CHAPTER – II

REVIEW OF LITERATURE
This chapter deals with a brief review of significant contributions made by various researchers in the fields of emission scenarios, Global Climate Models (GCMs), climate change studies, and snowmelt runoff modelling using remote sensing and GIS techniques. In addition, the review of literature on effect of projected climate change on the hydrologic cycle, snowmelt runoff modelling, and Snowmelt Runoff Model (SRM) are presented here. This chapter also contains a brief of using temperature index or degree-day approach in snowmelt runoff models.

2.1 Emission scenarios
Nakicenovic and Swart (2000) described that scenarios are images of the future, or alternative futures. They are neither predictions nor forecasts. Rather, each scenario is one alternative image of how the future might unfold. As such they enhance our understanding of how systems behave, evolve, and interact. They are useful tools for scientific assessments, learning about complex systems behaviour, and for policy making and assisting in climate change analysis, including climate modelling and the assessment of impacts, adaptation, and mitigation. Future levels of global GHG emissions are a product of very complex, ill-understood dynamic systems, driven by forces such as population growth, socio-economic development, and technological progress, among others, thus making long term predictions about emissions virtually impossible. However, near-term policies may have profound long term climate impacts. Consequently, policy-makers need a summary of what is understood about possible future GHG emissions, and given the uncertainties in both emissions models and peoples’ understanding of key driving forces, scenarios are an appropriate tool for summarizing both current understanding and current uncertainties. The Special Report on Emission Scenarios (SRES) involves both qualitative and quantitative components; they have a narrative part called "storylines" and a number of corresponding quantitative scenarios for each storyline. SRES scenarios can be viewed as a linking tool that integrates qualitative narratives or stories about the future and quantitative formulations based on different formal modelling approaches. Although no scenarios are value free, the SRES scenarios are descriptive and are not intended to be desirable or undesirable.
in their own right. They have been built as descriptions of plausible alternative futures, rather than preferred developments.

More precise specifications for the new SRES scenarios were developed with the following points. The new scenarios should:

a) cover the full range of radiatively important gases, which include direct and indirect GHGs and sulphur dioxide (SO$_2$);

b) have sufficient spatial resolution to allow regional assessments of climate change in the global context;

c) cover a wide spectrum of alternative futures to reflect relevant uncertainties and knowledge gaps;

d) use a variety of models to reflect methodological pluralism and uncertainty;

e) incorporate input from a wide range of scientific disciplines and expertise from non-academic sources through an open process;

f) exclude additional initiatives and policies specifically designed to reduce climate change;

g) cover and describe, to the extent possible, a range of policies that could affect climate change although they are targeted at other issues, for example, reductions in SO$_2$ emissions to limit acid rain;

h) cover as much as possible of the range of major underlying driving forces of emission scenarios identified in the open literature;

i) be transparent with input assumptions, modelling approaches, and results open to external review;

j) be reproducible - document data and methodology adequately enough to allow other researchers to reproduce the scenarios; and

k) be internally consistent - the various input assumptions and data of the scenarios are internally consistent to the extent possible.

2.1.1 IPCC Special Report on Emissions Scenarios (SRES)

Intergovernmental Panel on Climate Change (IPCC) SRES (Nakicenovic and Swart, 2000) describes that projected scenarios are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change. Their future evolution is highly uncertain. SRES scenarios which are considered in the present study are A1B, A2,
and B1. Main characteristics of A1B scenario include low population growth, very high gross domestic product (GDP), very high energy use, low-medium land use changes, medium resource (mainly oil and gas) availability, rapid pace and direction of technological change favouring balanced development. B1 scenario includes low population growth, high GDP growth, low energy use, high land use changes, low resource (mainly oil and gas) availability, medium pace and direction of technological change favouring efficiency and dematerialization. A2 scenario includes high population growth, medium GDP growth, high energy use, medium-high land use changes, low resource (mainly oil and gas) availability, slow pace and direction of technological change favouring regional economic development.

IPCC commitment scenario assumes that the temperature and precipitation will be restored to normal condition (present condition) within some years. This scenario is a non-SRES scenario (new constant-concentration commitment scenario that assumes concentrations are held fixed at year 2000 levels). In this idealised scenario, models are initialised from the end of the simulations for the 20th century, the concentrations of radiatively active species are held constant at year 2000 values from these simulations, and the models are integrated to 2100 (Solomon et al., 2007).

Castles and Henderson (2003) criticised the IPCC SRES that all the SRES scenarios were “technically unsound” in that, contrary to accepted international practice, they converted national GDP data to a common measure using market exchange rates (MER). Because of this procedure and built-in assumptions about the extent to which the gap between rich and poor countries will be closed, the scenarios yield projections of GDP for developing regions which are improbably high: this includes the scenarios which give the lowest figures for projected cumulative emissions in the course of the century. Nakicenovic et al. (2003) responded to the criticism in nine sections and revealed that Castles and Henderson (2003) have focussed on constructing a “problem” that did not exist. SRES scenarios were sound and the IPCC had responded seriously and conscientiously.

Tol et al. (2005) reported that the IPCC SRES emission scenarios were constituted by the standard scenarios, and their quality was not worse, and often better than
alternative emissions scenarios. Moreover, much of the critique was directed at the
demographic and economic details of the scenarios. This may had led to a small
upward bias of emissions projection. The range of future GHG emissions was
undisputed, and appropriate SRES scenarios were to be used in the ENSEMBLES
GCMs.

Girod et al. (2009) analysed the evolution of the structure, description, process
development and context of the IPCC’s emissions scenarios and identified the most
important changes and their scientific and political causes. These changes were
evaluated against the criteria of saliency, credibility, and legitimacy. The analysis
indicated that first, enhanced credibility through an improved scenario construction
methodology (multiple baseline scenarios, storylines) were achieved, but diluted by
particularities of the scenario approach used. Secondly, a reduced saliency through
absence of titles, an inappropriate classification and the relatively high number of
baseline scenarios, limits and weakens their wider applicability. They suggested the
employment of a more formal qualitative construction approach as well as revisions
to scenario labelling and classification practices.

ICSU (2010) released a statement indicating that “in proportion to the sheer volume
of the research reviewed and analysed, these lapses of accuracy are minor and they
in no way undermine the main conclusions” and “these errors have resulted in
attempts to discredit the main conclusions of the report, accusations of scientific
conspiracies, and personal attacks on scientists is unacceptable”. Scientific
assessments, such as those of the IPCC, are a crucial basis for making the decisions
that will shape our society now and in the future.

Yohe et al. (2010) along with 249 other climate change scientists working at
leading US universities, including both IPCC and non-IPCC authors released an
open letter which stated many in the popular press and other media, as well as some
in the halls of Congress, are seizing on a few errors that have been found in the
Fourth Assessment Report (AR4) of the IPCC in an attempt to discredit the entire
report. None of the handful of mis-statements (out of hundreds and hundreds of
unchallenged statements) remotely undermines the conclusion that “warming of the
climate system is unequivocal” and that most of the observed increase in global
average temperatures since the mid-twentieth century is very likely due to observed increase in anthropogenic GHG concentrations.

USNAS (2010) in an open letter from 255 members including 11 Nobel laureates stated that they were “deeply disturbed by the recent escalation of political assaults on scientists in general and on climate scientists in particular”. They outlined scientific methodology and the conclusions of climate science, in contrast to “recent assaults on climate science and, more disturbingly, on climate scientists by climate change deniers”. Regarding the mistakes found in the report, the letter expressed; IPCC and other scientific assessments of climate change, which involve thousands of scientists producing massive and comprehensive reports, have, quite expectedly and normally, made some mistakes. When errors are pointed out, they are corrected. But there is nothing remotely identified in the recent events that changes the fundamental conclusions about climate change.

The NEAA (2010) investigated the scientific foundations for the IPCC summary conclusions of the AR4 of 2007 on projected regional climate-change impacts. They reported that overall the summary conclusions are considered well founded and none were found to contain any significant errors. The working group II contribution to the AR4 shows ample observational evidence of regional climate change impacts, which have been projected to pose substantial risks to most parts of the world, under increasing temperatures.

2.2 Climate change projection
Climate change projections can be generated by the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM) as per the SRES given by AR4 of the IPCC.

Gleick (1986) reviewed approaches for evaluating the regional hydrologic impacts of global climatic changes and presented a series of criteria for choosing among the different methods. Modified water-balance models were found to offer significant advantages over other methods in accuracy, flexibility, and ease of use. The report suggested that such methods can be combined with general circulation models of
the climate and with plausible hypothetical climate-change scenarios to generate information on the water-resource implications of future climatic changes.

Houghton et al. (1990) reported that the warming would vary from 1.0 to 2.0 °C by 2030 for the Indian sub-continent under ‘business-as-usual’ scenarios and precipitation would change little in winter and generally increase throughout the region by five to 15% in summer. They also suggested that GCM was most highly developed tool which may predict future climate change.

Collins et al. (2006) reported that CCSM version 3 (CCSM3) had recently been developed and released to the climate community. CCSM3 was a coupled climate model with components representing the atmosphere, ocean, sea ice, and land surface connected by a flux coupler. CCSM3 was designed to produce realistic simulations over a wide range of spatial resolutions, enabling inexpensive simulations lasting several millennia or detailed studies of continental-scale dynamics, variability, and climate change. The report showed the results from the configuration used for climate-change simulations with a T85 grid for the atmosphere and land and a grid with approximately 1° resolution for the ocean and sea ice. There were significant improvements in the sea ice thickness, polar radiation budgets, tropical sea surface temperatures, and cloud radiative effects. CCSM3 can produce stable climate simulations of millennial duration without ad hoc adjustments to the fluxes exchanged among the component models.

Deser et al. (2006) revealed that simulations of the El Nino-Southern Oscillation (ENSO) phenomenon and tropical Atlantic climate variability in the newest version of the CCSM3 were examined in comparison with observations and previous versions of the model. The analyses were based upon multi-century control integrations of CCSM3 at two different horizontal resolutions (T42 and T85) under present-day carbon dioxide (CO₂) concentrations. The amplitude and zonal extent of equatorial Pacific sea surface temperature variability associated with ENSO was well simulated in CCSM3 at both resolutions and represented an improvement relative to previous versions of the model.
d'Orgeville and Peltier (2009a) revealed that in the low-resolution version of the CCSM3, the modelled north Pacific decadal variability was demonstrated to be independent of the epoch for which a statistically steady control simulation was constructed, either preindustrial or modern; however, it was demonstrated to be significantly affected by the different global warming scenarios investigated.

d'Orgeville and Peltier (2009b) investigated the nature of the multidecadal variability in the north Atlantic basin through detailed analysis of multicentury integrations performed using the low-resolution version of the CCSM3. The results of control simulations under both preindustrial and present-day perpetual seasonal cycle conditions were compared to each other and also to the results of five simulations with increasing CO₂ concentration scenarios.

Andres and Peltier (2013) reported that Greenland climate variability was connected to internal and external sources of global climate forcing in six millennium simulations using CCSM3.

2.3 Effect of projected climate change on the hydrologic cycle

Nemec and Schaake (1982) revealed the findings of deterministic modelling on influence of climate variations on reservoir storage systems of the Platte river basin, Texas and the Leaf river basin, Mississippi in USA. The results suggested that substantial effect of climate change on runoff and storage, and emphasized the importance of studies of sensitivity of water resource systems to climate variations.

Cohen (1986) studied the CO₂-induced climatic change scenarios, based on two models, the Goddard Institute for Space Studies (GISS) and the Geophysical Fluid Dynamic Laboratory (GFDL) to estimate future changes in water supply in the Great Lakes basin of USA. All projected scenarios were found to be decreasing in net basin supply, varied from a decrease of 28.9% for GISS-normal winds, to a decrease of 11.7% for GFDL-reduced wind speeds.

Gleick (1987) developed water-balance modelling techniques for assessing climatic impacts and tested for a major watershed in northern California of USA using both hypothetical and GCM generated climate-change scenarios. The results suggested
that due to increase in atmospheric trace-gas concentrations, strong plausible changes in temperature and precipitation could have major impacts on both the timing and magnitude of runoff and soil moisture in important agricultural areas. Moreover, consistent changes were reported in the timing of runoff, specifically, increase in winter runoff and decrease in summer runoff. These hydrologic results raised the possibility of major environmental and socioeconomic difficulties and would have significant implications for future water-resources planning and management.

Gleick (1989) reviewed the state-of-the-art research into the impacts of climatic changes for the hydrologic cycle and water resources and discussed the implications of such changes for future water resources planning and management.

Cooley (1990) projected a scenario of 10% change in precipitation, 4.0 °C warming up and slight cooling at snow dominated basin in southwestern Montana, USA. The National Weather Service river Forecast System (NWSRFS) model was first calibrated and simulated. The results showed that there would be variation of streamflow from -22 to +45% depending on the combination of climate changes imposed.

Nash and Gleick (1991) analysed the sensitivity of surface runoff in several sub-basins of the Colorado river, USA using a conceptual hydrologic model, developed and operated by the National Weather Service. The results showed that runoff was more sensitive to changes in precipitation than to changes in temperature. Seasonal changes were also simulated with peak runoff. Results revealed that streamflow was less sensitive to climatic changes than suggested by previous statistical studies.

Panagoulia (1993) analysed the long term hydrological responses of the medium sized mountainous Mesochora catchment of the Acheloos river in central Greece to climate changes imposed by a set of hypothetical monthly GISS temperature increase scenarios, coupled with precipitation changes. The study used US National Weather Service snowmelt and rainfall-runoff models. The observation showed that snow accumulations and runoff in spring and summer would decrease whereas winter runoff and spring evapotranspiration would increase. It was also found that
differences in hydrological numerical results among all climate cases were due to
the wide range of changes in the climate variables.

Burn (1994) examined the impact of climate change on the timing of spring runoff
events. Impact detection was accomplished using a non-parametric statistical test
for trend that was applied to the assembled data sets. The approach was applied to a
set of 84 natural rivers from the west central region of Canada. The results revealed
that the spring runoffs were more prevalent because of the impact of greenhouse gas
induced climatic change.

Chiew et al. (1995) evaluated the impacts of climate change on runoff and soil
moisture in 28 Australian catchments by using a hydrological daily rainfall-runoff
model using two methods. The analyses indicated that changes in rainfall were
always amplified in runoff in drier catchments and little effect on the soil moisture
in wet catchments. However in drier catchments, the percentage change in soil
moisture levels can be higher than the percentage change in rainfall. They also
suggested that a significant planning response may be required as the climate
change would bring about potential runoff modifications.

Mehrotra and Mehrotra (1995) analysed the possible impacts of climate change on
hydrology and water resources in India, including all aspect of agriculture. They
further suggested that this important subject area needs more research at the
national level with availability of data and computing facilities.

Loaiciga et al. (1996) examined the feasibility of general circulation models linked
with macro scale and landscape-scale hydrologic models that simulate regional and
local hydrologic regimes under global warming scenarios in mid latitudinal basins
of the United States. The simulation predicted shorter winter seasons, larger winter
floods, drier and more frequent summer weather, and overall enhanced and larger
hydrologic variability.

Haeberli and Beniston (1998) reported that climate change in the European Alps
during the 20th century was observed with increasing trend of global warming.
High-resolution climatologies for double-CO2 situations were simulated using
regional climate models (RCMs) with a 20-km horizontal grid. The results gave generally higher winter temperatures, as well as increase in summer temperatures, with indications that temperature increases more at higher elevations than at lower altitudes, and more intense precipitation in winter, but much dryer conditions in summer. They indicated that under such conditions, the Alps would lose major parts of their glacier cover within decades, warming of cold firm areas at high altitudes could become pronounced and lower limits of permafrost occurrence in the Alps could rise by several hundred meters. Pronounced disequilibria could result, in the water cycle, in mass wasting processes, and in sediment flux as well as in growth conditions of vegetation. For those directly involved with such changes, the main challenge would be to adapt to high and accelerating rates of environment evolution. In view of the uncertainties involved with future projections, they suggested that more attentions should be paid to appropriate monitoring programs.

Houghton et al. (2001) reported that the global average surface temperature had increased by about 0.6 °C over the 20th century. Satellite data showed that since the late 1960s the extent of snow cover had been decreased by about 10%. McCarthy et al. (2001) reported that climate change was likely to change streamflow volume, as well as the temporal distribution of streamflows throughout the year over Asian region. They also indicated that half of Europe’s alpine glaciers could disappear by the end of the 21st century and warming in high mountain regions could lead to disappearance of significant snow and ice surface over South America.

Singh and Gosain (2011) reported that the GIS-based Soil and Water Assessment Tool (SWAT) was used to assess the impacts of climate change on the hydrological regime of the Cauvery river basin of India. The impact of changes in land-management practices on water availability under present conditions was modelled first. Then, the same analysis was carried out under the future climatic scenarios. Finally, annual and monthly precipitation variability was compared under present, as well as future, climate change scenarios. The results indicated an intensification of the hydrological cycle in the future climate change scenario that appeared to be significant on an annual basis.
Gain et al. (2011) investigated the effect of climate change on both low and high flows of flood plains under the lower Brahmaputra basin. They applied a novel method of discharge-weighted ensemble modelling using model outputs from a global hydrological model forced with 12 different GCMs. Based on the GCMs outputs and long-term records of observed flow at Bahadurabad station, Bangladesh, the method resulted in a multi-model weighted ensemble of transient streamflow for the period of 1961–2100. Using the computed transient, they projected future trends in low and high river flows. The analysis showed that extreme low flood conditions were likely to occur less frequent in the future. However, a very strong increase in peak flow was projected.

Li et al. (2013) reported that two rainfall-runoff models (SIMHYD and GR4J) were applied to simulate the monthly and annual runoff across the Yarlung Tsangpo river (YTR) basin in the southeastern Tibetan Plateau under historical data (1962–2002) and future climate conditions (up to approximately 2030). The future climate series were obtained by using 20 GCMs outputs from the IPCC AR4 to reflect a 1.0 °C increase in the global average surface air temperature. The two rainfall-runoff models successfully simulated the historical runoff for the eight catchments in the YTR basins with monthly runoff Nash-Sutcliffe Efficiency of 0.86 and 0.83 for SIMHYD and GR4J, respectively. From most of the model results, the mean annual future precipitation and runoff were projected to increase across the region.

Baltas (2014) assessed the impact of climate change on the hydrological regime and water resources in the Venetikos river basin, Greece. A monthly conceptual water balance model was calibrated using historical hydro-meteorological data, to estimate runoff under a transient scenario referring to year 2080. Results showed that the mean annual, mean winter, mean summer, annual maximum and minimum, as well as, monthly maximum and minimum runoff would reduce. Additionally, an increase of potential and actual evapotranspiration was noticed due to temperature increase.

Swain et al. (2014) reported that precipitation data were downscaled from two GCMs: the CCSM and GFDL. Adapting the downscaled precipitation data to a coupled hydrodynamic surface-water/groundwater model of southern Florida...
allowed an examination of future conditions and their effect on groundwater levels, inundation patterns, surface-water stage and flows, and salinity.

2.4 Snowmelt runoff modelling
Rango et al. (1977) studied the simple photo interpretation techniques and low-resolution meteorological satellite data for mapping SCA during early April over the Indus river and Kabul river basins in Pakistan. The regression analyses showed that early spring SCA was significantly related to streamflow for both watersheds during 1st April through 31st July. For Indus river basin (1969–1973) and Kabul river basin (1967–1973), coefficients of determination ($r^2$) were obtained as 0.82 and 0.89, respectively. Estimation of seasonal streamflow of 1974 using the regression equations were marked within 7% of the actual flow. However, due to inadequacy of hydro-meteorological data, conventional streamflow predictions were not realistic in some of these remote regions, and the satellite-derived runoff estimates had immediate applicability for improved water resources management.

Gupta et al. (1982) studied the relation between SCA and snowmelt runoff. The LANDSAT images were used to map SCA for a number of years in various sub-catchments of the river Beas, in the northwestern part of India. The relationships between SCA and snowmelt runoff among various sub-catchments were found to be more correlated except one watershed which showed independent behavior due to geographic and geomorphic factors. It was, therefore considered that, for each type of geomorphic sub-catchment, a different empirical relation should exist between SCA and snowmelt runoff.

Dey and Goswami (1984) evaluated the estimates of seasonal snowmelt runoff in the Sutlej, Indus, Kabul, and Chenab rivers derived from the model of SCA vs. runoff against those obtained from cross correlation of concurrent flows in the rivers. The later model explained more than 90% of variability and the model of SCA vs. runoff explains less of variability in flow. However, the concurrent flow correlation model was not found suitable for operational forecasting procedures but the model had potential for use in retrospective analysis of flow for estimating missing data, extending time series, and for evaluating estimates derived from other models.
Lettenmaier and Gan (1990) analysed the hydrologic sensitivities to long term global warming in the Sacramento and San Joaquin river basins of USA. The US NWSRFS model was used to simulate the hydrologic responses of the basin which accounted the snowmelt and the soil moisture. The results indicated that more winter precipitation occurred as rain instead of snow resulting in increase in runoff while spring snowmelt runoff decreased. Moreover, annual flood maxima were also simulated and many large floods were found to be shifting from spring to winter primarily due to an increase in rain-on-snow events.

Singh and Quick (1993) carried out streamflow simulation for the Satluj river in the western Himalayan region of India using the UBC watershed model. The daily simulation was made taking the whole watershed as a single unit and also splitting it into two sub-basins. Better results were found when the watershed was divided into two different sub-basins. The results indicated that combining two hydrologically different watersheds into a single watershed reduces simulation or forecasting accuracy. It was reported that areal distribution of precipitation was the most important factor in the streamflow simulation because snowpack was built up by the model from precipitation-elevation relationships.

McCabe (1994) studied the winter mean 700 mb height anomalies (representing the average atmospheric circulation during the snow season) over the eastern north Pacific Ocean and the western USA for variability in snowpack accumulation. The results indicated that snowpack accumulations would be lower than normal with positive 700 mb height anomalies over the western USA. However, with negative 700 mb height anomalies, snowpack accumulations were higher than normal over the western USA and over most of the eastern north Pacific Ocean. It also indicated that the significant linear relationships between 700 mb height anomalies and snowpack accumulations can be used in conjunction with GCM simulations of 700 mb height anomalies for future climatic conditions to estimate future snowpack accumulations in the Gunnison river basin.

Rango and Martinec (1994a) examined the performance of snowmelt runoff models in conditions approximating real-time forecast situations. These tests were part of an inter-comparison of models conducted by the World Meteorological
Organization (WMO). Daily runoff from the Canadian snowmelt basin Illeilwaet (1155 km², 509–3150 m MSL) was forecasted for one to 20 days ahead. The performance of models was better than the previous WMO project which dealt with runoff simulations from historical data.

Singh and Kumar (1997) examined the effect of climate change on snow water equivalent, snowmelt runoff, glacier melt runoff and total streamflow and their distribution in the Spiti river basin of India. The UBC watershed model was used to simulate the hydrological response of the basin. The adopted changes in temperature and precipitation covered a range from 1.0 to 3.0 °C and from -10 to +10%, respectively. The snow water equivalent showed no significant change by the projected increase in air temperature (T+1 to T+3 °C). The results showed that annual snowmelt runoff, glacier melt runoff, and total streamflow increase linearly with changes in temperature (1–3 °C), but the most prominent effect of increase in temperature was observed on glacier melt runoff for this high altitude basin. The effect of change in precipitation (P-10 to P+10%) indicated a linear increase in snowmelt runoff and total streamflow, while, in general, glacier melt runoff was inversely related to changes in precipitation. Snowmelt runoff was found more sensitive than glacier melt runoff to changes in precipitation (P-10 to P+10%). Under a warmer projected climatic scenario, snowmelt runoff and glacier melt runoff caused an earlier response of total streamflow and a change in flow distribution.

Hasnain (1999) examined the characteristics of discharge and role of monsoon rainfall in the glacierized Dokriani catchment, India. The characteristics of discharge hydrograph were controlled by precipitation over the glacierized area and the monsoon cloud cover limited the energy inputs resulting delayed ice melt. A mass balance approach was applied to separate the monsoonal components from the bulk flow hydrograph and only 11.46% of the total discharge was found to be contributed by the rainfall over the catchment.

Singh et al. (2000) observed degree-day factors for snow and ice over Dokriani glacier located in the Garhwal Himalayas of India, at an altitude of about 4000 m. They observed that degree-day factor for clean ice was about 30% higher than that
for clean snow. Presence of dust increased the degree-day factor for snow and ice by about 12% and 9%, respectively. These observations suggested that the effect of dust on degree-day factor for snow was more pronounced than that for ice.

Singh and Jain (2002) used a water balance approach to determine the contribution of snow and glacier melt runoff into annual flows of the Satluj river at Bhakra dam, India. A relationship between temperature and evaporation was developed and used to estimate the evapotranspiration losses. The SCA, and its depletion with time, was mapped with the help of satellite data. The results indicated that the average contribution of snow and glacier melt runoff in the annual flow was about 59%.

Dyurgerov (2002) compiled all available sources of information, such as publications, archived data, personal communications, including time series of about 280 glaciers, and observed the following points: (i) the rate of annual melt-water production (ablation) by glaciers had been increasing, and comprised of about 1.7 m/year in water equivalent for the period; (ii) the annual accumulation (winter balance) rate had also been increasing with the average value of about 1.5 m/year in water equivalent; (iii) annual volume change had been 90 km$^3$/year adding about 15–20% (0.25 ± 0.11 mm/year) to sea-level rise over the period; (iv) the equilibrium-line altitude had risen by 200 m (square root error was about 100 m); (v) accumulation area ratio decreased from about 60% in 1968 to 50% in 1998 (square root error was about 5%); and (vi) the mass balance sensitivity with respect to air temperature had changed at the end of 1980’s and reached -700 mm per °C.

Hall et al. (2002) showed a case study of using Moderate Resolution Imaging Spectroradiometer (MODIS) snow covered product and its description at northeastern United States. They reported that MODIS snow covered product represented potential improvement to or enhancements of currently available operational products because of MODIS products were global with 500 m spatial resolution, and had the capability to separate most snow and clouds. MODIS snow mapping algorithms were automated which means that a consistent data set may be generated for long term climate studies.
Singh and Bengtsson (2003) studied the impact of three warming scenarios (T+1, T+2, and T+3 °C) and more than 160 new snow depletion curves were prepared for different elevation zones of the Satluj river basin, India, over a study period of nine years (1985/86–1990/91 and 1996/97–1998/99). The relationship between the cumulative melt and SCA for each zone was established and used to obtain the snow depletion curves under warmer climate. Projected snow depletion curves were derived by synthesizing the effect of warming for all zones. Warmer climatic conditions accelerated the melting of snow resulted in rapid disappearance of seasonal snow cover from the basin. For the study basin, acceleration in depletion of SCA were computed as 20, 31, and 40 days for T+1, T+2, and T+3 °C scenarios, respectively, by the end of the ablation season. The impact of warmer climate on accelerating the depletion of SCA was found to be higher in the early and later parts of the ablation season.

Singh and Jain (2003) developed a conceptual snowmelt model, which accounts for both the snowmelt and rainfall runoff, and applied for daily streamflow simulation for the Satluj river basin located in the western Himalayan region of India. The basic inputs to the model are temperature, precipitation and SCA. The snowmelt was computed based on the degree-day approach where rain induced melting was also considered. The model was calibrated for three years (1988/89 to 1987/88) and simulations of daily streamflow were made for period of six years (1988/89 to 1990/91 and 1996/97 to 1998/99). The model performed well for both calibration and simulation periods. The model was also used to estimate the contribution from the snowmelt and rainfall induced runoff to the seasonal and annual flows.

Singh and Bengtsson (2004) investigated the sensitivity of water availability to climate change for a large western Himalayan river (Satluj river basin, India). A conceptual hydrological model was calibrated to provide accurate simulations of streamflow. The hydrological response of the basin was simulated using different climatic scenarios over a period of nine years. Adopted plausible climate scenarios included three temperature scenarios (T+1, T+2, and T+3 °C) and four rainfall scenarios (P-10, P-5, P+5, and P+10%). Under warmer climate, lesser melt was found from the lower part of the basin owing to a reduction in SCA and shortening of the summer melting season. On other hand an increase in the melt from the
glacierized part was found owing to larger melt and an extended ablation period. The impact of climate change was found to be more prominent on seasonal rather than annual water availability.

Singh and Bengtsson (2005) studied the impact of warmer climate on melt and evaporation for rain-fed, snow-fed, and glacier-fed basins located in the western Himalayan region using a simulated conceptual hydrological model, which accounts for the rainfall-runoff, evaporation losses, and snow and glacier melt. Based on the future projected climate, three temperature scenarios (T+1, T+2, and T+3 °C) were adopted for quantifying the effect of warmer climate. The comparison indicated that maximum evaporation occurred for snow-fed basins. For a T+2 °C scenario, the annual evaporation for the snow-fed basins was much higher than the rain-fed basins. It was found that under a warmer climate, melt was reduced from snow-fed basins, but increased from glacier-fed basins. Thus, impact of warmer climate on the melt from the snow-fed and glacier-fed basins was opposite to each other. The study suggested that out of three types of basins, snow-fed basins were more sensitive in terms of reduction in water availability due to a compound effect of increase in evaporation and decrease in melt.

Vicuna et al. (2011) analysed the direct impacts of climate change on the hydrology of the upper watersheds of the snowmelt driven Limari river basin, north central Chile. A climate-driven hydrology and water resources model was calibrated using meteorological and streamflow observations. Two climate change projections (A2 and B2) showed an increase in temperature of about 3.0–4.0 °C and a reduction in precipitation of 10–30% with respect to baseline. The results showed that annual mean streamflow decreases more than the projected rainfall decrease because a warmer climate enhances water losses to evapotranspiration. Also in future climate, the seasonal maximum streamflow tended to occur earlier than in current conditions, because of the increase in temperature during spring/summer and the lower snow accumulation in winter.

Pandey and Venkataraman (2012) examined the change in the length of a benchmark glacier, Chhota Shigri of the Indian Himalayan mountain, in response to climate change. Remote sensing data and a toposheet map of 1962 was used to
study the change in the glacier from 1960–2008. It was found that the glacier had retreated by a length of about 950 m from 1960 to 2008.

Khadka et al. (2014) estimated the changes of runoff and SCA for changed climate of the Tamakoshi basin of Nepal. Remote sensing was extensively used to determine the extent of SCA in the basin. The study used future climate projection outputs from two GCMs (HADCM3 for SRES A2 and B2, and CGCM3 for SRES A2 and A1B scenarios). A temperature index based snowmelt runoff model was used to simulate basin runoff from the year 2000 to 2059. The analysed during observed period (2000–2009) showed that about 18% of the annual runoff was contributed by snow and ice melting. During summer snowmelt contribution was about 230 mm, which was about 17% of total water produced and it was found more significant during spring season which was about 25% of total runoff produced. Besides, basin runoff was also expected to increase in future at the rate of 5.6 mm/year.

Li et al. (2014) reported that the Hydrologiska Byrans Vattenbalansavdelning (HBV) model was used to simulate the runoff on two Himalayan basins; the Beas river basin in India and the Wang Chhu basin in Bhutan. The results showed that the HBV model gave a fair estimation on the runoff of these two basins and the effects of glacier and snow were largely dependent on the catchment characteristics and the glaciated area. For the Wang Chhu basin, rainfall induced runoff was the major contributor whereas melting of snow and glacier was dominant in the Beas river basin.

Nepal et al. (2014) analysed the hydrological system dynamics of a glaciated catchment, the Dudh Koshi river basin in Nepal, using the J2000 hydrological model and thereby understood how the rise in air temperature would affect the hydrological processes. The model results produced an efficiency of Nash-Sutcliffe, 0.85; logarithm Nash-Sutcliffe, 0.93; and $R^2$, 0.85, for the study period. The average contribution from glacier areas to total streamflow was estimated 17% and snowmelt accounted for another 17% which indicated the significance of the snow and glacier melt runoff in Himalayan region. Hypothetical rise in temperature at the rate of +2 and +4 °C indicated an increase in snowmelt volume during pre-
monsoon period, whereas, contribution during monsoon season decreased significantly. This indicated that the region was particularly vulnerable to global climate change and it was likely that in future, the river might shift from ‘melt-dominated river’ to a ‘rain-dominated river’.

Pradhananga et al. (2014) used a semi-distributed positive degree-day (PDD) model to estimate the present and future discharge from the glacierized Langtang river basin in Nepal. The model was calibrated for the period of 1993–1998 and validated for the period of 1999–2006 having Nash-Sutcliffe values of 0.85 and 0.80, respectively. The projected precipitation and temperature data from 2010 to 2050 were obtained from the Bjerknes Centre for Climate Research, Norway, for the representative concentration pathway 4.5 (RCP4.5) scenarios. The results indicated that the projected discharges had no significant trend; but in future, during pre-monsoon period, discharge would be high and peak would shift to July from August at present. Further the contribution of snow and ice melt would decrease in future. The model was sensitive to temperature, as the glacier area decreases by 25% and 50%, total discharge was reduced by 5.7% and 11.4%, respectively.

Yucel et al. (2014) investigated the snowmelt runoff and future runoff changes for 15 stations located in the Euphrates, Tigris, Aras, and Çoruh basins in eastern Anatolia, Turkey. Results indicated that temperature and precipitation were increased but the increase in precipitation was not significant. The streamflow timings were found backward shifted to earlier days indicating earlier spring melting of snowpack due to warmer temperatures. A regional climate change simulation based on a high emissions scenario suggested 10–30% declined in the annual runoffs of Aras, Euphrates, and Tigris basins and a slight increase in the annual runoff of Coruh basin by the end of the present century. It further indicated that the timing of the peak flows would continue to shift earlier in response to further warming, increasing fraction of winter runoff while decreasing fraction of spring runoff in all basins.

### 2.5 Snowmelt Runoff Model (SRM)

Martinec (1975) developed a simple snowmelt runoff model taking into account the variability of the degree-day factor, recession coefficient, and snow coverage. It
could be adapted to heterogeneous conditions of snow accumulation and temperature in mountainous basins.

Rango and Martinec (1979) used SRM model to simulate daily streamflow on the 228 km$^2$ Din Woody Creek basin in Wyoming, USA with the help of LANDSAT imageries. They reported that LANDSAT provides an efficient way to obtain the critical snow cover input parameter required by the model.

Rango (1980) reported that SRM was successfully used for hydrograph simulation during a six-month melt period in the Wind river mountains, Wyoming, USA. Results showed that the model had potential for hydrological studies in ungauged basins and for the operational prediction of snowmelt runoff.

Rango (1983) applied SRM to nine large river basins in Japan, Poland, US, France (200–4000 km$^2$) using remote-sensed snow cover data. The output showed that $r^2$ and absolute error between actual and simulated runoff volumes were 0.85 and 3%, respectively.

Martinec and Rango (1986) reviewed the application of SRM which were carried out at various institutes, universities, and agencies on 24 basins ranging in size from 0.77 to 4000 km$^2$ and in elevation from 171 to 6000 m MSL from 11 countries. Based on this review, the physically and hydrologically understandable range of parameter values was assessed for all input parameters of the model. They concluded that these parameter values in past applications may prove to be valuable for SRM applications in other basins and for initial selection of related parameter values in other snowmelt runoff models.

Dey et al. (1989) applied SRM to the large, international Kabul river basin. The initial simulation results were much higher than the observed streamflow values. Close inspection revealed that the initial application of SRM encountered several problems but it could be easily corrected with appropriate adjustment of some parameters and use of an automatic streamflow updating procedure. The improved simulation was comparable to other simulations on large, inaccessible basins. They
also suggested installation of weather station at the mean hypsometric elevation of basins.

Kumar et al. (1991) reported that SRM was applied to simulate snowmelt in the Beas basin in India. The results showed that even with incomplete or fragmented ground data, snowmelt runoff simulations can be carried out with adequate accuracy.

Rango (1992) applied SRM to over 50 basins in 15 countries around the world. The results showed that, the average $r^2$ and the average seasonal volume difference ($D_v$) were 0.84 and 3.8%, respectively. The testing of SRM had taken place on basins in different climatic regions to establish the wide applicability of SRM in evaluations of the hydrological effects of climate change.

Seidel et al. (2000) carried out successful simulation of SRM in large basin of river Ganga (917,444 km$^2$) and Brahmaputra (547,346 km$^2$). The runoff water was mainly governed by the distribution of rainfall resulting inflow peaks in summer and recession flow in winter. The model estimated that the proportion of snowmelt in the runoff was about 27% for Brahmaputra and about 9% for Ganga. The SRM accuracy of rainfall simulation was acceptable in view of available data and because SRM model was for the first time used in basins of this order of magnitude.

Baumgartner et al. (2001) reported that the estimation of the amount of snow stored in the central Asian mountains represented an important economic factor with regard to hydro-electric power generation and irrigation. Based on satellite remote sensing, GIS, and database technologies, real-time snowmelt runoff forecasts using SRM were performed for several basins in Uzbekistan and Kyrgyzstan.

Seidel and Martinec (2002) computed and forecasted runoff in 13 basins of the Swiss Alps by the SRM model, based on LANDSAT, SPOT, and NOAA/AVHRR data. The analyses showed that the satellite snow cover monitoring also helped in determining the duration of the snow cover, the areal water equivalent, as well as evaluation of the effect of changed climate on snow conditions and runoff. The
model was designed to exploit archived satellite data for evaluations of the snow accumulation in the past years.

Hong and Guodong (2003) verified the performance of SRM in the Gongnaisi river basin in the western Tianshan mountain. The results showed that SRM can simulate the effects of climate change on snow cover and the consecutive snowmelt runoff. The simulation results indicated that the snow cover was sensitive to climate change, especially to the increase of temperature. Major effect of climate change would be on time shifting of snowmelt runoff to early spring months resulting in a redistribution of seasonal runoff throughout the whole snowmelt season.

Harshburger et al. (2005) reported that SRM was used to simulate and forecast streamflow in the Big Wood river basin, Idaho. Several enhancements to SRM were evaluated including a new method to estimate degree-days; new technique to assign and temporally update model parameters, and incorporation of relative humidity and wind speed data into new (optional) module designed to improve model performance for rain or snow events. The model results indicated that the enhanced version of SRM did a good job simulating the actual stream discharge.

Li and Williams (2008) investigated the performance of simulating daily snowmelt runoff in an arid mountain watershed of Tarim basin, China with limited hydro-meteorological data using the temperature index SRM. MODIS snow cover data were used to feed the model. The model satisfactorily simulated snowmelt runoff with a model efficiency of 0.64 for the calibration year and efficiency of 0.78 and 0.51 for two validation years. They found that lapse rate was sensitive parameter to the model which can play a key role in successful simulation.

Boudhar et al. (2009) evaluated the performance of SRM on five main tributary watersheds of the High Atlas range. The performance of the model was compared for streamflow forecasting when the model was driven by in-situ snow data against remotely sensed snow data. The results showed that performances were comparable and simulations of streamflow satisfactory. However significant differences were observed for selected storms when using remote sensing data.
Sorman *et al.* (2010) applied two conceptual hydrologic models, SRM and HBV, to the upper Euphrates basin in the eastern part of Turkey. Ground observations and remotely sensed snow cover data (MODIS) were used as input for hydrologic modelling. They revealed that hydrologic modelling studies gave promising results and also indicated the possible operational use of runoff forecasting can be an important decision support tool for reservoir and basin management.

Wang *et al.* (2010) used SRM to simulate snowmelt runoff and to forecast the change of snowmelt runoff in the mountainous region of north western China. Climatic warming was apparent and annual average air temperature at three weather stations located in the basin had increased by 2.1 °C, 2.6 °C, and 2.9 °C, respectively. The SRM forecasted scenario showed that the snowmelt runoff shifted ahead and discharge became larger in response to increasing air temperature. The simulated discharge indicated an increasing trend with the increase in precipitation and the results also showed that the increase in precipitation had no influence on the timing of snowmelt runoff.

Alam *et al.* (2011) used SRM for the estimation of snowmelt runoff in the Kolahoi watershed of western Himalayas for the year 2001. They revealed that the computation of snowmelt runoff using SRM can be treated as reliable tool in ungauged mountainous area. The volume difference found to be only 7.8% between measured runoff and computed runoff. Nazari *et al.* (2011) reported that WinSRM performed better in monthly river flow simulation at Talar river basin, Iran in comparison with two other models (Hydrological Simulation Program-Fortran, HSPF and SWAT) with lack of snow observation data. Sorman *et al.* (2011) reported that SRM was applied in upper Euphrates basin in Turkey to forecast runoff with a two-day lead time for 2011 snowmelt period. They concluded that promising results were found and recommended possible operational use of runoff forecasting for future flood events.

Uysal *et al.* (2011) showcased the ability of the SRM at upper Euphrates basin, Turkey, to forecast daily discharge with estimated snow cover depletion and numerical weather prediction data. The simulation provided promising results in forecasting daily discharge with an overall Nash-Sutcliffe model efficiency greater
than 0.7 during melting period. Tahir et al. (2011) studied the impact of climate change on discharge of Hunza river basin of Pakistan. SRM was used to simulate the daily discharge using MODIS satellite data. It was observed that the SRM can be used efficiently in snow-fed and glacier-fed sub-catchments of the upper Indus river basin. The future simulations under climate change scenarios resulted in almost double summer runoff until the middle of this century.

Abudu et al. (2012) presented an overall review of worldwide application of SRM in mountainous watersheds, particularly in data-sparse watersheds of northern China. Preliminary applications were relatively acceptable although most of watersheds lacked measured hydro-meteorological data. They recommended that future researches could explore utilizing snow and glacier cover remote sensing data and GIS tools, field measurements, and innovative ways of model parameterization.

Fuladipanah and Jarabloo (2012) used SRM to estimate daily discharge in Gharasoo basin, northwest of Iran during 20th February 1998 to 5th June 1998. The model outputs showed good agreement with measured data. The results of $r^2$ were 0.78 and 0.80 during calibration and validation periods, respectively. Sharma et al. (2012) showed strong correlation between snow cover extent (SCE)-temperature, SCE-discharge, and discharge-precipitation. WinSRM was used for streamflow simulation of the entire Jhelum basin, northwest Himalaya. A good correlation was observed between simulated streamflow and observed discharge.

Ma et al. (2013) developed an integrated modelling system for estimating the impact of climate change on snowmelt runoff in Kaidu watershed, northwest China. They used SRM to simulate daily discharge and verified against observed discharge. The output indicated that the model was reasonably accurate having $r^2$ of 0.8 and volume difference of ±10%. Four seasons were considered for analysing the climate change impact and the results indicated that watershed hydrology would alter under different climate change scenarios.

Pokhrel et al. (2013) used two hydrological models, GR4J lumped precipitation runoff model and SRM in the Dudh Koshi basin of the Nepalese Himalaya. The
runoff pattern was analysed with past years and sensitivity analysis was performed for possible future climatic conditions (i.e., temperature and precipitation). The results revealed that snow and glacier melt contributed significantly to runoff, and therefore, the SRM model performed better in Nepalese catchments than the GR4J model. The SRM model was a better tool for computing the snowmelt runoff in this region and was recommended for use in the other parts of the Koshi basin of Nepal as well, considering its simplicity and its robustness.

Aggarwal et al. (2014) used SRM for simulating snowmelt runoff in the sub-basins of Ganga river of India, i.e., Alakhnanda and Bhagirathi river basins up to Joshimath and Uttarkashi, respectively. The study was done to integrate temporal SCA and digital elevation model (DEM) derived from satellite remote sensing data with GIS and finally into SRM model. The temporal SCA (2002–07 for Bhagirathi river, and 2000 and 2008 for Alakhnanda river) was derived from remote sensing data and DEM was used to find elevation zones and aspect maps. Overall accuracy of SRM for Alakhnanda river in terms of $r^2$ was 0.84–0.90 for years 2000 and 2008, and 0.74–0.84 in Bhagirathi river for 2002–2007.

### 2.6 Critique

Review on different aspects of future projected scenarios, GCMs, climate change studies, snowmelt runoff modelling using energy budget approach or temperature index approach helps in selecting the appropriate methodology and hydrological snowmelt runoff model which can be used effectively in mountain region and evaluate the effect of climate change on streamflow in the eastern Himalayan region of India. The following conclusions are drawn from this review.

As stated above the emission scenarios projected by IPCC are the future images, or alternative futures which are neither predictions nor forecasts. Rather, each scenario is plausible alternative image of how the climate of earth might develop in future and example of what can happen under such assumptions. This gives us more understanding on how systems behave, evolve and interact. They are useful tools for scientific assessments, learning about complex systems behaviour and for policy making and assisting in climate change analysis, including climate modelling and the assessment of impacts, adaptation and mitigation. Many scientists around the
world including Noble laureates agreed with the conclusion of the IPCC report. These emission scenarios are the only scenarios which can help to evaluate the potential impact of climate change and vulnerabilities under a changed climate.

The climate change projections can be generated by the NCAR CCSM, for the emission scenarios as proposed by AR4 of the IPCC. NCAR is one of the world’s leading climate modelling and research centers, a strong supporter of the IPCC scientific assessment process. CCSM3 was developed in 2004 and released to the climate community. CCSM3 was a coupled climate model with components representing the atmosphere, ocean, sea ice, and land surface connected by a flux coupler. The CCSM3 allows researcher to study the earth’s past, present and future climate states.

Snowmelt can be simulated using different hydrological models. Generally, based on the data requirement of the model, there are two main approaches to estimate the snowmelt, i.e. energy balance and temperature degree-day method. Energy balance method can be used when required data is available to solve physical equations. If enough data is not available to use energy balance equations, temperature degree-day method is useful. The snowmelt runoff models including snow coverage provide more effective results in the mountain basin which are inaccessible with limited hydro-meteorological station. One of the most popular model used in high elevation snow dominated catchments to simulate and forecast daily streamflow is SRM, based on degree-day approach. The model is a well-accepted and popular model because of its simplicity, applicability with limited data availability, and option to analyse potential impact of climate change. The model had been applied by various agencies, institutes, and universities for over 100 basins, situated in around 29 countries. The SRM required three basic inputs, viz., daily temperature, precipitation, and SCA. Availability of satellite images make the model more suitable to be used in remote and inaccessible high mountainous regions.

In the Himalayan region, many studies are conducted on the effect and potential impact of climate change on snow/glacier and their corresponding induced runoff. Eastern Himalayan region particularly Arunachal Pradesh, India is lacking behind
such studies. This present work will support the studies relating to climate change and help the water resources management of the state and non-state agencies.