 2006).
mudflats into agricultural land (Fig. 7). Out of the 8,463 ha area high land erosion of approximately 2,911 ha was calculated at the sea side. Land erosion map highlights the historic and current deltaic extents in blue and red colors respectively (Fig. 8).

In many ways the Indus Delta study characterize a crisis situation which has already reached critical point, and is likely to deteriorate further in the future. The situation requires immediate revisit and shifting in present policies opted only to allocate scarce water to maximize financial and commercial gains to agriculture even at cost of ecosystem. as a result, require to accept a holistic approach towards the managing of our environmental resources so as to maintain them for our desires and so as to our future generations.

3. CONCLUSION

The existence of the delta is dependent on the accessibility of clean water and sediment. The severe decline of mutually as a consequence of barriers, bombardment and connected construction on upstream has outcome in the evident erosion in vicinity of the delta; therefore in the decline of the mangroves. The health of Indus Delta demands a sensible evaluation of the smallest amount of fresh water and sediments necessary to avoid total vanishing of the delta. Present is requiring for a positive quantity of fresh water and sediment to be release in to the delta on year about basis. Above mentioned facts and figures suggest to the least amount of clean water flow to the Delta region set by the Indus stream agreement 1994, (12.3 BCM) is insufficient to uphold effective ecology role of the swampland of the Indus Delta. The result, important decline in the natural property of the Delta has been experiential. It is consequently recommended that the inclusive, free study of collective and ecological impacts of the current irrigation structure on the Delta bionetwork should be carry out and the executive of the delta should be made a part of an integrated Indus Basin management.

REFERENCES:


