Climate Change, Water and Hydropower

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1.0 Introduction

The hydrological system is potentially sensitive to changes in climate (Arnell *et al*., 1996; IPCC, 2007a). The interactions between increases in greenhouse gases and the hydrological system are very complex and are shown in **Figure 1**. Increased concentrations of greenhouse gases result in increases in net radiation at the surface of the earth. This ultimately results in changes in temperature, precipitation and evapotranspiration. Increased temperature accelerates the hydrological cycle and process that involve evapotranspiration, soil moisture, and infiltration (Huntington, 2006). Increased atmospheric CO_2 may increase global mean precipitation as indicated by all GCMs (Kattenberg *et al*., 1996). Changes in *precipitation* could affect water availability in soils, rivers and lakes, with implications for domestic and industrial water supplies, hydro-power generation, water quality and agricultural productivity. The increased evapotranspiration enhances the water vapour content of the atmosphere and the greenhouse effect, so that the global mean temperature climbs even higher. Land uses will also play a key role in increased evapotranspiration. Possible changes in temperature, volume and timing of precipitation, whether precipitation falls as snow or rain, evapotranspiration and snowmelt may result in changes in soil moisture regimes, groundwater recharge and runoff and could intensify flooding and droughts in various parts of the world (Arnell *et al*., 1996; IPCC, 2007a).

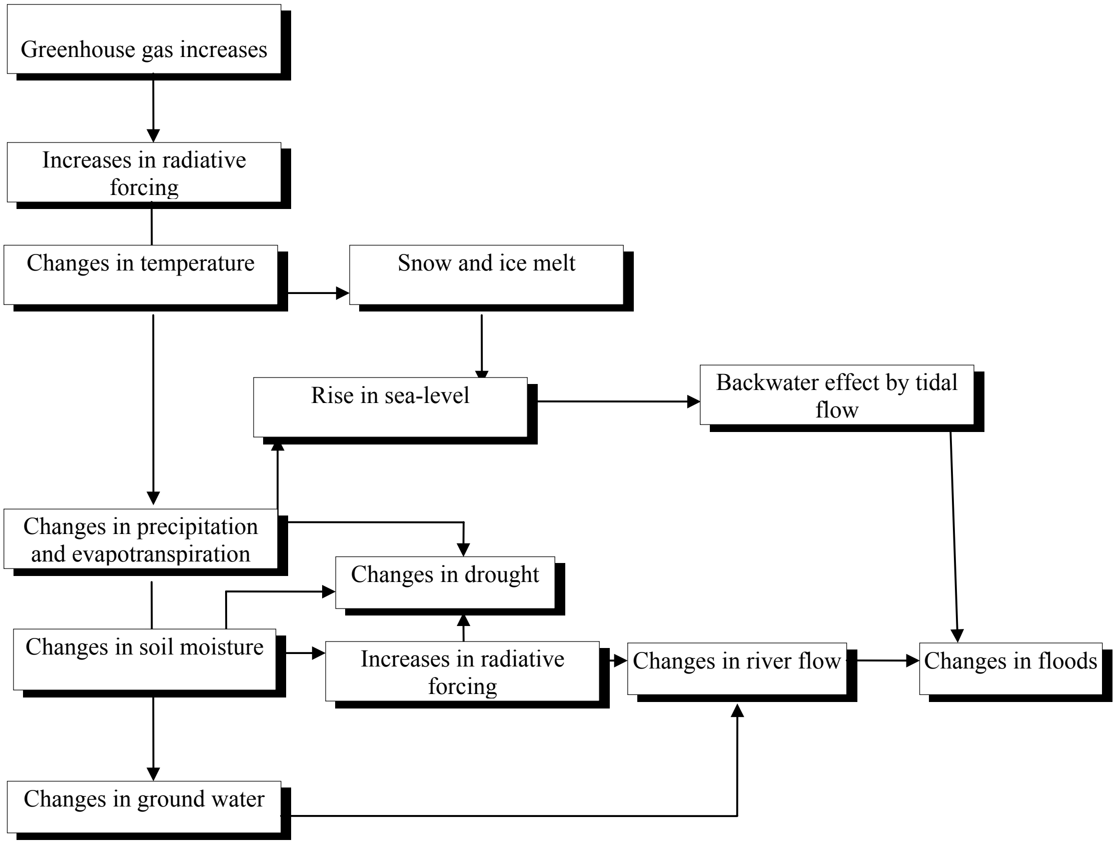

Figure 1*: Relationship between climate change and hydrology. Source: Mirza, 1997 (modified from Arnell, 1992).*

Energy (especially hydropower) and water are integrally related. For hydropower generation, adequate storage of runoff is necessary and any drop in water level affects generation. In recent years, many cases of reduction in generation occurred in various regions in the world. As a relatively cleaner and cheap energy, demand of hydropower is rapidly increasing. In near future, hydropower use is expected to increase by 63% in 2030 from the 2002 level (IEA, 2004). In the recently released fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), projected mixed result about future of water resources. It has also raised caution about possible adverse impacts on the hydropower industry. The major objective of this article is to examine future of hydropower in the context of climate change.

2.0 Observed Climate Change and Impacts on Global Water

Temperature

“Warming of the climate system is unequivocal, as is now evident from the observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level.” This is one of the major conclusions drawn in the IPCC AR4. Eleven of the last twelve years rank among the warmest years in the instrumental record of global surface temperatures since 1850. The updated 100-year linear trend (1906-2005) of 0.74°C (0.56°C to 0.92°C) was found to be larger than the corresponding trend of 0.6^{o}C (0.4^{o}C to 0.8^{o}C) for 1901-2000 calculated in the Third Assessment Report (TAR) of the IPCC. The AR4 further concluded that most of the observed increase in globally averaged temperatures since the mid-20th century was very likely (> 90% probability of occurrence) due to the increase in anthropogenic greenhouse gas concentrations. In the last 100 years, temperatures in the Arctic regions increased at a rate twice as the global average. Satellite data since 1978 show that annual average arctic sea ice extent has shrunk by 2.7 [2.1 to 3.3]% per decade, with larger decreases in summer of 7.4 [5.0 to 9.8]% per decade (IPCC, 2007b) (**Figure 2**). Widespread changes in extreme temperatures have been observed over the last 50 years. Cold days, cold nights and frost have become less frequent, while hot days, hot nights and heat waves have become more frequent.

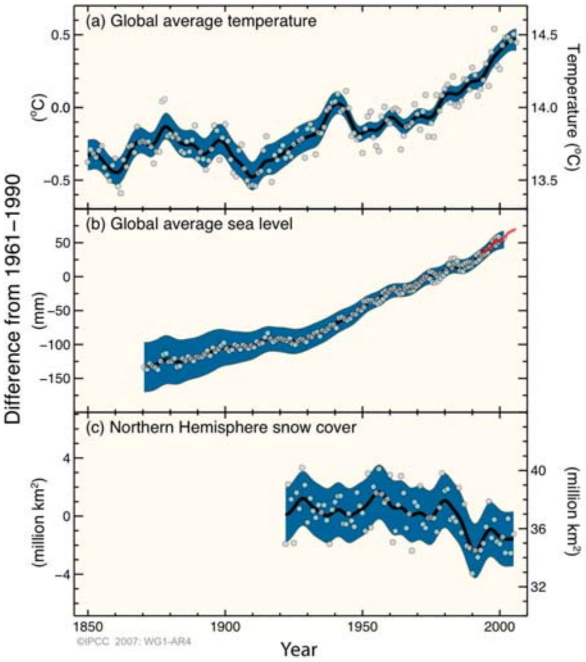

Figure 2: *Changes in global average temperature, sea level rise and northern hemisphere snow cover (IPCC, 2007b).*

Precipitation

The analysis that has been carried out during the IPCC's Fourth Assessment Report (AR4), long-term trends from 1900 to 2005 have been observed in precipitation amount over many large regions. Note that the assessed regions are those considered in the regional projections of the IPCC's Third Assessment Report (TAR). The analysis demonstrates two important facets of precipitation patterns. *First*, significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapor. *Second*, drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought. More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Changes in sea surface temperatures, wind patterns and decreased snowpack and snow cover have also been linked to droughts. Long-term trends (increasing or decreasing) have not been observed for the other large regions assessed. There are some limitations with regard to analysis of precipitation. For example, precipitation is highly variable spatially and temporally, and data are limited in some regions (IPCC, 2007b).

The AR4 (IPCC, 2007b) has concluded that some aspects of climate have not been observed to change. *First*, the TAR reported a decrease in diurnal temperature range (DTR) based on the data available from 1950 to 1993. Analysis of updated observations from 1979 to 2004 shows that DTR has not changed because of rise of both day- and night-time temperature at about the same rate. The trends are highly variable from one region to another. *Second*, no statistically significant average trends detected in the Antarctic sea ice extent but it continues to show inter-annual variability and localized changes. This is consistent with the lack of warming that reflected in atmospheric temperatures averaged across the region.

The AR4 analysis demonstrates faster sea-level rise (3.1 mm per year) from 1993 to 2003 compared to 1.8 mm per year over 1961 to 2003. However, whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer term trend is unclear. New data since the TAR now show that losses from the ice sheets of Greenland and Antarctica have *very likely* (>90% probability of occurrence) contributed to sea level rise over 1993 to 2003. The IPCC put *high confidence* at the rate of observed sea level rise that increased from the 19th to the 20th century. The total 20th-century rise is estimated to be 0.17 [0.12 to 0.22] m.

Observed Impacts on Water

The IPCC WGI (IPCC, 2007) has identified changes in a number of components of the hydrological cycle and systems which include: changing precipitation patterns, intensity and extremes; widespread melting of snow and glaciers; increasing atmospheric water vapor; and changes in soil moisture and runoff. The changes are consistent with the observed climate warming. However, all components of the hydrological cycle and systems demonstrate a significant natural variability over various time-scales which help concealing long-term trends. Large scale atmospheric circulation patterns such as ENSO, NAO and PNA also influence variability.

Although there are regional variations (increasing or decreasing) in runoff changes, at the global scale, Milly *et al.* (2005) have identified a coherent pattern of change in annual runoff (**Table 1**). One study conducted by Labat et al. (2005) found a 4% increase in global total runoff per 1°C rise in temperature (Labat et al., 2004). However, some experts have criticized these findings on the grounds of methodology, non-climatic drivers, coverage and quality of data points used in the study (Legates *et al*., 2005). In the IPCC AR4, increases in total annual runoff together with winter runoff in the northern Eurasia are particularly important and consistent with the higher rates of warming in that region. Shifting in timing of peak flows of the rivers has significance for summer runoff as well as for management of reservoirs.

***Table 1**. Climate-related observed trends of various components of the global freshwater systems*.*

Parameter	Observed changes	Period	Location/catchment	Comments
Runoff/streamflow	Annual increase of 5%, winter increase of 25 to 90%.	1935-1999	Arctic drainage basin (Ob, Lena, Yenisey and Mackenzie)	Large impact of winter melting and thawing of permafrost. Summer has very little impact.
	Onset of streamflow peaks one to two-week earlier than before	1936-2000	Western North America, New England, Canada and northern Eurasia	Early onset of spring
Increased runoff in the glacial basins in Peru	23% increase in glacial melt	2001-2004 vs. 1998-1999	Yanamarey	Increased warming
	143% increase	1953-1997	Llanganuco	
	169% increase	2000-2004	Artesonraju	
Floods	Increasing catastrophic flood frequency (200 to 100-year flood)	Last few years	Russian Arctic rivers	Caused by earlier break-up of river ice accelerated by warming and heavy rainfall events

Hydrological Droughts	29% decrease in annual maximum streamflow	1847-1996	Southern Canada	Rise in temperature and increased streamflow
Water Temperature	0.1 to 1.5^{o}C increase in lakes	40 years	Europe, North America and Asia (100 stations)	Due to atmospheric warming

* modified from Table 1.3, Chapter 1, WGII of the IPCC AR4 (IPCC, 2007a).

3.0 Future Changes in Water

Future changes in water demand and availability will arise from two fronts. *First*, climatic parameters such as precipitation, temperature and evaporative demand changes will drive water availability as well demand (depending on the direction of future changes). In the snow and glaciers melt dependent rivers or water bodies, temperature is very important. It will also play a major role in the process of sea level rise through thermal expansion. Sea level rise could affect surface water in the coastal areas and ground water through salinity intrusion. Note that historically, thermal expansion has contributed 42% to the sea level rise that is recorded from 1961-2003 (IPCC, 2007b). Thermal expansion will continue to contribute to global sea level rise for centuries even the greenhouse gases are stabilized in the atmosphere. Future runoff changes and its direction are shown in **Figure 3**. *Second*, non-climatic drivers that would play major roles in future water demand include: population increase, food demand and changing dietary habits, increased income through economic development, lifestyle changes and ecological water demand.

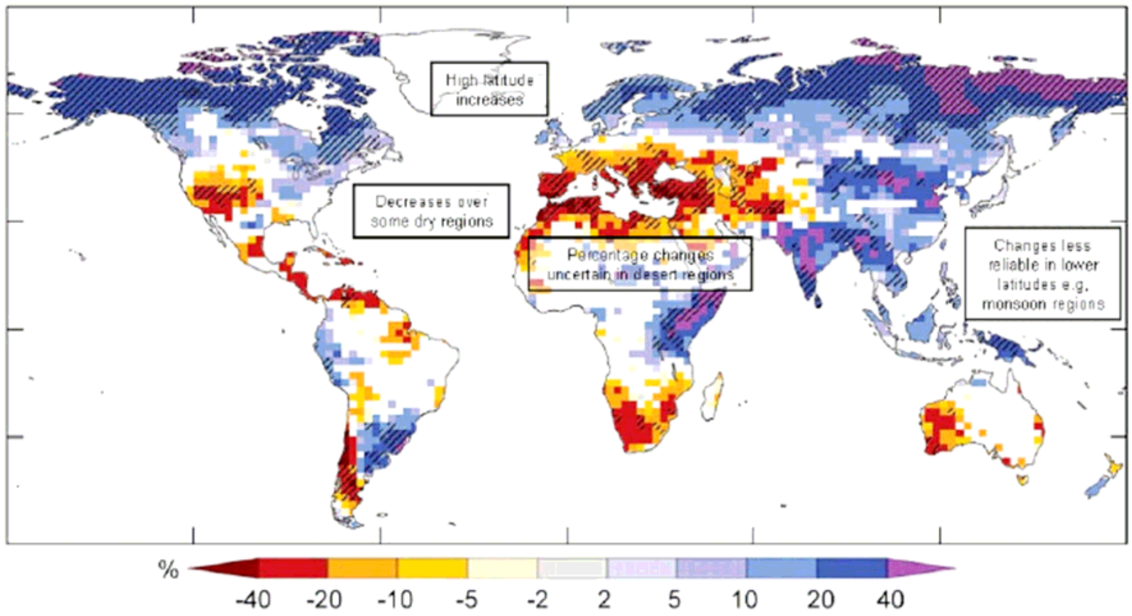

Figure 3. Large scale relative changes in annual runoff (water availability, in %) for the period 2090-2099, relative to 1980-1999. Values represent the median of 12 climate models using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change. The quality of the simulation of the observed large scale 20th century runoff is used as a basis for selecting the 12 models from the multi-model ensemble (IPCC, 2007c).

Major changes will be expected in flooding and droughts. In northern latitude countries, flooding from rain is projected as most of the precipitation would be in the form of rain than snow. Timing of flooding will also change, .i.e, early spring flooding could occur. Flood related damages will increase in many parts of the world unless proper measures are developed and implemented. However, if flood waters can be stored could beneficial for hydropower, irrigation, urban and rural water supplies, etc. Droughts would result from low rainfall and high temperature. **Table 2** summarizes regional impacts of climate change on water.

Table 2. *Regional impacts on water resources*

Region	**Impacts on water**
Africa	By 2020, between 75 and 250 million of people are projected to be exposed to increased water stress due to climate change
Asia	By the 2050s, freshwater availability in Central, South, East and South-EastAsia, particularly in large river basins, is projected to decrease. Coastal areas, especially heavily-populated megadelta regions in South, East and South-East Asia, will be at greatest risk due to increased flooding from the sea and, in some megadeltas, flooding from the rivers
Australia and New Zealand	By 2030, water security problems are projected to intensify in southern and eastern Australia and, in New Zealand, in Northland and some eastern regions
Europe	In Southern Europe, climate change is projected to worsen conditions (high temperatures and drought) in a region already vulnerable to climate variability, and to reduce water availability, hydropower potential, summer tourism and, in general, crop productivity
Latin America	Changes in precipitation patterns and the disappearance of glaciers are projected to significantly affect water availability for human consumption, agriculture and energy generation
North America	Warming in western mountains is projected to cause decreased snowpack, more winter flooding, and reduced summer flows, exacerbating competition for over-allocated water resources
Small Island States	By mid-century, climate change is expected to reduce water resources in many small islands, e.g. in the Caribbean and Pacific, to the point where they become insufficient to meet demand during low-rainfall periods

Source: IPCC, 2007c.

4.0 Climate Change and Hydropower

The hydropower industry is particularly vulnerable to climate change and extremes. In the past few decades, extreme weather events have caused significant impacts on hydropower generation around the world. Hydropower is the main electrical energy source for most countries in South America, and is vulnerable to large-scale and persistent rainfall anomalies due to El Niño and La Niña, e.g. in Colombia, Venezuela, Peru, Chile, Brazil, Uruguay and Argentina. Increased energy demand combined with drought caused a virtual breakdown in hydroelectricity generation in most parts of Brazil in 2001, contributing to a GDP reduction of 1.5% or about US $10 billion (Magrin *et al*., 2007). The same year, lengthy droughts caused Great Lakes water levels to fall resulting in significant reductions in hydropower generation at both the Niagara and Sault St. Marie power stations in Canada (Field *et al*., 2007); a similar low flow in 1965 caused a 20% decrease in generation (Mirza, 2004). In 2007, the water level of Lake Volta – the largest man-made lake in West Africa, which normally supplies 60% of Ghana's energy needs – was at an all-time low (235 ft or 71.6 m), 1.5 m below the critical minimum, due to low rainfall. The lack of water in the lake created a 300-MW power shortfall. Similar episodes were also reported in 1993 and 1994. In July 1993, a catastrophic flood due to erratic cloudburst caused excessive erosion in the Kulekhani watershed in Nepal, resulting in deposition of an unforeseen amount of sediment in the hydropower reservoir. Measurements taken in December of 1993 showed a deposition of 4.8 Mm3, equal to a deposition rate of 381 m^3/ha/yr. Deposition the following year was even worse, jumping by 10.5 million m^3; however by 1995, deposition dropped back down to 4 Mm^3.

Future climate change will pose some challenges to the hydropower industry. Generally, three climate parameters – temperature, precipitation and wind – are highly related to hydropower generation. Increases in temperature result in higher evaporation (wind speed also has a role in evaporation) in the reservoir and frequent cooling of the turbine; changes in precipitation affect runoff. Changes in the average climate may not have serious impacts on hydropower but extreme weather events will eventually affect hydropower generation, transmission and distribution. Climate change and extreme weather events would likely impact the hydropower industry in many regions of the world. Tajikistan, with a potential of generating 527 billion kWh of hydropower a year, may experience significant impacts on its power output due to changes in river basin runoff (Cruz *et al*., 2007). Possible changes in hydropower in Europe are mixed. By the 2070s, potential may decline by 6% overall or by 20 to 30% in the Mediterranean. However, increases of 15-20% are projected in Northern and Eastern Europe, while stable patterns are projected for Western and Central Europe (Alcamo *et al*., 2007). Over the next decades, Andean inter-tropical glaciers are very likely to disappear, affecting water availability and hydropower generation in South America; runoff changes from precipitation variability will also affect hydropower generation in many Latin countries (Magrin *et al*., 2007). In the USA, hydropower yields in the Colorado River will likely decrease significantly. Diminished snowmelt runoff could lead to a decrease in the potential for hydropower production, which now comprises about 15% of California's in-state electricity production. If temperatures rise to the medium warming range and precipitation decreases 10 to 20%, hydropower production may be reduced up to 30%. However, there is uncertainty in future precipitation projections; it is also possible that precipitation may increase and expand hydropower generation potential (CCC, 2006). In the Columbia River basin, runoff required for generation in the summer will likely conflict with other environmental needs (Field *et al*., 2007).

5.0 Adaptation Challenges

Depending on rate and magnitude of climate change, future impacts on the hydropower industry would be mixed. In some regions, the industry will be benefited; but in some regions it will be adversely impacted. In both cases, hydropower industry has to adapt to the changed climatic environment. But can it adapt to the challenges of future climate change?

But three potential climate change scenarios may emerge – increased frequency and magnitude of drought, flood or both. In this context, adaptation (**Figure 4**) of the hydropower industry to changing climate may not be simple and straightforward. Many hydropower reservoirs and their operation criteria have been built on the largest single observed event. But in future, both magnitude and frequency of extreme events will likely to increase. So the hydropower reservoirs may not be able to hold up extra water or cannot generate electricity in case of rapid drop in water level due to drought triggered by failure of rainfall. Retro-fitting of spillway or resign the reservoir to increase capacity may possible options. However, in many cases retro-fitting could be expensive and unfeasible. Economic and engineering life-cycles of many hydropower project either recently built or undergoing construction are within time-lines of climate change.

Regarding adaptation, another major piece of obstacle is mainstreaming climate change into policy planning. Hydropower planners often talk about uncertainty of scenarios projected by the climate models. Climate modelers agree with this notion but that does not mean the planners should not act until the level of uncertainty becomes smaller than now. For future adaptation, one solution could be to use a range of scenarios to capture this uncertainty. Economic cost is another obstacle but there is a need of thorough analysis on the additional cost of inclusion of climate change into engineering design now. Retro-fitting is always a possibility but it could be expensive in future compared to present cost.

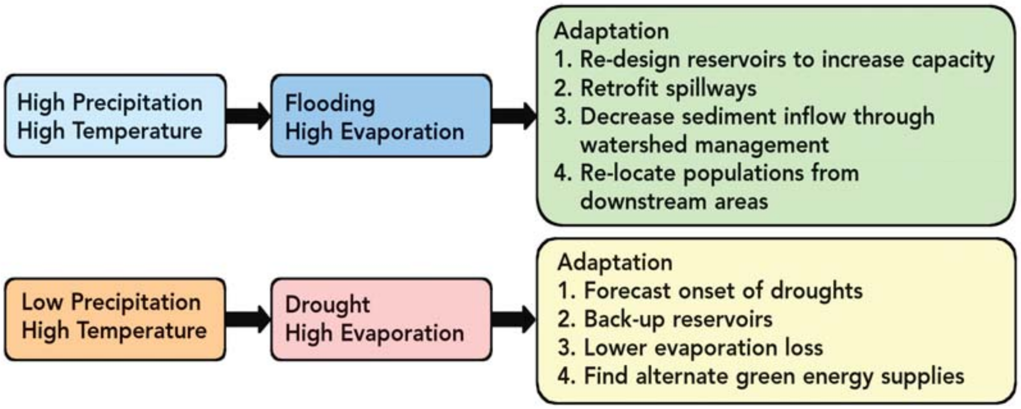

Figure 4. Possible future scenarios and adaptation options (Mirza, 2007).

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