Hydroclimate of the Indus

Synthesis of the literature relevant to Indus basin hydroclimate processes, trends, seasonal forecasting and climate change

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<th>Description</th>
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<tr>
<td>AR</td>
<td>Assessment Report (of the IPCC)</td>
</tr>
<tr>
<td>AWS</td>
<td>Automatic weather station</td>
</tr>
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<td>CMIP</td>
<td>Coupled Model Intercomparison Project</td>
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<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organisation</td>
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<tr>
<td>ENSO</td>
<td>El Niño Southern Oscillation</td>
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<td>IB</td>
<td>Indus Basin</td>
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<tr>
<td>ICIMOD</td>
<td>International Centre for Integrated Mountain Development</td>
</tr>
<tr>
<td>GCM</td>
<td>Global Climate Model (also General Circulation Model)</td>
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<tr>
<td>HKH</td>
<td>Hindu-Kush Himalaya</td>
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<tr>
<td>HKKH</td>
<td>Hindu-Kush Karakoram Himalaya</td>
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<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<td>ISM</td>
<td>Indian Summer Monsoon</td>
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<tr>
<td>MODIS</td>
<td>Moderate Resolution Imaging Spectroradiometer</td>
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<td>NAO</td>
<td>North Atlantic Oscillation</td>
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<tr>
<td>NCP</td>
<td>North Sea Caspian Pattern</td>
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<tr>
<td>PMD</td>
<td>Pakistan Meteorology Department</td>
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<tr>
<td>SCA</td>
<td>Snow Cover Area</td>
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<td>SOI</td>
<td>Southern Oscillation Index</td>
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<tr>
<td>SRM</td>
<td>Snow Runoff Model</td>
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<tr>
<td>TRMM</td>
<td>Tropical Rainfall Monitoring Mission</td>
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<td>UIB</td>
<td>Upper Indus Basin</td>
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<td>WAPDA</td>
<td>Water and Power Development Authority</td>
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<td>WD</td>
<td>Western Disturbance</td>
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Key points

- Better seasonal forecasting of Indus flows will help address the current water crisis in Pakistan, allowing improved management of stressed supply systems in a changing climate.

- Indus water supply is dominated by the Upper Indus Basin (UIB). UIB precipitation has both tropical monsoon and temperate mid-latitude (western disturbances, WD) sources. The WD contribute more to UIB flow than the monsoon.

- Glaciers, snowmelt and precipitation contribute to flow, with sub-basins in the UIB responding differently depending on whether they have snowmelt (precipitation) or glacier-melt (temperature) dominated flow process.

- Temperature trends indicate the UIB has warmed over the last century. Increased rates of warming are evident in recent decades. Warming trends are greater in winter than summer and greater with elevation. Declining snow cover has been linked to warming.

- Precipitation trends are less consistent and vary across the UIB, with season, and for different time periods. Total monsoon precipitation has decreased and winter WD precipitation has increased.

- High-elevation glaciated basin flow correlates with temperature, middle-elevation basin flow correlates with both temperature and precipitation, and lower-elevation basin flow correlates with seasonal rainfall only.

- Over 80% of UIB total flow occurs during the June-September period and is snowmelt dominated, with glacier-melt an important secondary source. Tarbela inflows comprise 70% melt water (20% glacial melt and 50% snowmelt). Some estimates of glacier-melt contribution are 40%.

- Potential seasonal forecasting skill for snowmelt dominated basins is seen in the relationship between spring and summer flow and preceding winter precipitation or snow-cover area. Teleconnections with large-scale climate drivers, e.g. ENSO or NAO, are a possible source of predictability of seasonal variation of temperature for glacial-melt dominated basins, where flow volumes relate to summer temperature rather than precipitation.

- Long-term climate change will impact UIB precipitation and temperature magnitudes, variability and extremes and thus UIB flow.

- Several studies suggest flow will increase at least until mid-century as glacier melt increases in response to rising temperature projections. Precipitation projections are a lot more uncertain than temperature projections, thus the flow response of snow-melt dominated basins is less certain.

- A greater proportion of WD precipitation falling as rainfall rather than snow in a warmer climate would reduce snowpack and thus reduce snowmelt contribution to total flow, potentially changing the timing and magnitude of peak flow (earlier and less).
Summary

The Pakistan water sector faces increased stress given the compounding impacts of a steadily rising population, infrastructural inefficiencies and a changing climate. The Government of Pakistan supports the use of the best available international science to underpin long-term water sector reforms. This report reviews the literature on Indus basin hydroclimate processes, trends, seasonal forecasting and climate change, focusing on the Upper Indus Basin (UIB). Synthesis of this knowledge informs research that is developing better seasonal forecasting tools to improve river operations, thus helping Pakistan to better manage its water crisis.

The majority of Indus water supply is contributed by the glaciated and snow covered sub-basins of the UIB, within the northern Hindu-Kush, Karakoram and western Himalayan (HKKH) mountain ranges. The summer monsoon and western disturbances (WDs) are the main climatological drivers of precipitation magnitude and variability in these sub-basins. The monsoon draws moisture from the Arabian Sea and Bay of Bengal into South Asia, across Pakistan and into the southern UIB during June to September. It is the predominate source of precipitation during this season, coinciding with the period of maximum snow and glacier melt. Hence UIB flow peaks during this season. WDs are mid-latitude low-pressure systems from the Mediterranean Sea, or even the eastern Atlantic Ocean, together with secondary sources from the Persian Gulf and Arabian Sea. During the October to March period they propagate from west to east across Iran, Iraq, Afghanistan, Pakistan and northern India, interacting with the steep HKKH orography to produce heavy winter snowfalls across the UIB. WDs contribute more to UIB flow than the monsoon. Glacier melt, which is temperature driven, is a significant contributor to UIB flow (~20% of flow).

The high altitude regions of the HKKH have limited numbers of stations recording climatological data. Thus data limitations make it difficult to reach firm conclusions regarding hydrological and glaciological response to the climatology of the UIB. It is likely that the precipitation at high altitudes is up to an order of magnitude higher than that recorded in weather stations in lower altitude valley locations. Gridded products are correspondingly impacted by the lack of high altitude station inputs, resulting in reduced confidence in the climatological inputs to hydrological models at high altitudes.

Within the limitations of data availability, several climatological and hydrological data studies have presented evidence of trends in climate drivers and hydrological response across the UIB. It is clear that the UIB has warmed over the last century, with increased rates of warming seen in recent decades. Warming trends are greater in winter than summer, with some studies showing summer cooling, and also warming is greater with elevation. Declining snow cover trends have also been linked to warming. Summer cooling may be linked to increased penetration of monsoon precipitation into the UIB.

Precipitation trends are less consistent than temperature trends, as various studies have found increasing, decreasing or no trends in different regions of the UIB and for different seasons and time periods. For example, Archer and Fowler (2004) found 1961-1999 winter precipitation has increased for 17 stations across the UIB; in contrast Bhutiyani et al. (2007) and Bhutiyani et al.
(2010) found no trend in winter precipitation with a decreasing trend in monsoon precipitation for the north western Himalayas.

Flow trends are a direct response to precipitation and temperature trends, as precipitation determines the amount of accumulated snow cover and temperature controls melt processes (snow and glacier melt). High-elevation glaciated basin flow correlates with temperature, middle-elevation basin flow correlates with both temperature and precipitation, and lower-elevation basin flow correlates with seasonal rainfall only. Thus, for example, Khattak et al. (2011) suggest the increasing trend in flow at Besham upstream of Tarbela is a result of increasing maximum temperature in winter and spring together with increasing precipitation in autumn. Similarly, Sharif et al. (2013) found high elevation glacial catchments, the Hunza in particular, showed declining runoff trends attributed mainly to the declining trend in summer temperatures, whereas winter snow melt dominated catchments showed increasing runoff trends, attributed to the increasing trends in winter precipitation.

The sub-basins of the UIB have flow regimes that are either glacier-melt (e.g. Hunza, Shigar and Shyok) or snowmelt (e.g. Jhelum, Kabul, Gilgit, Astore and Swat) dominated, with direct rain-generated flow less of a contribution. Over 80% of total flow occurs during the June-September period and is snowmelt dominated, with glacier-melt an important secondary source. Prediction of the hydrological response to changes in climate drivers is complex given the feedbacks and nonlinear interactions between the climate drivers, glaciers and flow generation processes. It is also made more difficult due to data limitations.

As less snow cover results in more glacier exposure, years of less precipitation may be compensated for by greater glacial input to flow. Thus in highly glaciated basins the summer (June-September) flow correlates with concurrent summer temperatures but not preceding winter precipitation. In contrast, seasonal snow melt dominated basins do show strong correlations between summer flow and preceding winter (October-March) precipitation. A study by Mukhopadhyay and Khan (2014a) concludes the majority of Tarbela inflow comes from the three basins with the largest glaciated area (Shyok, Shigar, and Hunza), with a combined contribution of 20–31% to April to June flow, 48–54% to July to September flow, 33–39% to October to December and 31–32% to January to March with overall Tarbela inflows comprising 70% melt water, of which ~20% is glacial melt and ~50% snowmelt. Other estimates of glacier-melt contribution are higher (e.g. Hewitt (2014) estimates 40%).

For basins with flow dominated by snowmelt, potential seasonal forecasting skill is seen in the relationship between spring and summer flow and preceding winter precipitation (e.g. Archer and Fowler (2008)) or snow cover data obtained from satellites (e.g. MODIS). For glacial-melt dominated basins, where flow volumes relate to summer temperature rather than precipitation inputs, obtaining skilful forecasts is a challenge as it is difficult to predict temperature anomalies a season ahead. Teleconnections with large-scale climate drivers, e.g. ENSO or NAO, are a possible source of predictability of seasonal variation of temperature.

Climate change resulting from global energy balance (due to increasing concentrations of greenhouse gases) and regional aerosol emission (e.g. Asian brown cloud) changes will impact UIB precipitation and temperature magnitudes, variability and extremes and thus UIB flow throughout the century ahead. Several studies suggest flow will increase at least until mid-century as glacier melt increases in response to rising temperature projections. Precipitation projections are a lot
more uncertain than temperature projections, thus the response of snow-melt dominated basins is uncertain. A shift to a greater proportion of WD precipitation falling as rainfall rather than snow in a warmer climate (i.e. shorter snow season) would reduce snowpack and thus reduce snowmelt contribution to total flow, changing the timing and magnitude of peak flow (earlier and less). Monsoon season precipitation is projected to increase and thus a future stronger monsoon may mean a greater monsoon contribution to UIB flow than currently experienced.
1 Introduction

Pakistan’s steadily rising population, together with infrastructural inefficiencies and the compounding impacts of climate change, result in an increasingly water stressed country (Ringler and Anwar, 2013). The deepening concerns regarding future water supplies result in the need for better knowledge-based approaches in managing the water sector (Briscoe and Qamar, 2005; Qureshi, 2011). Realising that the imbalance between water demand and supply is increasing, the Government of Pakistan has made clear its intentions to support water sector reforms underpinned by the best available international science (Ministry of Planning Development & Reform, 2014).

The challenges facing Pakistan are also faced by other countries in the region. In a recent editorial on the combined pressures of climate, socio-economic and demographic changes impacting water, food and energy demand across the countries of the Hindu Kush Himalayas (HKH), Mukherji et al. (2015) summarises the dire situation faced by the region: “Even though the HKH is the source of 10 mighty rivers [Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtze, Yellow, Amu Darya and Tarim], has the largest snow and ice cover outside of the two poles, and receives high rainfall during the monsoon season, the reality remains that many people in the HKH face acute water scarcity throughout the year. The reasons are many and depend on the circumstance, but they include villages situated at higher elevations than rivers, drying-up springs, demand outstripping supply in cities, and absence of prudent water management. Such water-related distress at the local level is likely to increase further due to climate change and increase in water demand due to socio-economic changes.”

The Pakistan Government’s ‘Vision 2025’ report (Ministry of Planning Development & Reform, 2014) lists goals for water security that focus on increasing water storage capacity, minimising wastage through conservation and efficiency gains, enabling effective allocation encompassing social and economic considerations, establishing effective and well integrated water management institutions, and providing every citizen a minimum baseline of suitable water. The report ‘A Productive and Water-Secure Pakistan’ (WSTF, 2012) comprehensively outlines the steps required to direct Pakistan onto a development and reform path to achieve many of these goals. Annex 6 of the report outlines specific priorities of relevance to knowledge development. Priorities of relevance to CSIRO’s Indus SDIP Project include ‘Develop a river simulation model’ and ‘Develop a decision support system for inflow forecasts and river operations’. This current report, on the hydroclimate of the Indus basin, provides a review of the literature in the key areas relevant to process understanding of trends, seasonal forecasting and climate change with a focus on the Upper Indus Basin (UIB). This knowledge will be used to inform seasonal forecasting research and thus contributes directly to addressing these priorities.
2 Objectives

The objectives of this report are to:

- Summarise the climatological process influencing the hydrology of the Indus Basin.
- Synthesis current knowledge of trends in observed climatological records for the Indus Basin.
- Synthesis current knowledge of relevance to seasonal forecasting of Indus flow.
- Synthesis current knowledge of relevance to climate change impacting on Indus flow.
3 Hydroclimatology of the Indus basin

3.1 Background

The Indus Basin (IB) covers over one million square kilometres of central and south Asia. The river’s headwaters originate on the Tibetan Plateau (China) and cover over parts of India, Pakistan and Afghanistan. Over half of the IB resides within Pakistan where it provides the majority of the country’s irrigation water, as well as being crucial for hydroelectric power generation.

The Upper Indus Basin (UIB), encompassing glaciated headwater catchments within the northern Hindu-Kush, Karakoram and western Himalayan (HKKH) mountain ranges, dominates water generation within the IB (Alford et al., 2014). The UIB’s tributaries include the Hunza, Shigar, Shyock and Gilgit in the Karakoram Himalaya, the Astore, Jhelum, Chenab, Ravi and Sutlez in the western Himalaya, and the Kabul, Swat and Chitral in the Hindu Kush mountains.

![Figure 3.1 Upper Indus Basin catchments and major dams](image)

3.2 Hydroclimate processes

The monsoon (commonly referred to as the South Asian monsoon or the Indian summer monsoon, ISM) and western disturbances (WDs) are the two major climate processes influencing precipitation magnitude, timing and variability across the Indus Basin (Dimri et al., 2015; Pant and Kumar, 1997). The monsoon is the annual reversal of wind direction caused by excess heating over the South Asian land mass. It draws moisture from the Arabian Sea and Bay of Bengal into South Asia, across Pakistan and into the southern UIB during June to September. It is the predominate source of precipitation for Pakistan and the Indus Basin during the June to September period, and as it is the period of maximum insolation it coincides with the period of maximum snow and glacier melt contribution to flow in the UIB.
WDs are mid-latitude low-pressure systems originating in the Mediterranean Sea, or even the eastern Atlantic Ocean, together with secondary sources from the Persian Gulf and Arabian Sea. They propagate from west to east across Iran, Iraq, Afghanistan, Pakistan and northern India during the October to March period. They interact with the steep orography to be the dominant source of heavy winter snowfalls across the Hindu Kush, Karakoram and western Himalayas (Cannon et al., 2015; Dimri and Mohanty, 2009; Lang and Barros, 2004). Dimri et al. (2015) review current knowledge on WDs, discussing their interaction with southward extensions of the Subtropical Westerly Jet (SWJ). The interaction is enhanced during El Niño events, intensifying the WDs and providing a stronger moisture flow resulting in higher precipitation over the western Himalayas. In the recent period (1979-2010) there has been an enhancement in the magnitude and frequency of WDs affecting the Karakoram/western Himalaya producing an increase in the frequency of heavy (85th percentile) precipitation events, with these trends related to Arctic Oscillation, Siberian High and Polar/Eurasian Pattern phases (Cannon et al., 2015).

While the monsoon is the major source of precipitation in the semiarid south of Pakistan and a significant contributor in the lower reaches of the UIB (Imran et al., 2014), hydrologically the monsoon contributes less than WDs to Indus flow (De Scally, 1994; Farhan et al., 2015). Thus the monsoon and WDs have differing influences and contributions to UIB flow with the WDs dominating in the northwest of the UIB and monsoon contribution increasing from northwest to southeast across South Asia. Given the dominance of the high mountain HKKH sourced contributions to UIB flow it is important to account for both climate processes as well as glaciological melt processes that are also a significant contributor to UIB flow (Bookhagen and Burbank, 2010). Yu et al. (2013) estimate that 18% of annual UIB flow comes from glacier melt water with the majority of the remaining 82% most probably contributed by snowmelt.

Bookhagen and Burbank (2010) assessed spatiotemporal precipitation and river discharge variability across the Himalayas, from the Indus in the west to the Tsangpo/Brahmaputra in the east, using TRMM (Tropical Rainfall Monitoring Mission) precipitation (1998-2007) and a modified snowmelt runoff model. The strong east-to-west precipitation gradient means all basins to the east of the Sutlej (western Himalaya) receive 70% or more of their annual precipitation in the June to September monsoon period whereas basins to the west of Sutlej receive less than 50% of their annual precipitation during these months. Correspondingly, snowmelt is shown to contribute 50% or more of annual discharge in the Indus and Sutlej, in contrast to the eastern basins where the majority receive less than 20% from snowmelt (an exception being the large Tsangpo/Brahmaputra where around 34% of flow is snowmelt sourced).

Although definitive statements are difficult given data limitations, and whilst the western Karakoram precipitation is likely winter dominated, studies by Hewitt and associates conclude that the central Karakoram snowfall is distributed evenly in winter and summer, often with a reasonable monsoonal contribution (Hewitt, 2014; Wake, 1989). The orography of the high mountains of the Karakoram, together with a year round snowfall-driven accumulation regime, concentrates and enhances precipitation resulting in annual precipitation contributions of 1000 to 2000 mm, an order of magnitude greater than that recorded by valley weather stations (Hewitt, 2011).

Hewitt (2014) criticises the prevailing belief that the higher glaciated areas of the Karakoram experience low, winter dominated precipitation with little monsoonal contribution (traditionally
explained as a consequence of their location in the rain shadow of the Greater Himalayas), stating these are ‘fallacies’ resulting from a lack of data for the region. Mayer et al. (2014) also emphasises the poor data situation, noting the total lack of weather stations within the 4800 and 7000 m band of the Karakoram where most glacial accumulation occurs. Their field study, on the Urdok glacier in the northeast Karakoram, found annual precipitation to be 1060 mm compared to 230 mm at the 1400 m lower elevation Urdukas automatic weather station (AWS). They find the majority of precipitation is western wind sourced, however monsoon incursions can bring significant amounts in intense individual events. An earlier study by Winiger et al. (2005) also notes that unreliably low Karakoram annual precipitation totals of 100 to 300 mm are shown in atlases and text books, such as the Atlas of Pakistan (Survey of Pakistan, 1986), based on data from stations in valleys that are not representative of elevated zones. Using a combination of high-altitude meteorological stations, satellite data and modelling Winiger et al. (2005) infer annual precipitation totals of between 1500 and 1800 mm for the west Karakoram at 5000 m elevation. Thus the commonly reported precipitation climatology for Karakoram underestimates reality by an order of magnitude.

Saeed et al. (2013) concluded that during the summer months of July and August, the heat low developed over land areas due to central Asian high that causes advection of moisture from external sources towards the UIB, such as the Arabian Sea, are insufficient to account for the large amount of precipitation that is experienced over the UIB. They conclude, through modelling, that the necessary moisture is supplied by the evapotranspiration of irrigated water, causing convection and hence resulting in precipitation which is further supported by the complex topography of the region (Saeed et al., 2009; Saeed et al., 2013).

### 3.3 Hydroclimate data sources

The Pakistan Meteorological Department (PMD) has responsibility for maintaining the network of official observing stations across Pakistan and the Water and Power Development Authority (WAPDA) maintain an observing network across the high altitude zone of northern Pakistan (Figure 3.2). WAPDA also provide stream flow records for all Indus tributaries within Pakistan. Use of this data in CSIRO hydrological modelling will be reported elsewhere.

Gridded products, often produced by international efforts, provide coverage across the entire UIB. These rely on the underlying station networks and so in data poor regions they offer limited additional knowledge of hydroclimate processes or trends. A commonly used product is the Asian Precipitation HighlyResolved Observational Data Integration Towards Evaluation of the Water Resources (APHRODITE) dataset which is 0.25° daily precipitation and temperature for 1961 to 2007 (Ali et al., 2012; Yatagai et al., 2012; Yatagai et al., 2010). Gridded datasets were reviewed by Lutz et al. (2014a) who concluded APHRODITE is more accurate over the UIB than other products given its higher spatial resolution, a caveat being the lack of high elevation station inputs limits accuracy and realism for the high elevation areas.
Palazzi et al. (2013) compared a variety of gridded precipitation data sets for the HKK. These included station-based products (APRHODITE, CRU, GPCC); a satellite product (TRMM 3B42); a merged satellite and station product (GPCP), a reanalysis product (ERA-Interim), and precipitation data from the EC-Earth global climate model (GCM). They concluded that the limitations of each of the observational, satellite and reanalysis data sets, such as under measurement or detection of snowfall in station or satellite data (Rasmussen et al., 2012), preclude their use as reference or ‘ground truth’ precipitation inputs to hydrological modelling. Such rainfall errors are also discussed by Andermann et al. (2011) for swathes across the Nepalese Himalaya. As well as lack of spatial coverage, particularly at high altitudes, the errors and inhomogeneities in the station measurements themselves are also highlighted as a major source of uncertainty in gridded products in the analysis of Rana et al. (2015). Gerlitz et al. (2015) used an ANN-based downscaling approach to account for topographically driven precipitation heterogeneity not accounted for in products that suffer from insufficient underlying station coverage.

Remotely sensed precipitation from the Tropical Rainfall Measuring Mission (TRMM) has been used in a number of other studies also (Cheema and Bastiaanssen, 2012; Immerzeel and Bierkens, 2010; Immerzeel et al., 2009; Khan et al., 2014; Rasmussen et al., 2014; Yatagai and Kawamoto, 2008), however it requires correction due to the effects of the extreme orography of the HKKH mountains, for example Cheema and Bastiaanssen (2012) find errors in monthly precipitation of 35% reduced to 15% by calibration to rain gauge data.

Immerzeel et al. (2015) use remotely sensed glacier mass balance trends to back-calculate the precipitation inputs required to sustain the observed quantities of ice stored in the glaciers of the UIB. They determine that UIB glacier mass balance requires precipitation amounts to be much higher, and of different spatial pattern, to those provided in available gridded data sets. Their median precipitation gradients for the entire upper Indus are calculated to be 0.0989%/m, with large regional differences with median precipitation gradients in the Hindu-Kush and Karakoram
ranges (0.260%/m and 0.119%/m, respectively) significantly larger than those for the Himalayan range (0.044%/m). These precipitation gradients result in an average annual precipitation estimate for the entire UIB is 913 ± 323 mm/yr (a volume of 399 ± 141 km³/yr), more than double the corresponding APHRODITE values of 437 mm/yr (191 km³/yr).

Snow cover is also assessed by remote sensing (Afzal et al., 2014; Bashir and Rasul, 2010a; Butt, 2013; Forsythe et al., 2012b; Gurung et al., 2011; Hakeem et al., 2012; Hasson et al., 2014; Immerzeel et al., 2009; Khan et al., 2015; Tahir et al., 2011a; Tahir et al., 2015) with more site-specific studies using field observations, e.g. snow pits, (Mayer et al., 2014; Wake, 1989).

Glacier inventories and assessments also rely on remotely sensed estimates of glacial extent and variation as well as ground-truthing using direct monitoring (Alford et al., 2014; Bambri et al., 2013; Frey et al., 2012; Immerzeel et al., 2015; Kaab et al., 2012; Minora et al., 2013; Nuimura et al., 2015; Pfeffer et al., 2014; Rankl et al., 2014; Sakai et al., 2015; Sarikaya et al., 2013; Sharma et al., 2013). Bajracharya et al. (2015) suggest that none of the global glacier inventories are complete for the HKH region, recommending a dataset created specifically for the region (Bolch et al., 2012). Rankl et al. (2014) studied satellite derived glacier changes in the Karakoram over the 1976 to 2012 period and concluded 80% (969 out of 1219) of the glaciers have stable terminus positions; i.e. they aren’t shrinking, in contrast to trends elsewhere in the Himalayas (Zemp and al., 2015).

3.4 Hydroclimate trends

Archer and Fowler (2004) assessed long-term precipitation trends for 17 stations across the UIB obtained from a variety of sources (PMD, IMD, WAPDA). No long-term trends (annual or seasonal) were found for the three stations having records from 1895 to 1999 (Gilgit, Skardu and Srinagar). In contrast, for the shorter and more recent 1961-1999 period the winter precipitation had increased at all stations with a statistically significant (p<0.05) increasing trend for Skardu in the east and Shahpur and Dir in the west UIB. The 1961-1999 summer precipitation had increased for Astore, Bunji and Skardu. Winter precipitation was found to correlate with monthly indices of the NAO for November to January, suggesting winter NAO indices could be a suitable predictor for seasonal forecasting of flow in the following Kharif season.

In addition to these precipitation trends, Fowler and Archer (2005) determined temperature trends of winter warming since 1961 (maximum temperature, predominantly) at Gilgit, Skardu and Dir, and summer cooling with reductions in summer minimum temperatures more significant than summer maximum temperature reductions. Fowler and Archer (2006) analysed these temperature trends in more detail, noting diurnal temperature range increases for all seasons and annually. The linear relationship between spring and summer temperatures and runoff in the Hunza River suggests a 20% flow reduction for the observed cooling trend, with actual reductions in flow exceeding this prediction over the period of record. They noted recorded expansion of glaciers in the Karakoram are consistent with the summer temperature reductions and winter precipitation increases reported in their analysis.

The studies of Bhutiyani et al. (2007) and Bhutiyani et al. (2010) investigated long-term temperature and precipitation trends, respectively, for the north western Himalayas (the Indian states of Jammu and Kashmir and Himachal Pradesh with the river basins of the Jhelum, Satluj,
Chenab, Ravi and Beas). They concluded the region has warmed 1.6 °C over the 20th century, and at a faster rate since the late-1960s. Winters have warmed faster than summers and the diurnal temperature range has increased as the rate of increase of maximum temperatures is larger than minimum temperatures. For precipitation, they find no trend in winter precipitation but a decreasing trend in monsoon precipitation. Concurrent with winter warming, total winter precipitation of the Pir Panjal Range has a decreasing snow component since 1991. A previous strong relationship between precipitation fluctuations and the NAO in winter months appears to have considerably weakened in the last thirty years.

Immerzeel et al. (2009) identify a significant negative winter snow cover trend for the UIB in MODIS (Moderate Resolution Imaging Spectroradiometer) data for 2000 to 2008. For UIB 1972 to 2002 temperature trends, they find warming in all seasons (strongest in winter and weakest in summer), with higher rates at higher elevations (0.028 °C/year at 2000 m and 0.043 °C/year at 5000 m). Trends in glacier melt are reported by Prasad et al. (2009), who relate them to mid and lower tropospheric warming trends over the 1979 to 2009 period. Warming is predominantly in the December-May half-year. This seasonality is explained, at least in part, by variability in controlling factors such as sunlight duration, CO2, water vapor and aerosol distribution trends.

The findings of Khattak et al. (2011) also support warming trends for winter (December-February) in the UIB that are larger with elevation, as they find 1967 to 2005 maximum temperature trends of 0.046, 0.043 and 0.031 °C/year in the upper, middle and lower regions of the UIB in Pakistan, respectively. Precipitation trends were inconsistent, showing no definite pattern and no correlation with temperature trends. Runoff in the upper catchments correlates with temperature, in the middle catchments runoff correlates with both temperature and precipitation, and in the lower catchments it is correlated with seasonal rainfall only. Temperature trends (particularly increasing winter maximum temperature trends for upper region climate stations, including Astore, Bunji, Gilgit, Gupis, and Skardu) relate to streamflow trends at Besham station upstream of Tarbela Dam, which shows increasing streamflow in winter and spring and decreasing flow in summer. They conclude that the increasing trends in maximum temperature in winter and spring together with the increasing precipitation trend in autumn are the cause of the increasing trend in flow at Besham.

Salma et al. (2012) divided Pakistan into 5 zones, predominately on a north-south basis, and using 30 stations with 30 years of precipitation data (1976-2005) investigated precipitation trends by zone. They note Pakistan experiences two main precipitation producing seasons, the summer Monsoon and the winter seasons. The summer Monsoon precipitation enters the north and north-east during July – September. The primary winter (December – March) precipitation occurs in western disturbances crossing from the north and north-west (i.e. Afghanistan) which provide the snowfall in the northern ranges crucial for water supply. Secondary systems crossing from Iran influence the majority of the country. Overall they find decreasing precipitation trends, a result of the drier 1998-2001 period towards the end of the record during which the southern and central zones experienced severe drought (Khan and Khan, 2015; Xie et al., 2013).

Bocchiola and Diolaiuti (2013) investigated 1980 to 2009 trends for 17 northern Pakistan PMD stations ranging in altitude from 614 m (Kolti) to 2394 m (Astore) for monthly precipitation, number of wet days, monthly average of daily maximum and minimum temperature, 24 hr maximum precipitation, and monthly average 12 noon cloud cover. They confirm other findings of
mostly non-significant changes in total precipitation, maximum precipitation mostly unchanged, number of wet days increasing in the Gilgit area, decreasing in the Chitral area, minimum temperatures increase except in summer, with decreasing trends particularly evident in Gilgit and Chitral, maximum temperatures increasing at all stations, and cloud cover significantly increasing in Gilgit and decreasing elsewhere, particularly in the Kolti region. They suggest the slightly decreased summer temperatures together with increased winter precipitation may result in increasing snow cover areas and thus a mechanism for the lack of glacier reduction, i.e. “Karakoram anomaly” (Hewitt, 2005).

Analysis of 1952 to 2009 monthly, seasonal and annual mean temperature trends for 37 PMD stations by del Río et al. (2013) show an overall increase of 0.036 °C/year. Investigating climate drivers, NAO (North Atlantic Oscillation), ENSO (El Niño Southern Oscillation) and NCP (North Sea Caspian Pattern) were found to have the greatest correlation with mean temperature for March, April and May, suggesting they would be candidates for seasonal forecasting of snowmelt processes.

Hanif et al. (2013) examined areal average annual and monsoonal precipitation trends for northern and southern Pakistan using data from 48 stations for 1951 to 2010. They also summarise recent literature on observed trends in the region, with the majority of these focussing on India. They conclude both annual and monsoonal precipitation is increasing in the north, with the area of maximum precipitation shifting westward. Whilst there were no significant trends in the south as a whole, sub-regions (i.e. south Balochistan and the coastal strip) show declines in monsoonal rainfall.

Naheed and Rasul (2011) define four seasons for Pakistan, Winter from December to March, Pre-monsoon April to June, Monsoon July to September, and Post-monsoon October and November. They refer to the El Nino induced shortfall of precipitation causing Pakistan’s most severe drought on record from autumn 1998 to spring 2003, as detailed in Chaudhry et al. (2009). Rainfall variability increases from north to south. In a follow-up study, Naheed et al. (2013) investigated regional precipitation trends across Pakistan. They found large variations in trends (magnitude and direction) from region to region, with northwestern summer monsoon rain frequency decreasing whereas for the winter season increasing, and for northern areas and Gilgit Baltistan all four seasons showing decreasing trends in rain frequency.

Ahmad et al. (2014) analysed meteorological trends in the middle and lower Indus basin for temperature and rainfall at 12 stations, using monthly data from 1971 to 2010. On a seasonal basis minimum temperatures had larger increasing trends than maximum temperatures for all seasons (0.29, 0.12, 0.36 and 0.36 °C/decade for Tmin compared to 0.16, 0.03, 0.00 and 0.04 for Tmax, for spring, summer, autumn and winter respectively). No significant trends in seasonal rainfall were detected.

A gradual increase in annual precipitation was seen in southwestern coastal areas of Pakistan and the Cholistan desert when Hussain and Lee (2014) investigated trends across three climate normal periods, 1961-1990, 1971-200 and 1981-2010. Precipitation climatology shifted towards drier conditions in the Murree hills, the upper Indus plain, and the northwestern Baluchistan plateau whereas a shift to wetter conditions has been experienced in the central plain, the northwestern mountains, and the southern part of the country.
WAPDA flow data for UIB 19 stations (16 daily, 3 monthly only) from 1960s to 1998 were analysed by Sharif et al. (2013), with a 30 year common period for 12 stations from 1966 to 1995 used to test conclusions. They summarise the geographic variability and magnitude of trends in annual and seasonal flow magnitude. They conclude high elevation glacial catchments, the Hunza in particular, show declining runoff trends that result in a reduced proportion of glacial melt contribution to the main stem of the Indus. This is attributed mainly to the declining trend in summer temperatures. In contrast nival catchments dependent on winter snow melt show increasing runoff trends, attributed to the increasing trends in winter precipitation. There were no consistent changes in runoff timing for spring runoff onset or for the centre of volume of the annual hydrograph. They conclude “Whilst trends in flow magnitude and timing are potentially of practical importance for river basin management and particularly for the operation of the control reservoirs at Tarbela and Mangla, trends at stations upstream from Tarbela (Besham) and Mangla (Kohala) are still small in comparison to variability. It is concluded that if reservoir operating systems are flexibly designed to respond to the variability of experienced droughts and floods, such as have occurred in the past decade, then they are likely to be able to cope with changes expected in the short to medium term as the result of climate change” and finish by recommending that “trend analysis be brought up to date for the upper Indus as soon as flow records are made available.”

Mukhopadhyay and Khan (2014b) show that river discharge during the melting season of the glaciers in central Karakoram has increased from 1985 to 2010, and summarise their findings as follows:

- Melt water from winter snows is the dominant constituent of June and July flows. Glacial melts predominantly contribute to August and partially to September flows, which are controlled by monsoonal snowfall too at elevations approximately >3500 m.

- For all four summer months, flows increased from 1985 to 2000. August flows, which actually reflect the states of the glaciers, have continued to rise steadily after 2000 at the same rate as those did for the period 1985–2000. However, the rising trends of June and July flows changed to slightly declining trends from 2000 to 2010.

- These trends most likely indicate drop in winter snowfall over Karakoram and do not provide direct indications about the states of the glaciers. The rising trend of August discharge is due to change in glacial storage at a steadily decreasing rate of approximately 0.04–0.05 mm/day/year for the period 1985–2010. This rate is nearly equal to the rate of increase in precipitation during the summer months over Karakoram Mountains in recent decades as determined from the ERA-40 and GPCP precipitation datasets. Thereby, this is most plausibly, why the glacial mass balance in central Karakoram is nearly neutral.

- The rising river flows accompanying neutral or slightly positive glacier mass balance are consistent with predicted future river flows derived from hydrologic modelling coupled with a climate projection suggesting increasing temperature and precipitation with unchanged glacier covers.

Ahmad et al. (2015) analysed Swat River basin monthly, seasonal and annual precipitation trends for the period 1961 to 2011. Trends varied from positive to negative between the various stations for different months and seasons. Annually, no significant trends were detected on a basin level. Saidu Sharif, Mardan, and Charsadda stations exhibited significant positive trends in annual
precipitation at a 95% confidence level. Seasonally, negative trends were detected in summer and positive trends in winter and autumn. Monthly trends were positive in May and June and negative in July and August.

Farhan et al. (2015) analysed hydro-meteorological data for the Astore Basin and determined that annual and summer mean temperatures have decreased over the 1980 to 1995 period, concurrent with increased annual, winter and summer precipitation and annual mean discharge. The following 1996 to 2010 period had slightly increasing annual and summer mean temperatures and slightly decreasing annual and summer precipitation, with little change to discharge. The discharge increases were correlated with winter precipitation increases, rather than temperature variations, and so not determined by enhanced glacier melt. They hypothesise that the reduced summer temperatures and positive trends in winter precipitation have reduced ablation and increased accumulation in the Astore glaciers, resulting in a balanced or positive glacier ice mass balance.

Hasson et al. (2015a) present a comprehensive and up to date analysis of trends in maximum, minimum and mean temperatures, diurnal temperature range (DTR) and precipitation for a set of 18 UIB stations (from 1250 to 4500 m elevation) that includes, for the first time, observations from high altitude weather stations. The period of analysis was 1995 to 2012, and also for six stations with long term records (1961 to 2012). For the recent period (1995 to 2012) they find cooling during July to October (monsoon season) and warming during March to May and November. The winter season has a negative trend for maximum temperature and there is a year round decrease in DTR (in direct contrast with 1961 to 2012 long term trends). DTR decrease is stronger and more significant in stations above 2200 m elevation, mostly due to greater reduction in maximum temperature than in minimum. There is a significant decrease in late-monsoonal precipitation at lower latitudes contrasting an increase at higher latitudes. Winter precipitation increases for Hindukush, western- and whole Karakoram, UIB-Central, UIB-West, UIB-West-upper and whole UIB regions. Spring warming and drying results in early-melt season flow increases. The early-melt rise together with monsoon cooling results in a substantial decrease in flow from higher latitude regions and weaker increase in flow from lower latitudes such as Himalaya and UIB-West-lower regions during the late-melt season. They conclude that these flow trends, driven by changes to the monsoon system and western disturbances, combine to promote the contribution from snowmelt sources at the expense of glacial sources, indicating a substantial change to the hydrology of the UIB.

Tahir et al. (2015) determined that MODIS data (2000 to 2012) indicates that the UIB is experiencing a stable or slightly increasing trend in snow cover in both the Central Karakoram in the north and the Western Himalaya in the south, possibly a result of increasing winter precipitation and decreasing or constant summer temperature trends. A 34 year flow series for the Astore River basin (1974 to 2007) shows an increasing trend. This corresponds with increasing winter and summer precipitation and decreasing summer mean temperature. The northern Hunza is dominated by snow and glacier melt, whereas the southern Astore is a combination of melt and rainfall-runoff from winter rainfall systems. Monsoon contribution to both the Hunza and the Astore basins is deemed insubstantial.

Hartmann and Buchanan (2013) examined trends in precipitation extremes (1-day and 10-day 90th and 99th percentile precipitation) from NCEP-DOE Reanalysis 2 over the Indus Basin for the period 1979 to 2011. They concluded the western Indus Basin has experienced significantly decreasing
trends whereas significantly increasing trends have been experienced by the mountainous regions of the Transhimalaya and the Himalayas, as well as at the foot of the Himalayas in the eastern part of the Indus basin and in the Karakorum and the Hindu Kush in the north of the basin.

Forsythe et al. (2015) used 2001-2012 cloud cover data from MODIS MOD06L2 to produce a cloud climatology for the UIB, focusing on NW UIB tributaries. They find that trends of decreasing daytime cloud cover coincide with trends of strong increases in maximum temperatures and diurnal temperature range. Decreasing minimum temperatures in the peak summer months are plausibly related to trends of less night-time cloud cover which results in greater overnight cooling.

Bajracharya et al. (2015) report on glacial trends across the HKH inferred from Landsat images commencing in 1976 and ending in 2011, focusing on a small set of representative basins for detailed decadal glacier change analysis including the Shyok Basin in Pakistan. They find most of the glaciers in the Shyok Basin lost area and retreated in the period 1980–1990, showed little change in 1990–2000, and remained static or advanced in 2000–2010. Over the 30 years, most glaciers showed some loss of area, but there was almost no change in the area of the largest glacier. Overall they conclude that glaciers are retreating slowly but steadily in the Hindu Kush, show a mixed response in the Karakoram glaciers (varying from thinning of large DC tongues to advancing and surging tributaries) and are retreating rapidly in the Himalayas, with glacial lakes playing a marked catalytic role.

Madhura et al. (2015) investigated meteorological drivers of the observed trends in increased frequency of heavy precipitation over the western Himalayas in winter (DJFMA season). They conclude that pronounced warming over the Tibetan Plateau over the recent decades has influenced regional synoptic weather systems, enhancing the variability of western disturbances that has resulted in the increased occurrence of heavy precipitation.
4 Indus hydrology, variability and forecasting

4.1 Hydrology of the Indus

La Frenierrre and Mark (2014) review studies across the high elevation regions of the globe that have quantified glacier melt discharge contribution. Studies in the headwaters of the Indus include those involving direct discharge measurement (Thayyen and Gergan, 2010), those using hydrological balance equations (Singh and Jain, 2002; Singh et al., 1997), those using hydrological tracers (Maurya et al., 2011), and those (a majority of the studies cited) using hydrological modelling (Akhtar et al., 2008; Jeelani et al., 2012; Mukhopadhyay, 2012; Mukhopadhyay and Dutta, 2010; Pellicciotti et al., 2012; Rees and Collins, 2006; Singh et al., 2006). La Frenierrre and Mark (2014) emphasise the variation between definitions of what constitutes glacial meltwater, with some studies reporting total contribution from glacierised areas (i.e. ice melt and seasonal snowmelt considered together) whilst others exclude snowmelt. Thus comparing conclusions across studies is not straightforward. Annual studies would not pick up seasonal variation in snow and ice contribution. Location of discharge measurement within the basin is also an issue, as measurement within a basin may not be representative of the whole basin. Data limitations (hydrological, glaciological, and climatological) are a pervasive source of uncertainty for many regions, including the HKH. As contributions from glacier melt are able to buffer for low snow and rainfall sourced flow in dry periods, they note understanding the inter-annual variability in contribution is important. This buffering capacity would be relevant to seasonal forecasting, as less snow cover would result in more glacier exposure and thus years of less precipitation may be compensated for by greater glacial input to discharge.

Savoskul and Smakhtin (2013) review the status of meltwater (glacier runoff and seasonal snowmelt runoff) resources across the major river basins of South Asia (Indus, Ganges, Brahmaputra, Syr Darya, Amu Darya and Mekong) for baseline (1961-1990), and current (2001-2010) periods, as well as assessing likely future changes. They define ‘glacier runoff’ as the combined discharge from ice melt, snowmelt and rainwater of an ice-covered area (noting rainwater contribution on ice areas is negligible). Seasonal snowmelt contributes to flow typically over half a year or more, starting several months earlier than glacier ablation. The snowmelt period is longer than the glacier melt period as snowmelt occurs across a wider range of elevation bands, with seasonal peaks that progress from lower elevations to higher ones. Typically, maximum snowmelt contribution occurs 2-3 months prior to maximum glacier contribution. Glacier melt contributes to river flow for 2-3, maximum 4 months, mainly from early/mid-summer, till late summer/early autumn and reaches its maximum in July-August. The simulation component of the study by Savoskul and Smakhtin (2013) estimated meltwater contribution to Indus flow at 37% (for 1961-1990), with half coming from snowmelt and half from glacier melt. For the more recent 2001-2010 period, their estimate is a 31% contribution. Their simulation accuracies are stated to be within ±30%. Regarding future climate change, they state precipitation regimes changes coupled with effects of temperature rise on evapotranspiration will impact future hydrological regimes much more significantly than changes to glacier and seasonal snow extent (changes to which will result mainly in changes to flow seasonality).
The basins in the Upper Indus can be classified as having a flow regime that is either glacier-melt dominated (Hunza, Shigar and Shyok) or snow-melt dominated (Jhelum, Kabul, Gilgit, Astore and Swat) (Hasson et al., 2013). The majority (>60%) of flow in the Indus comes from the Upper Indus, the predominate source being snowmelt, followed by glacier melt as a secondary source, with 80% occurring during the June-September period. The interannual variability is thus controlled by two processes, the amount of winter precipitation (snowfall) and the summer temperatures. Whilst snowmelt is a function of both winter precipitation and summer temperatures, glacier melt is primarily a function of summer temperatures, although glacier melt is also influenced by snow cover.

The isotopic analysis performed by Karim and Veizer (2002) determined that during the year March 1994–February 1995, up to 72% of Indus annual discharge derived from snowmelt runoff in the Karakoram and the Himalayas. The isotopic composition indicates the water in the snow originated as evaporation from a closed inland basin such as the Mediterranean or other inland sea.

Jeelani et al. (2012) show that snowmelt is the dominant source of runoff for the Liddar catchment within the Jhelum basin, accounting for 60% of simulated flow. Glacial melt is inconsequential to runoff for most months, peaking at a 9% contribution in August with a 2% annually averaged contribution. Trends of increased warming, greater in winter than summer, and decreasing winter and increasing spring precipitation mean less precipitation falls as snow leading to an earlier runoff peak in June, from July as seen earlier in the 20th century.

Archer (2003) notes “For the River Hunza ... summer runoff is unrelated to winter precipitation but depends largely on the energy input, represented by temperature, for the current season” and notes there are “significant correlation coefficients greater than 0.65 between summer [July to September] temperature and runoff” and that “for the ablation period, April to September, each month (with the surprising exception of June) shows strong correlation with temperature.”

They conclude: “In a generalized way, melt water from high-altitude catchments in UIB, is a mixture of glacial melts, melts from seasonal snows that fall in the winter and spring prior to the melting season, and summer snowfall that takes place concurrently. Hence, the headwaters are jointly influenced by variations in both glacial melt and seasonal snowmelt. Because of the concomitant melting of the three different genetic sources, it is difficult to differentiate the respective contributions they make to the final river discharge. For this reason, this source water is collectively designated as high-altitude melt.”

Archer (2003) regressed streamflow data from nineteen long-period stations (annual and seasonal runoff) with climatic variables for three key basins, the River Hunza, River Astore and Khan Khwar followed by regional analysis of twelve further basins. Analysis shows distinct hydrological regimes with summer volume governed by: melt of glaciers and permanent snow (thermal control in the current summer), melt of seasonal snow (control by preceding winter and spring precipitation), or winter and monsoon rainfall (precipitation control in current season). Thus in highly glaciated basins, such as the Hunza and Shyok rivers in the Karakoram, the summer (June-September) flow correlates with concurrent summer temperatures but not preceding winter precipitation. In contrast, seasonal snow melt dominated basins, such as parts of the Astore and Upper Indus adjacent the Jhelum, do show strong correlations between summer flow and preceding winter (October-March) precipitation. Summer rainfall, from monsoon incursions, is not a major
contributor to flow in the Upper Indus with suppression of melting at higher elevations due to lowered temperatures and reduced energy inputs compensating for any increased contribution at lower elevations from direct rainfall inputs (Archer, 2004).

Butt and Bilal (2011) provide an example of the suitability of the SRM (Snow Runoff Model) (Martinec et al., 2008) coupled with MODIS based SCA (Snow Cover Area) for runoff simulations for the Astore River for 2000-2006. While noting recession flow is overestimated, they conclude SRM runoff simulations are accurate (Nash–Sutcliffe coefficient of determination of 0.87 and volume difference of 1.18%).

SRM and MODIS were also used by Sharma et al. (2012) for a study of the Jhelum River basin. The basin has a discharge regime dominated by seasonal snow melt given it is minimally glaciarised. A decreasing snow cover extent (SCE) trend is seen between 2000 and 2011, correlated with increases in mean temperature.

Mukhopadhyay and Khan (2014a) produce a more up to date and detailed assessment of the sources of river discharge within the UIB using a combination of statistical and hydrological analysis. Based on an analysis of hydrograph peaks, inflection points and monthly flow autocorrelation they partition the year into four regimes:

- October to December: a low flow, mostly baseflow, regime of meltwater from the preceding summer and monsoon, contributing 8-9% UI main stem and 8-10% main tributary flow;
- January to March: also a low flow regime, representing baseflow recession of remnant baseflows from the October-December regime, contributing 4-6% UI main stem and main tributary flow;
- April to June: a high flow regime of predominantly seasonal snow meltwater from sources <3500 m elevation with some from > 3500 m, contributing 24-32% UI main stem and 15-38% main tributary flow;
- July to September: also a high flow regime of glacier, perennial snow and ice pack, winter snow, and monsoonal snow melt from sources predominantly in the 3500-5300 m elevation band, contributing 53-62% of UI main stem and 47-74% main tributary flow.

High altitude basins are shown to contribute more to UIB flow than mid-altitude basins, with the elevation band 3500-5300 m contributing 41-54% along the main stem and 37-65% main tributary flow from glacial and seasonal snow melt. The elevation band 2500-3500 m contributes 16-29% along the main stem and 12-34% main tributary flow as seasonal snow melt. The majority of Tarbela inflow comes from the three basins with the largest glaciated area (Shyok, Shigar, and Hunza) with a combined contribution of 20–31% to April to June flow, 48–54% to July to September flow, 33–39% to October to December and 31–32% to January to March. Overall Tarbela inflows are 70% melt water of which 21% is glacial melt and 49% snowmelt.

Hewitt (2014) estimates that for average annual inflow into Tarbela Dam, 40% is provided by glacier melt, mainly from the Karakoram. Around 50% is estimated to come from snowmelt across the whole UIB, and the remaining 10% from rainfall runoff, mainly from Northwest Himalayan watersheds. Monsoon rains do not contribute significant input to average flow, however they are a source of flood waters in extreme years such as occurred in 2010.
Shrestha et al. (2015) simulate Hunza River flow using an energy budget-based distributed model that accounts for snow and glacier melt runoff. They determine snowmelt, glacier melt and rainfall account for 50%, 33% and 17% of annual flow, respectively, for their 2002-2004 study period. A sensitivity analysis to model inputs showed precipitation changes are important throughout the year whereas air temperature influences flow during the summer period only.

4.2 Indus seasonal forecasting

Given that the majority of annual flow in the Indus is contributed by the Upper Indus, seasonal forecasting investigations have focussed on understanding snowmelt and glacier melt processes and how climate forcing influences their variability. Given the significant economic and social costs resulting from sub-monthly regional-scale floods such as those experienced in 2010, an additional research focus has been short-term flood forecasting. Short-term flood forecasting (Houze et al., 2011; Rasmussen et al., 2014; Shrestha et al., 2014; Webster et al., 2011) is not covered here. There is also a large body of literature relevant to forecasting the Indian Summer monsoon (see Bibliography) that is also not covered here, other than to note some studies have been applied to summer (i.e. monsoon) forecasting for the Indus or in Pakistan (Ding and Ke, 2013; Karori and Zhang, 2008).

As emphasised through the examples discussed in Section 4.1, winter precipitation and summer temperatures are key determinants of the magnitude and timing of snowmelt and glacier melt contribution to Upper Indus flow. Ferguson (1985) presents an early analysis of the nonlinear flow response to combined snow and glacier processes from a forecasting perspective. Snowpack water equivalent increases non-linearly with snow cover area so for transient snowpack, non-glaciated, situations the snowmelt runoff increases at a proportionally greater rate than snow cover area and only the timing of runoff, but not the total amount, is influenced by spring and summer temperatures. For glaciated basins the processes are more complicated as total runoff includes snow melt (from non-glaciated areas and snow on glaciers), glacier melt, rainfall runoff, and groundwater discharge. Snowfall onto glaciers retards glacier melt, so glacier melt is earlier and greater when snowfall is less. Thus interannual variation in runoff can be dampened in glaciated basins relative to non-glaciated (i.e. snow melt only) basins (Figure 4.1a). For lightly glaciated basins a positive correlation between winter snow cover area and summer runoff remains, however in highly glaciated basins the snow cover induced reduction in glacier melt may exceed the snowmelt contribution, thus more runoff may occur in years with less snow cover. Ferguson (1985) was able to model this relationship, as shown in Figure 4.1b.
Makhdoom and Solomon (1986) reviewed early attempts to forecast seasonal flow in the Indus by regressing runoff volumes on satellite derived snow cover area. Examining the Rango et al. (1977) study of the Besham Qila station upstream of the Tarbela dam, Makhdoom and Solomon (1986) note the forecast errors for 1974-79 are larger than if the preceding year’s recorded runoff values had been used as the forecast. This, and similar studies from this period, consistently show the regression of flow on snow cover area does not add skill over that which would be obtained by using average flows as forecasts. The inadequacy of the relationship is attributed to snow cover area not being proportional to actual snow volume, given snow depth and density variations.

De Scally (1994) investigated relationships between annual flow in lightly glaciated tributaries of the River Jhelum and their total winter snowfall, annual maximum snowpack water storage, and total precipitation (divided into winter and summer precipitation, so as to determine the summer monsoon rainfall contribution to flow). Highest correlations with annual flow were obtained from the annual maximum of snowpack water storage and total winter precipitation. Overall, summer precipitation data had little correlation with annual flow, highlighting the limited input of monsoon rains into the basin.

Majid et al. (2006) develop regression relationships to estimate Tarbela Dam Kharif season inflow volume (aggregate snow and glacier melt) as a function of meteorological parameters (winter rainfall and cloudy day count), thus avoiding the need for direct snow pack measurements. The Kharif season rainfall contributes from 1% to 20% of annual inflow (average 5%) and is assumed a constant (i.e. this approach does not account for anomalously large summer rainfall volumes). Also published as Majeed et al. (2009). Most of their 1981 to 2004 Kharif season forecasts were within 5% of the actual flow, with only three years having errors greater than 10% (1984, 1990 and 2004).

Archer and Fowler (2008) determined runoff in the Jhelum and its main tributaries could be forecast (hindcast) using precipitation measurements from valley stations; producing correlation coefficients of ~0.7 between winter precipitation and spring and summer runoff. Multiple linear regression models using precipitation and temperature from valley stations could forecast summer season flows at stations upstream from the Mangla Dam with a lead time of up to three months. Summer (April to September) season flows could be forecast within 15% of observed flows for 92% of years (ROC score = 0.77) and spring (April to June) flow forecasts could be estimated within 15% of observed flows for 83% of years (ROC score = 0.93).
Forsythe et al. (2012a) note that for UIB seasonal forecasts to have practical value they have to be skilful for summer runoff at the end of winter (late Mach / early April), i.e. a 3 to 6 month lead-time. They refer to Archer and Fowler (2008)’s findings that such skill is possible for the large snowmelt dominated catchments of the Western Himalayas, where runoff is governed by the winter precipitation inputs producing the snowpack. For the ice melt (i.e. glacial) dominated catchments where runoff volumes relate to summer temperature rather than precipitation inputs, obtaining skilful forecasts is a challenge as it is difficult to predict temperature anomalies a season ahead. Teleconnections with large-scale climate drivers, as discussed below, could be a possible source of predictability of seasonal variation of temperature.

Bashir and Rasul (2010b) investigated Gilgit Basin runoff prediction for the summer of 2003 using remote sensing derived snow cover (Normalized Difference Snow Index, NDSI, from MODIS data (Bashir and Rasul, 2010a)), a digital elevation model and meteorological parameters as input to the snowmelt runoff model (SRM). They identified limitations of the approach including precipitation data limitations and SRM’s use of a single Degree Day Factor per elevation zone, given that in reality it changes with differing meteorological conditions, varying according to elevation, aspect and landform, as well as varying according to the changing snow properties throughout the snowmelt season.

Pal et al. (2013) investigated 1978 to 2004 spring (March-June) inflow forecasting for the Bhakra Dam on the Satluj River in northern India, an Indus tributary allocated to India under the Indus Waters Treaty. They used multiple linear regression to relate flow to the preceding winter average snow volume, measured at stations high in the basin, and rainfall and temperature at lower elevation stations. They obtained skilful forecasts for most years, better than climatology, for late winter or the beginning of the spring season (1 March or 1 April, respectively) forecasts using gridded precipitation and station snow information as predictors.

### 4.2.1 Current Pakistan agency seasonal forecasting

**PMD**

PMD undertake experimental seasonal forecasting of monthly precipitation for three months ahead: [http://www.pmd.gov.pk/rnd/rndweb/rnd_new/seasonal.php](http://www.pmd.gov.pk/rnd/rndweb/rnd_new/seasonal.php). The methodology is applied to 31 stations across Pakistan, using a multiple linear regression based statistical downscaling model to account for the relationship between station precipitation and large-scale fields simulated by a GCM prediction produced by the CGCM of the Beijing Climate Center (Karori and Zhang, 2008).

In addition, the National Agromet Centre within PMD provide seasonal outlooks of regional weather (precipitation and temperature) using an ensemble of GCM predictions, corrected on a regional basis. These are issued the 10th of each month, with a three month outlook: [http://namc.pmd.gov.pk/seasonal-weather-pak.php](http://namc.pmd.gov.pk/seasonal-weather-pak.php).

**WAPDA**

WAPDA produces Kharif and Rabi forecasts of inflows to the Tarbela Dam, issued at the beginning of each respective season (D. Hashmi, WAPDA, pers. comm.). They are based on running hydrological models (e.g., UBC and SRM) with observed meteorological inputs (e.g., observed SCA) to the beginning of the forecast season and then using a scenario approach using the observed
inputs from each previous year (e.g., 2003-2011) to produce an ensemble of forecasts. Then, from the distribution of the resulting simulated seasonal flow volumes, the 10%, 50% and 90% flows are reported as the forecast probability range. The addition of predictors based on prevailing climate conditions, via the BJP framework (Robertson et al., 2013; Robertson and Wang, 2012), is a potential method to add skill to such forecasts.

### 4.2.2 Potential climate predictors

#### North Atlantic Oscillation (NAO)

Variability in the NAO influences the latitude of the subtropical jet, impacting on the positioning and strength of mid-latitude storm tracks that bring moisture from the Atlantic Ocean, Mediterranean, Caspian, Arabian Seas and Persian Gulf to the Indus Basin (i.e. westerly disturbances). Indices of the NAO have been related to: UIB station winter precipitation (Afzal et al., 2013; Archer and Fowler, 2004; Filippi et al., 2014); western Indus basin’s winter snow cover and station precipitation (Hasson et al., 2014); Pakistan station temperature (del Rio et al., 2013); and winter precipitation in northwest India (Kar and Rana, 2014).

#### ENSO, SOI and NINO SST indices

The variability in both western disturbances and monsoon processes are related to ENSO. The commonly used SOI (Southern Oscillation Index) has been related to: winter HKH precipitation (Afzal et al., 2013); Indian Summer Monsoon Precipitation (Ashok et al., 2004; Ashok and Saji, 2007); central southwest Asian winter precipitation (Syed et al., 2006); Pakistan station temperature (del Rio et al., 2013); northwest India winter precipitation (Kar and Rana, 2014).

The modelling study of how ENSO and NAO impact precipitation across central-southwest Asia (CSWA) by Syed et al. (2010) concluded: “A detailed analysis of the simulated storm characteristics showed that the NAO and ENSO precipitation signal over the CSWA region is mostly associated with an intensification of western disturbances originating in the Eastern Mediterranean and Middle East regions and moving eastward across CSWA during the positive NAO and the warm ENSO phases. This intensification is associated with the effect of an enhanced SLP and 500 hPa trough which develops over the region during these NAO and ENSO phases. Although the structure of the trough is similar for the NAO and ENSO cases, its origin is different. The trough originates from an eastward extension of the Icelandic low during the positive NAO phase and from a weak establishment of the Siberian High during the warm ENSO phase. .... In the positive phase of the NAO and (to a lesser extent) the warm phase of ENSO, the composite of vertically integrated moisture convergence from 1000 to 500 hPa indicates that the transport of extra moisture from the Mediterranean, Caspian Sea and Arabian Sea contribute to the observed precipitation signals.”

Afzal et al. (2013) correlated winter precipitation at 14 Pakistan stations with NAO and ENSO and found a stronger relationship with ENSO than NAO, with positive precipitation anomalies with positive NAO and negative SO showing strong westerly and El Nino conditions result in more snowfall over the HKH.

#### Indian Ocean Dipole (IOD)

The IOD has been related to Indian Summer Monsoon precipitation (Ashok et al., 2004; Ashok and Saji, 2007). Ashok et al. (2004) discuss relative influences of ENSO and IOD events on Indian summer rainfall as studied using observational data and a GCM. The IOD, while significantly
influencing the Indian summer monsoon rainfall, also significantly reduces the impact of ENSO on the Indian summer rainfall whenever these events with the same phase co-occur. Ashok and Saji (2007) determined that the spatial distribution of partial correlations between the IOD and summer rainfall over India indicated a significant impact on rainfall along the monsoon trough regions, parts of the southwest coastal regions of India, and also over Pakistan, Afghanistan, and Iran. ENSO events had a wider impact, although opposite in nature over the monsoon trough region to that of IOD events.

**South Asian High (SAH) / Tibetan High**
The SAH has been related to Pakistan summer precipitation by Zahid and Rasul (2013), who investigated the temporal relationship between the SAH and monsoonal rainfall over Pakistan for the period 1979-2010. They concluded there is a strong correlation between strength and position of the SAH and the Pakistan monsoon (July-September) precipitation, finding that “when SAH oscillates more westward and strengthens, a substantial amount of precipitation sometimes leading to flooding state in Pakistan and when SAH weakens and oscillate more eastward from its mean position (28°N-80°E) scanty amount of rainfall is experienced by the country.”

**Artic Oscillation (AO)**
The AO has been related to northwest India winter precipitation (Kar and Rana, 2014); and Pakistan station temperature (del Río et al., 2013). Cannon et al. (2015) find that the strong positive phase of the AO is related to a strengthening in WD activity in the Himalayas and resulting increased precipitation.

**North Sea – Caspian Pattern (NCP)**
The NCP has been related to Pakistan station temperature (del Río et al., 2013).

**Geopotential Height (GPH) Anomalies**
Western disturbances have been related to heavy precipitation in the KH through upstream 200 GPH anomalies (Cannon et al., 2015).

**SST**
SST fields have been used for station rainfall prediction in Pakistan. van Ogtrop et al. (2014) concluded: “Strong correlations were found between the VARIMAX rotated principal components of SSTs (the climatic predictors) and well known SST anomalies associated with the El-Niño Southern Oscillation, Pacific Decadal Oscillation, Indian Ocean Dipole and the tropical Atlantic Ocean. The Generalized Additive Models revealed linear and non-linear relationships between agriculturally relevant rainfall periods and multiple time-lagged climatic predictors. Based on the statistical models developed, skilful forecasts of seasonal rainfall totals (continuous and categorical probabilistic forecasts) can be produced for Chakwal, Talagang and Islamabad. Forecasts such as the probability of exceeding median monsoon rainfall and volumetric rainfall with 95% confidence intervals can be provided with minimal financial investment.”

The evidence in the literature, as outlined above, suggests both NAO and ENSO indices should be investigated for potential skill in seasonal forecasting of UIB Kharif flow, as an input to the Bayesian joint probability model (Robertson et al., 2013; Robertson and Wang, 2012) being developed within the project.
5 Climate change

Archer et al. (2010) assessed the impact of climate change on resources in the Upper Indus in terms of the three dominant hydrological regimes – the nival regime dependent on melting of winter snow, the glacial regime, and the rainfall regime dependent on concurrent rainfall. On the basis of historic trends in climate, most notably the decline in summer temperatures, they concluded there was no strong evidence in favour of marked reductions in water resources for any of the three regimes. They noted evidence for changes in trans-Himalayan glacier mass balance is mixed. Thus they concluded sustainability of water resources appears more threatened by socio-economic changes than by future climatic trends.

Bocchiola et al. (2011) attempted to evaluate the impact of possible climate change upon the hydrology of the upper Indus river. Given lack of knowledge of hydrological processes and data limitations in the HKH they state “development of a generally valid and accurate approach to regional hydrological modeling in this area seems beyond the present know how.” Thus their approach was to utilise a minimalist hydrological model that made use of limited available data from multiple sources, in a case study of the Shigar catchment. They used a power law (Winiger et al., 2005) to infer precipitation at altitude, with coefficients estimated from PMD station data (TRMM produced annual precipitation of 350 mm, compared to 550 mm from their power law equation, i.e. 35% difference). A degree day approach was used for ice melt and snow melt rates. Modelled snow cover area was compared to MODIS data. Their daily hydrological model is a “semi-distributed altitude belts based model …, able to reproduce deposition of snow and ablation of both ice and snow, evapotranspiration, recharge of groundwater reservoir, discharge formation and routing.” The note the melt factor approach is simple and possibly not as accurate as energy balance approaches, but these would require data such as solar radiation, wind velocity and air moisture that was unavailable. They assess changes by driving the hydrological model with precipitation and temperature adjusted according to projected changes from the CCSM3 CMIP3 GCM for the A2 scenario for the period 2050-2059, relative to 2000-2009 (average temperature increase of 1.9 °C and precipitation increase of 20%). For four glacier coverage scenarios (no change, and 10, 25 and 50% areal reduction), they find increased flow in the first three scenarios due to greater glacial melt and the fourth showed a discharge reduction due to reduced glacial melt.

Tahir et al. (2011b) applied the snowmelt runoff model (SRM), based on a degree day factor approach, to the Hunza River basin using MODIS derived snow cover as input. Scenario assessment for future mean temperature, precipitation and snow cover changes suggests summer runoff has the potential to double until mid-century. They note that the problem of non-representative precipitation inputs, given that both the gauges and the APHRODITE gridded data underestimate high altitude precipitation, is circumvented as the SRM is more responsive of snow cover data given that snow and glacier melt contribute the majority of runoff for these high altitude UIB catchments. They note the need to apply to the other UIB catchments (i.e. Shigar, Shyok, Astore, Gilgit and Kharmong).
Miller et al. (2012) review the evidence for the impact of climate change on the glacial hydrology (i.e. observed and modelled runoff response to changes in snow and glacier melt) of the Indus, Ganges and Brahmaputra basins of the HKH. They state the minimal evidence on trends in discharge from the UIB does not corroborate the hypothesised increase in meltwater expected from increased temperatures. One of their conclusions is that “models suggest that glaciers to the west provide a significant contribution to annual discharge in the lower reaches of the Indus, because of weaker monsoon rains and greater aridity at lower altitudes, whereas the limited observed data can indicate otherwise.” They base this on modelling that indicates snow melt contributes 34% and glacier melt 26% of total discharge (Immerzeel et al., 2010) contrasting observations reporting 70% of annual flow is derived from seasonal monsoon rains in the lower Indus plains (Winiger et al., 2005) and that only 49% of annual flow at Akhnoor on the Chenab River is derived from snow and glacier melt (Singh and Bengtsson, 2005).

Immerzeel et al. (2013) contrast modelled climate change impacts on the Baltoro basin of the Indus with those for the Langtang basin of the Ganges. The variation in precipitation change between climate models produces the largest source of uncertainty. They concluded that total runoff will increase in both basins until 2100, in contrast to earlier research that suggested future runoff reductions in both the upper Indus and upper Ganges basins (Immerzeel et al., 2010) due to a crude mass balance estimate of glacier retreat leading to underestimation of future glacier melt. The Baltoro experiences a larger contribution from glacier melt and increased glacier melt is the main contributor to runoff increase, whereas increased precipitation is the main contributor to runoff increase in the Langtang. The Baltoro also experiences increases in snow melt runoff from seasonal snow cover on areas that lose glacier cover due to warming. They suggest that future runoff changes will become increasingly dependent on precipitation changes as the contribution from glacier melt declines after reaching a peak mid-century.

In a broader scale study, Lutz et al. (2014b) assessed potential changes to water availability for the Indus, Ganges, Brahmaputra, Salween and Mekong rivers, with increased runoff projected to 2050 for the upper Ganges, Brahmaputra, Salween and Mekong primarily due to projected precipitation increases and for the Indus due to accelerated glacier melt in the upper basin. They determined the contribution of rainfall runoff, snow melt, glacier melt and baseflow to total annual runoff. For the Indus River they determined glacier melt currently contributes 40.6% of total flow resulting in peak flow in summer when glacier melt is highest. Flow in the Kabul River, also in the UIB, is snow melt dominated with flow peaks in spring and the Satluj River is monsoon rain dominated, with flow also peaking in summer. As Indus River flow is dominated by the temperature-driven glacier melt projection uncertainty is relatively small as all GCMs investigated project similar temperature increases. Larger uncertainties in change occur for the Kabul and Satluj given their greater snow and rainfall runoff contributions. They conclude “The contradictory precipitation projections for this basin make water availability in the UIB highly uncertain in the long run, requiring further research.”

Munir (2013) applied defined climate change scenarios of a 2 °C temperature increase and a 20% precipitation increase, individually and in combination, to a SRM of the Neelum River, which contributes approximately 40% of Mangla dam inflow. The temperature increase alone resulted in a 21% discharge increase, the precipitation increase alone a 6% increase and the combined effect a 27% increase.
Palazzi et al. (2013) assessed broad scale properties of observed data products for precipitation across the HKH (TRMM, ERA-Interim, APHRODITE, CRU, GPCC, GPCP). They determine all datasets reproduce the east-west differences in seasonal cycle, with the Himalaya (east) having only summer (monsoon) rainfall whilst the western Hindu-Kush Karakoram winter inputs from mid-latitude westerly disturbances. A long-term decline in Himalayan summer precipitation is statistically significant and there are no statistically significant trends in winter for the Hindu-Kush Karakoram. Projected precipitation trends (for RCP 4.5 and RCP 8.5) show Himalayan summer increases due to increased extremes and mean intensity, however the model also has increasing precipitation in the 1950-2009 period that are opposite to the observed trend, attributed to poor representation of aerosols in the GCM used.

Palazzi et al. (2015) assessed 32 CMIP5 GCMs for their ability to reproduce the observed 1901-2005 precipitation climatology (mean and trend) of the Hindu-Kush Karakoram (HKK) and the Himalaya regions. Given the drivers of regional precipitation seasonality, they focussed on two seasons – the winter season (DJFMA) of relevance to HKK westerly sourced winter and spring precipitation and the summer season (JJAS) relevant to the monsoon precipitation of the more eastern Himalaya. They determined it is difficult to select better performing models as none reproduce all features, i.e. annual cycle as well as seasonal precipitation trend. Precipitation changes for RCP4.5 and RCP8.5 were assessed for 2021–2015 and 2071–2100, relative to 1971–2000. Noting the robust finding that all models indicate an increase in summer (i.e. monsoon) precipitation for the Himalaya, they however caution against using projections with confidence given the limitations for historical-period performance. They particularly caution against relying on the multi-model ensemble mean given the wide spread of projected changes.

Ragettli et al. (2013) simulated changes in snow, glacier and runoff for the Hunza River Basin in northern Pakistan using a physically based glaciohydrological model (TOPKAPI-ETH), finding that parameter uncertainty (particularly for subcatchments with high glacial cover) can affect future projections more that climate change uncertainty from the three GCMs used (to 2050 using A1B).

Regional climate model projections of winter snowfall from western disturbances affecting the Karakoram are assessed by Ridley et al. (2013). Results from downscaling two GCMs (HadCM3 and ECHAM5) vary with one projecting a 37% increase in winter snowfall due to more frequent WDs and the other no significant change, by 2100.

Forsythe et al. (2014) combined the stochastic rainfall model RainSim with the rainfall conditioned weather generator CRU-WG to assess local climate change impacts for three stations (Gilgit, Skardu, and Astore) in the Upper Indus Basin. Change factors were obtained from RCM (PRECIS driven by HadAM3P for A2) differences between control (1961-1990) and future (2071-2100) simulations. Year round increases in precipitation were projected (mean annual change 18%) with increased intensity in the wettest months (February, March and April) as well as year round temperature increases (4.8 °C mean annual).

Kapnick et al. (2014) determined that the Karakoram’s non-monsoonal winter precipitation dominance reduced its sensitivity to projected snowfall reductions as modelled snowfall increases in winter offset snowfall reductions during the summer. They note “Owing to the high interannual variability relative to climate trends in snowfall, precipitation and rainfall, long records are required to calculate significance in the present climate, and are not possible for several more decades for total precipitation. This suggests that monitoring systems from the recent past are
insufficient to detect a uniform significant signal across all hydroclimate variables, mirroring contradictory observational studies in the region.”

Panday et al. (2014) compared eastern Himalaya (EH) and western Himalaya-Karakoram (WH) projections from CMIP3 and CMIP5 for seven extreme temperature and precipitation indices. Precipitation projections indicate increased mean precipitation with more frequent extreme rainfall during monsoon season in the EH region, and a wetter cold season in the WH region. Time series of all MMA precipitation indices exhibit significant increasing trends over the 1901–2099 period. The greatest increases in temperature for both the EH and WH regions occurred during monsoonal months (July to September) in the A2 scenario, which coincides with the projections of increased precipitation extremes in the EH region and little change or small decreases in precipitation in the WH region.

Terzago et al. (2014) assessed snow depth and snow water equivalent simulations from CMIP5 GCMs over the HKKH. Future projections, evaluated in terms of the ensemble mean of GCM simulations, indicated a significant reduction in the spatial average of snow depth over the HKK and an even stronger decrease in the Himalayas, where a reduction between 25% and 50% is projected by the end of the twenty-first century.

Ali et al. (2015) assessed UJB hydrological projections (inflows to Tarbela Dam) from the UBC model driven by inputs from CCAM and RegCM RCMs (nested in the MPI ESM GCM) for RCP4.5 and 8.5 scenarios. Both RCMs projected an increase in temperature and precipitation. Projections are for almost doubled flow in 2041–2071, compared to the 1976 – 2005 baseline, with consistent increase in June-August and peak flow in July for all future periods investigated (2006–2035, 2041–2070 and 2071–2100).

Hasson et al. (2015b) reviewed the skill of thirty CMIPS climate models in terms of reproducing properties of the seasonal cycle of precipitation over the major river basins of South and Southeast Asia (Indus, Ganges, Brahmaputra and Mekong) for the historical period (1961-2000). They investigated projected changes by these models by the end of century (2061-2100) under the extreme scenario RCP8.5. Most of the models projected a slightly delayed monsoon onset, and a general increase in monsoon activity, precipitation and extent of its concentration, all suggesting a higher seasonality of the future monsoon for all basins. Similarly, a modest inter-model agreement suggests a less intermittent westerly precipitation associated with a general decrease in number of wet days and a decrease (increase) in precipitation over the Indus and Ganges (Brahmaputra and Mekong) basins. The multi-model mean suggests an extension of the monsoonal domain westward over northwest India and Pakistan and northward over China. They state this has serious implications for the food and water security of the region in the future.

Chaturvedi et al. (2014) examined projections of glacial mass balance loss due to CMIP5 projected temperature and precipitation changes across the Karakoram and Himalaya (from Gilgit basin in the northwest Karakoram to Subansiri basin in the Eastern Himalaya). Their modelling suggests the current (year 2000) glacial mass loss for the entire KH region is -6.6±1 Gt/year and under RCP8.5 scenario this will rise to -35±2 Gt/year by 2080 (compared to -12±2 Gt/year for RCP2.6). Complete glacial loss for 27% and 10.6% of current glaciers could occur by the end of the century, under RCP8.5 and RCP2.6 scenarios respectively.

Soncini et al. (2015) reported on a comprehensive field campaign that obtained three years (2011-13) of detailed meteorological, glaciological and hydrological data for the Shigar River Basin in the
UIB for calibration of a hydrological model that accounts for instream flows and snow and ice melt. Then they forced the model with inputs derived from three downscaled CMIP5 GCMs for RCP 2.6, 4.5 and 8.5 scenarios to 2100. Their projected future flows increased, for all scenarios, peaking mid-century but still above control (1980-2012) flows until 2100 in most cases. Snowmelt occurs earlier and ice melt contribution increases, with significant glacial retreat seen below 4000 m.

Rajbhandari et al. (2015) applied the HadCM3-PRECIS RCM (three ensemble members) over the entire Indus river basin for an A1B scenario. The model was found to reproduce spatial and seasonality patterns for temperature and precipitation, although with biases in magnitude. Projections simulated an increase in winter precipitation over the upper Indus basin and decrease over the lower Indus basin with decreases particularly evident over the southern part of the basin. Monsoon summer precipitation changes were inconsistent across the three ensemble members, highlighting uncertainties in future change. Warming was greater over the upper than the lower Indus, with greater warming in winter than in the other seasons. There was an overall increase in the number of rainy days over the basin, but in the border area between the upper and lower basins (where, they state, the rainfall amount is highest) there was a decrease in the number of rainy days accompanied by an increase in rainfall intensity.
6 Conclusions

Published studies of the hydroclimate of the HKKH and Indus are significant in their collective breadth and depth (see Bibliography section below). This review is an initial attempt to summarise current knowledge, focusing on the most important and recent research of relevance to the processes, trends and changes impacting upon Indus water supply. It thus aims to inform the ongoing CSIRO research into improving seasonal forecasting, as is being undertaken in collaboration with WAPDA and PMD project partners.

A fundamental issue, pervasive throughout the literature, relates to the lack of sufficient data coverage, record length and quality, particularly in the sparsely populated and partially accessible high mountains of the northern UIB. The situation is improving given monitoring network development by WAPDA in recent decades and improved techniques to relate remotely sensed data to on the ground observations. However large uncertainties in the hydrological budget of these northern basins are still an important issue, as shown by studies attempting to improve data inputs to hydrological models to better reflect the large orographic lapse rates inferred, for example Immerzeel et al. (2015).

The complexity of UIB hydrology is implicit given the interaction of different climate drivers (the dominant processes being the western disturbances and the summer monsoon) with glacial, snow melt, and rain runoff processes that interact in nonlinear ways. These interactions vary from sub-basin to sub-basin depending on the relative dominance of glaciers (high elevations), snow melt (mid elevations) and rainfall (lower elevations). In addition, complexity is magnified by flow changes occurring throughout the HKKH in response to long-term trends in warming and rainfall pattern changes that may be a function of global anthropogenic climate change. A significant proportion of the more recent literature focusses on studying long term (mid to end of 21st century) hydrological response to climate changes, given concerns of reduced glacial and snow pack sources under a warming climate. While concerns are justified and uncertainties difficult to reliably quantify, the most recent research does not predict large flow reductions this century except under the most severe scenarios.

Surprisingly there appears to be limited advancement in the application of seasonal forecasting methodologies to Indus water supply prediction in the literature. While there are several (valuable) studies investigating correlations between UIB flows and concurrent or preceding season climate variables and also some investigation of climate drivers (e.g. indices related to NAO or ENSO), there does not appear to be a ‘bringing together’ of this knowledge to develop more informed seasonal forecasting methodologies suitable for seasonal water planning and management in the UIB. This project will address this limitation.
Overview reports, books and reviews


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7.2 Climatology

7.2.1 Western disturbances


7.2.2 Monsoon


Yadav RR (2013) Relationship between winter precipitation over the western Himalaya and central northeast India summer monsoon rainfall: A long-term perspective. Quaternary International 304(0), 176-182. Doi: http://dx.doi.org/10.1016/j.quaint.2013.03.022.


7.3 Climate trends


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### 7.4 Glacier and snow processes, observations and projections


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7.5 Hydrology


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ICIMOD (2011) Glacial melt and downstream impacts on Indus Basin-dependent water resources and energy : Full report ADB Islamabad, Pakistan


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7.6 Hydrological trends


7.7 Seasonal forecasting

7.7.1 Pakistan and Indus


7.7.2 Monsoon


7.8 Climate change

7.8.1 Pakistan and Indus


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7.8.2 Monsoon


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