CHALLENGES POSED BY CLIMATE CHANGE AND SEDIMENTATION OF RESERVOIRS FOR FLOOD MITIGATION AND SUSTAINED WATER SUPPLY

DEVENDRA KUMAR SHARMA
Chairman, Bhakra Beas Management Board, Chandigarh

ANIL VYAS
Asstt. Design Engr., Bhakra Beas Management Board, Chandigarh

TARUN AGARWAL
Secretary, Bhakra Beas Management Board, Chandigarh

SUKHDEEP SINGH
Deputy Secretary, Bhakra Beas Management Board, Chandigarh

ABSTRACT

The global climate crisis increases variability in the water cycle, reduces the predictability of water availability, affects water quality and aggravates water scarcity. These are compounded by number of contributing factors, including population increase, unmanaged migration, land use changes, reduced soil health, accelerated groundwater extraction, widespread ecological degradation and biodiversity loss. While all regions of the globe are affected, the impacts of climate change are highly variable. Some regions are experiencing drought while others are facing frequent-intensified floods and storms. In the past three years Bhakra Beas Management Board (BBMB) has tackled the problems posed due to climate change including drought, floods, historical minimum and maximum snow deposition, one of the highest inflows and witnessed maximum rainfall in sub-catchments in the century. It is often said that climate change impacts are observed more straight forward through water resources. Transboundary cooperation as well as cooperation between different states/provinces is needed to address climate impacts that cross national boundaries, to minimize adverse consequences from a basin perspective and also to harness the potential co-benefits of improved regional cooperation, such as reduced uncertainty due to exchange of data, enlarged planning space and shared costs and benefits.

Bhakra Beas Management Board operates two major reservoirs formed by Bhakra and Pong Dam, comprising varying inflows from 19-35 billion cubic meter (BCM) in a water year with average inflow of 27 BCM for both the reservoirs. The designed capacity of Bhakra and Pong Dam is 9.87 BCM and 8.58 BCM respectively from which the average water of 27 BCM from both reservoirs is supplied to the partner states. These reservoirs provide food and energy security and great immunity in case of droughts and floods in the North-West India. Due to sedimentation storage capacity of Bhakra and Pong reservoir reduced by 23% and12% respectively. Area downstream of the dams face danger especially in case of floods. The rivers beds are silted up and rivulets having catchment area downstream of the dams are carrying high inflows flood large areas.

To encapsulate the climate change, Bhakra Beas Management Board has taken various initiatives such as climate change studies, soil erosion hot spot identification, sediment transfer, both agriculture and non-agriculture productive use of sediments in the reservoir. The climatic studies show that by 2070 precipitation in Satluj and Beas basins would increase by 94 mm and 79 mm respectively compared to long term average of the year 1960-90 and temperature in these basins is likely to increase by 2.22 and 2.24 degree Celsius respectively. Systematic database and analysis of snow position, seasonal forecasting along with modern mathematical models is being done to minimize water scarcity conditions as well as to tackle the extreme floods. The paper brings out case study of the Beas and Satluj river basins.

1. INTRODUCTON

Water is considered as second most important thing to survive. Only 3% of the total water across the globe rest is saline water in oceans. Out of this fresh water Icecap, glaciers contains around 68.7% and 30.1% is available as ground water so only a small amount i.e. 0.9% is available on the surface in the form of rivers, swamps and lakes. If we talk in volumetric terms the (useable)water available in World are 10,633,450 BCM and most of it is deep in the ground and unavailable for humans. Only 93,113 BCM is available to humans through lakes, reservoirs and snow. The estimated volumes available in India 4,000 BCM and we are able to use only 688 BCM. The present storage capacity of India is 253 BCM. This storage capacity has, however, been reduced due to sedimentation. The per capita available fresh water in India 1.545 MCM whereas in World 5.9 MCM. For distribution of freshwater in Eastern and Western rivers, India and Pakistan signed Indus Water Treaty (IWT) in September 1960. IWT controls boundary river waters flowing from India into Pakistan. Indus water basin has 170 million acre feet (MAF) water out of which 34 MAF used to come from eastern rivers and 136 MAF from western rivers. Table 1 shows storage capacities permitted for India on Western rivers under IWT, 1960

Table 1 : Storage capacities permitted on western rivers under Indus Water Treaty, 1960

Western River systems (Names)	Conservation storage capacity (As per IWT, 1960), in Million Acre Feet (MAF)		
	General storage capacity	**Power storage capacity**	**Flood storage Capacity**
The Indus	0.25 MAF	0.15 MAF	Nil
Jhelum (Tributary)	0.5 MAF	0.25 MAF	0.75 MAF
The Jhelum (main)	Nil	Nil	Not divert/hold
Chenab (Tributary)	0.50 MAF	0.60 MAF	Nil
The Chenab (main)	Nil	0.60 MAF	Nil
Ravi/Beas/Satluj	33MAF	33MAF	
Total storage	1.25 MAF	1.60 MAF	0.75 MAF

The Indus river basin area 1.12×106 km^2 and 170 MAF water is distributed among Pakistan (47%), India (39%), China (8%) and Afghanistan (6%). Pakistan uses 95 MAF water for irrigation and stores 13.86 MAF in Tarbela, Mangla and Chashma. The annual water flow varies from 97 to 186 MAF (average 137 MAF) out of which 80% water flows in 100 days from June to September every year. Figure 1 shows location map of important dams and barrages on Indus System.

1.1 Western Rivers Water Run-off and Storage Dams.

The Indus system of Rivers carry nearly 170 MAF out of which India can utilize nearly 33 MAF (19 %) from the assigned three eastern rivers while Pakistan uses the balance 135 MAF(81%). In addition, India is entitled to use western river's waters for limited agricultural uses and unlimited domestic, non-consumptive, hydro power generation, etc. Even out of the assigned 19% share, a part of it flows down to Pakistan during monsoon and from Ujh river throughout the year.

Present situation around the world with increasing water and energy demand on one hand, while catchment degradation and sediment-induced problems in rivers and reservoirs on the other hand may diminish the safety of dams and shorten the reservoir life. Almost all reservoirs worldwide share this sedimentation problem in common, to a differing degree depending upon the characteristics connected to the hydrological, geo-morphological, socio-economic and ecological behaviors of its river basin. Reservoir sedimentation is a significant concern faced across the globe and the assessment of sediment deposition in reservoirs and its decisive management can be considered as one of the key factors in achieving the sustainable benefits from dams and reservoirs.

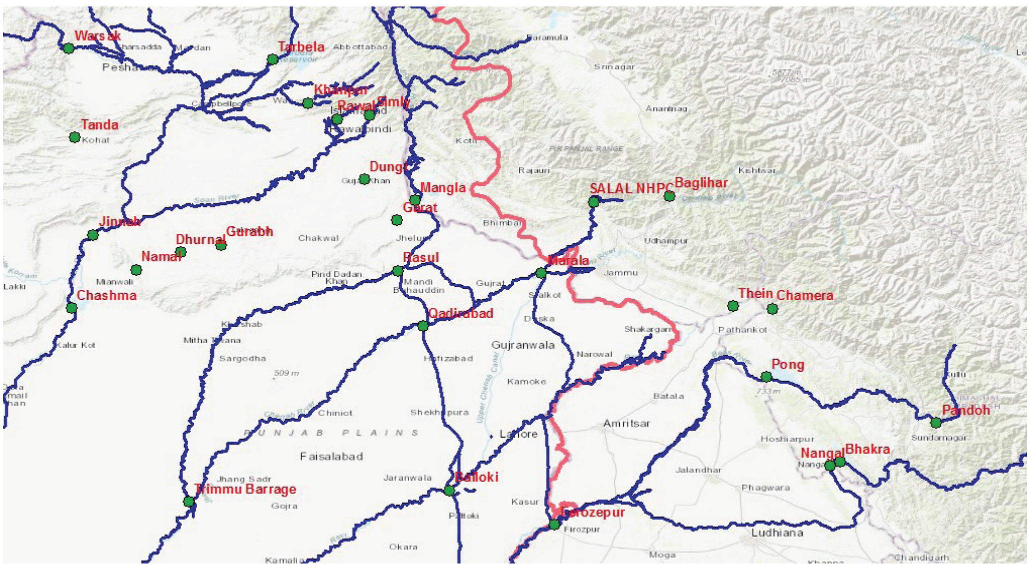

Fig. 1 : The location map showing important dams and barrages on Indus System

Bhakra Beas Management Board (BBMB) manages two storage Bhakra & Pong Dam and one diversion reservoir Pandoh Dam. Bhakra and Pong Dam has varying inflows from 14-22 BCM and 5-13 BCM respectively in a water year with average inflow of 18 BCM for Bhakra dam and 9 BCM for Pong Dam. The designed capacity of Bhakra and Pong Dam is 9.87 BCM and 8.58 BCM respectively from which the average demands 18.23 BCM and 8.97 BCM from Bhakra and Pong Dam are met of partner states. The current depleted storage volume of Bhakra and Dams due to sedimentation and flood control are of 7.04 and 6.79 billion cubic meter respectively.

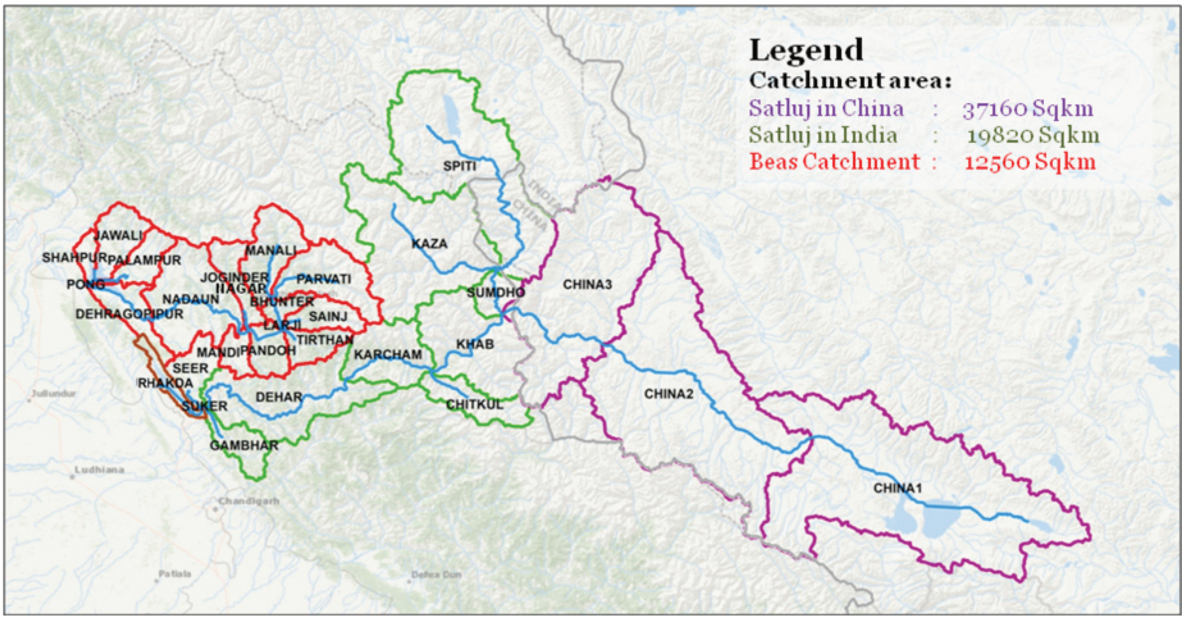

Fig. 2 : Satluj and Beas basins shapefile

The study area comprises of the Satluj and Beas River basins which have a total geographical area of 56,860 km^2 and 12,560 km^2 respectively as shown in Figure 2. The Satluj River rises to the west of Mt. Kailash in Tibet at an altitude of 5250 m and has a catchment area of 37,160 km^2 in Tibet and 19,820 km^2 in India at Bhakra dam site. The Satluj River flows through the Himalayas up to Bhakra Dam having elevation of 512 m above sea level. Two power houses are located at toe of the dam on left and right banks of the river have a total capacity of 1379 MW. The reservoir provides irrigation water to an area of 40,000 km^2 in the states of Punjab, Haryana and Rajasthan.

The Beas river rises from the southern face of Rohtang Pass in the Kullu district at an altitude of 3,400 m upstream of Manali and flows 116 km downstream to Pandoh Dam where water is diverted to the Satluj River through Beas Satluj Link Project. From Pandoh Dam, it is a further 130 km downstream to Pong Dam. The total catchment area at Pong Dam is 12,560 km^2 of which 777 km^2 is snowbound. Further downstream, the Beas River joins the Satluj River at Harike after traversing a distance of over a 400 km.

2. CLIMATE CHANGE IMPACTS ON RIVER DYNAMICS

The Intergovernmental Panel on Climate Change (IPCC) report (2017) informs that the climate change is happening in distinguished ways and global warming is effecting our environment. As per observations, six river catchments showed an increase in rainfall whereas 15 river catchments had shown decrease in rainfall. Further, four river basins experienced increasing patterns in rainy days and 15 river basins had the decreasing patterns. Temperature data showed a monotonous rising pattern. Many studies have used the combination of climatic models and hydrological models to determine the climate change effects on river hydrology.

3. DATA SOURCEFOR CLIMATE CHANGE STUDY - GCM & RCP

General Circulation Models (GCMs) are highly complex mathematical models which use various atmospheric and oceanic variables to generate future temperature & precipitation data. A number of GCMs developed by the modeling groups of various countries have been used by pioneer organization like IPCC (Inter-governmental Panel on Climate Change) for different climate change scenarios with different emission standard. Community Earth System Model (CESM) is one of them. CESM is a fully-coupled, community, global climate model that provides state-of-the-art computer simulations of the Earth's past, present, and future climate states. CESM is sponsored by the National Science Foundation (NSF) and the U.S. Department of Energy (DOE). Administration of the CESM is maintained by the Climate and Global Dynamics Laboratory (CGD) at the National Center for Atmospheric Research (NCAR). The CESM project addresses important areas of climate system research. In particular, it is aimed at understanding and predicting the climate system.

Community Earth System Model, version 1–Biogeochemistry CESM1 (BGC) characterize the fidelity of the Community Earth System Model (CESM1) carbon cycle with terrestrial carbon–nitrogen dynamics and an ocean biogeochemical model. Two sets of pre-industrial control and 20th century experiments were initialized and forced with prescribed CO_2 emissions (PROG) and CO_2 mole fractions (PRES). The Representative Concentration Pathway, RCP 4.5 scenario assumes that green housegas emissions stabilize by the middle of the twenty-first century with an anthropogenic radiative forcing of 4.5 W/m2 at year 2100 (Thomson et al. 2011). The CESM1 (BGC) RCP4.5 simulation was run with prescribed atmospheric CO_2 levels.

4. GCM DATA ANALYSIS

Preliminary results have shown a consistent temperature & precipitation increase across the Satluj and Beas catchments i.e. 0.5-0.6 degree rise per decade for temperature and increase in annual precipitation per decade by 15-20 mm. Analysis for each decade for both these basins till 2090 has been carried out.

4.1 Precipitation Variation

The cumulative increase of annual mean precipitation in mm for the Satluj and Beas basins in 2070 (as per GCM CESM1_BGC AND RCP 4.5) with respect to observed mean precipitation from 1960-1990 for Satluj and Beas Catchment as shown in Figure3. Table 2 shows decadal precipitation increase w.r.t. long term average 1960-90.Graphical representation of decadal precipitation increase in the river Satluj and the river Beas Sub-Catchments w.r.t. long term average is shown in Figure 4 & 5 respectively.

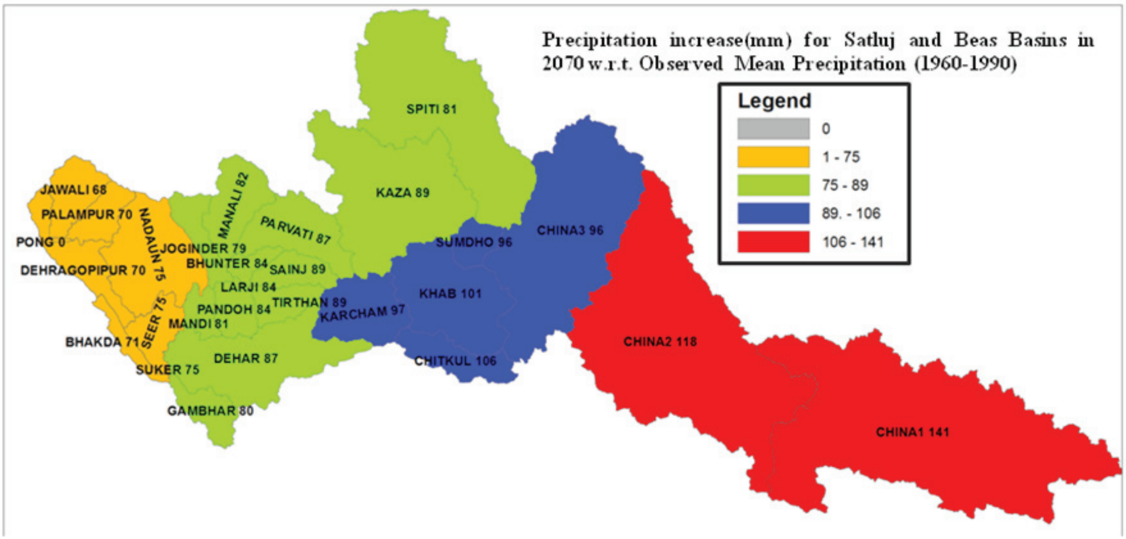

Fig. 3 : Cumulative increase of annual mean precipitation in "mm" for the river Satluj and Beas Basins in 2070 with respect to Observed Mean Precipitation from 1960-1990.

Table 2 : Decadal precipitation increase w.r.t. long term average

S. No.	Basin	Long term average(1960-90) in mm	Increase from average in 2020 in mm	Increase from average in 2030 in mm	Increase from average in 2050 in mm	Increase from average in 2070 in mm
1	Satluj	863	29	52	69	94
2	Beas	1551	31	44	57	79

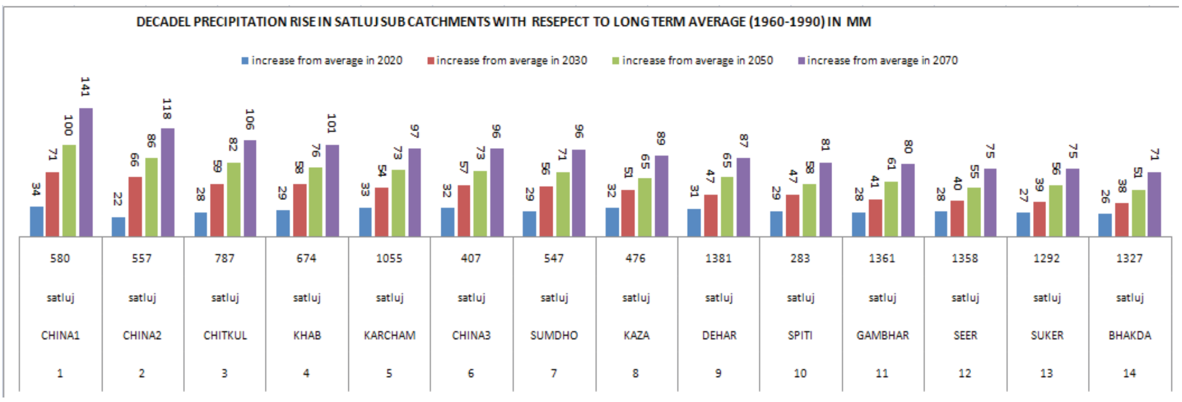

Fig. 4 : Graphical representation of decadal precipitation increase in Satluj Sub-Catchments w.r.t. long term average

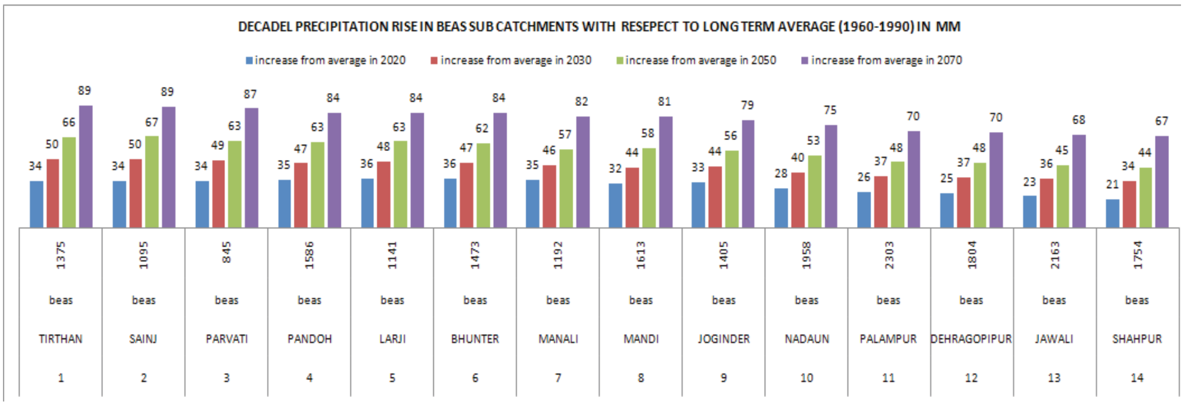

Fig. 5 : Graphical representation of decadal precipitation increase in Beas Sub-Catchments w.r.t. long term average

The maximum increase of annual precipitation approx. 100-140 mm by 2070 has been noticed in the Satluj in Tibet region, and approx. 80-100 mm by 2070 for Khab-Chitkul-Rampur region against an average annual increase of 94 mm rainfall for Satluj catchment in 2070. Similarly, for the Beas catchment the maximum increase of annual precipitation approx. 90 mm by 2070 against an annual average increase of 80 mm by 2070 has been observed in the snow bound sub basins above the Pandoh dam namely Tirthan, Sainj, Parvati and Manali.

4.2 Temperature Variation

Decadal Temperature Increase w.r.t Long Term Average for the River Satluj and Beas Catchments

The decadal rise in the Satluj and Beas catchment is 0.4 to 0.5 degree Celsius w.r.t. long term average temperature 1960-90.Summary of decadal temperature increase w.r.t long term average for Satluj and Beas Catchment is shown in Table 2. Spatial distribution shows comparatively more increase in temperature in snowbound region of the study area as depicted in Figure 6. Graphical representation of decadal temperature increase in the river Satluj and the river Beas sub-catchments w.r.t. long term average is shown below in Figure 7 & 8respectively.

Table 2 : Summary of decadal temperature increase w.r.t long term average for Satluj and Beas Catchments

S.No.	Basin	Long term average (1960-90)	Increase from average in 2020	Increase from average in 2030	Increase from average in 2050	Increase from average in 2070
1	Satluj	6.93	0.48	1.27	1.91	2.22
2	Beas	14.87	0.48	1.30	1.87	2.24

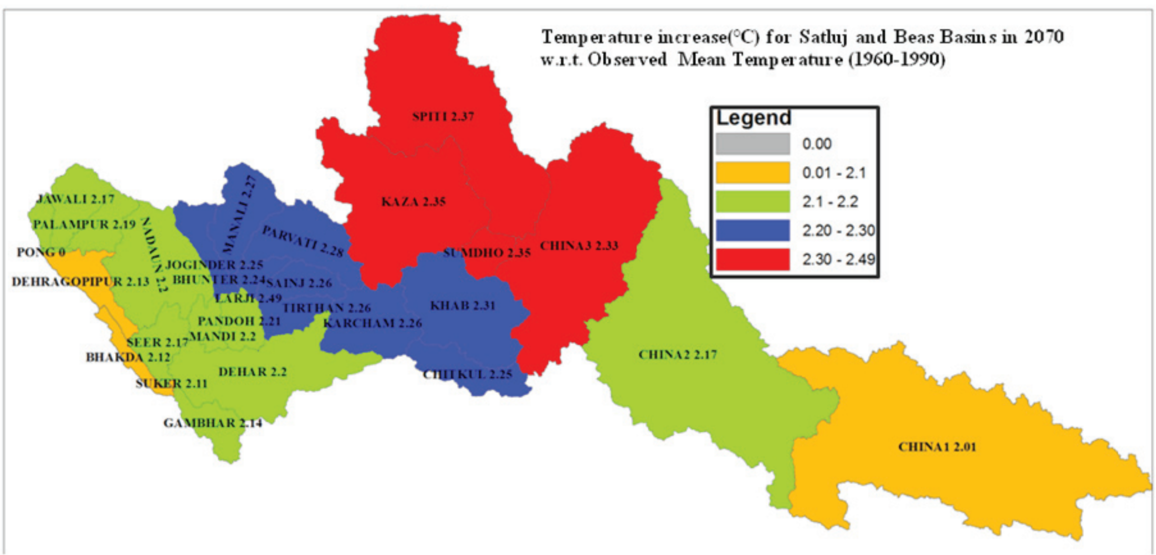

Figure 6 : The Increase of Annual Mean Temperature in Degree Celsius for the Satluj and Beas Basins in 2070 as per GCM Prediction (As per GCM CESM1_BGC and RCP 4.5)with respect to observed mean temperature from 1960-1990.

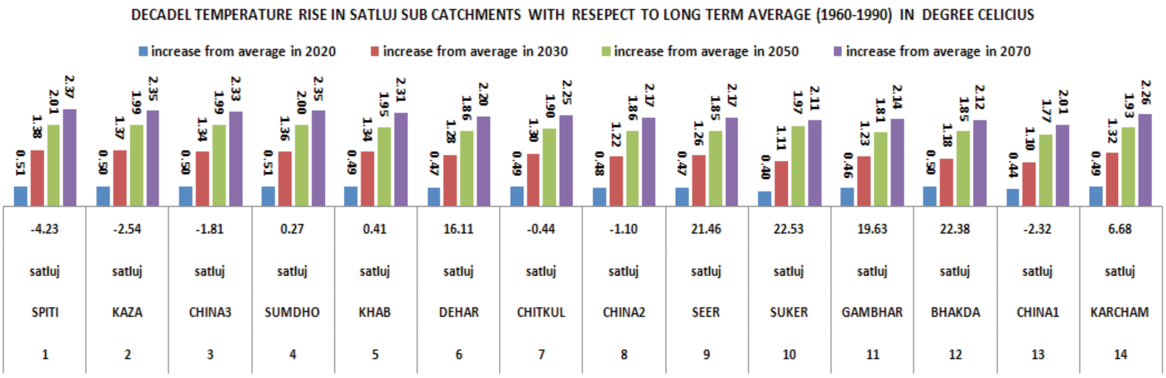

Figure 7 : Graphical representation of decadal temperature increase in Satluj Sub Catchments w.r.t. long term average

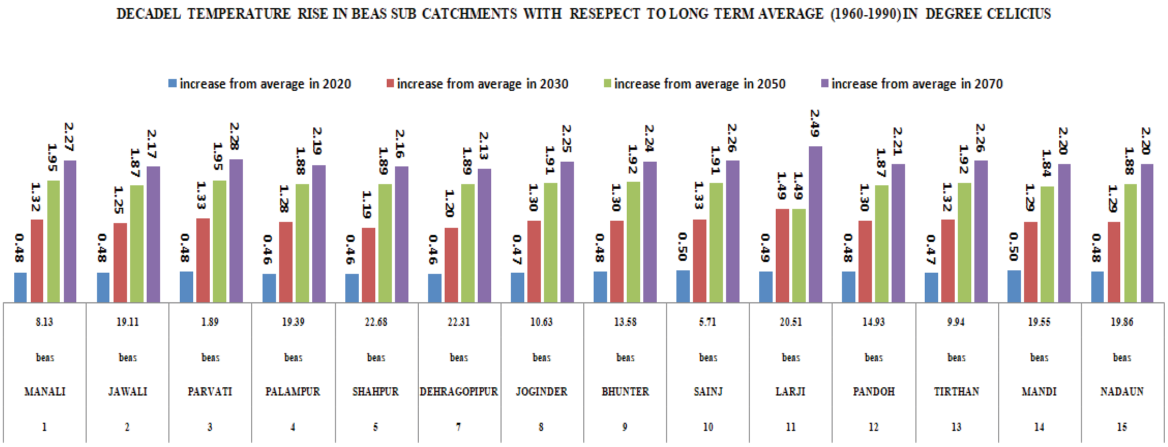

Figure 8 : Graphical representation of decadal temperature increase in Beas Sub Catchments w.r.t. long term average

The major catchment area of Satluj basin falls in snow bound sub basins region ranging from Rampur to source Mansarovar, Spiti and Kaza region. The mean annual temperature of the Satluj basin shows the variation from a minimum of -12 degree Celsius annual average in Tibet to a maximum of 23 degree Celsius annual average for region near Bhakra Dam. Similarly, the mean annual temperature of Beas basin shows the variation of minimum of 1.89 degree Celsius annual average in Parvati region to maximum of 22.68 degree Celsius annual average for Shahpur region.

An increase of temperature by 2-2.5 degree Celsius by 2070 would lead to major change in snow accumulation pattern affecting the snowmelt inflow to reservoirs. These increases in temperature is likely to change the hydrological behaviors of some of the sub basins which in turn would affect the inflows received from these sub basins into the system. Further studies require establishing the impact of these climatic change parameters on hydrological behavior of the basin.

5. SEDIMENTATION OF RESERVOIRS

A. BHAKRA DAM

Length of Bhakra reservoir is 96.56 km and area of reservoir is 168.35 square km. The curculios reach from Kasol to Bilaspur i.e. from 83,210 m to 48,463m follows a narrow and circuitous course which fans out near Bilaspur to a width of about 914 m. It again narrows down from 42,976.8m to 25,298m after which it opens into a wide expanse leading to a width of 6.44 km at full reservoir level just upstream of the dam. River reaches, where width of the reservoir increases act as silt traps. With the decrease in velocity due to the increased width, the heavy sediment settles down at the start of the wide reaches. This settled silt again gets eroded from the upper reaches due to the heavy inflows of water which carry this heavy charge to unload at the point where the still reservoir level meets, thus, giving way to the formation of delta at that point. Deposition of sediments over the years has created a hump from 12,497m to 27,737 m. The movement of crest of the hump towards the dam has not taken place beyond 12,497m during 2013-16 due to operation of reservoir at higher water level than the level of tip of hump. The average trap efficiency so far is 99.2%. Due to high trap efficiency, sediments have deposited over the years in the reservoir and are not discharging downstream of the dam. L-Section of reservoir of Gobind Sagar reservoir of Bhakra Dam before and after sedimentation is shown in Figure 9.

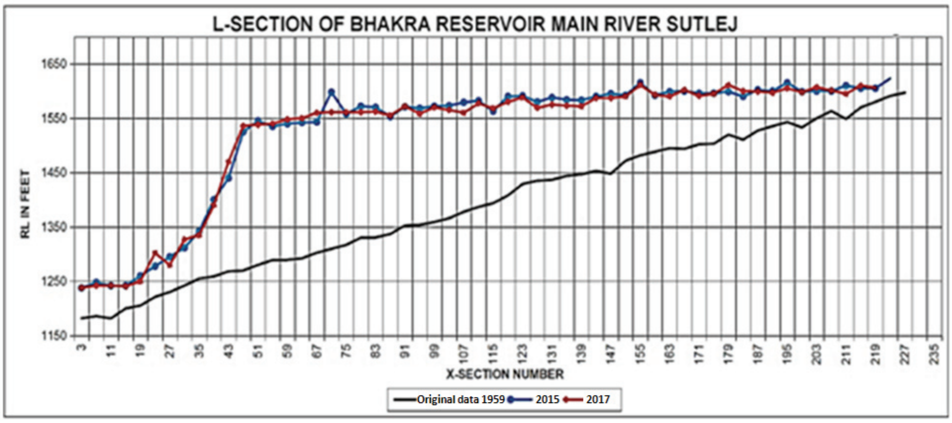

Fig. 9 : L-Section of Gobind Sagar Reservoir

The silt deposited during the year 2016-2018 is 54.01 Mm^3 as compared to 119.98 Mm^3 observed during the year 2013-2016. The average annual rate of siltation has come down during last two years. This may be in view of construction of Kol Dam Project upstream of Govind Sagar Reservoir. This dam is acting as check dam and is definitely resulting in decrease of silt inflow and will increase the useful life of Gobind Sagar reservoir. The average annual rate of siltation has been worked out as 38.51 Mm3 for the year from 1959 to 2018 against a designed figure of 33.61 Mm3. The rate of sedimentation has shown a higher trend after the year 1990. Rate of sedimentation has increased noticeably after 2005, probably due to increased construction activities in the catchment area amongst other influencing factors. The average trap efficiency of the reservoir for the last 53 years is 99.2 %. Bed load carried by the river and its tributaries has been taken as 15% of the total suspended sediment load. Silt erosion index from Rampur to Kasol varies from 0.771 to 18.97 which indicates that erosion in this reach mainly cause contribution of silt into Bhakra Reservoir. Approximately 43% of the total sediment contribution is from Spiti and Satluj catchments above Khab (Namgia), located downstream of the place (Shipki-La) where the river Satluj enters India.

Loss of Storage Capacity in Gobind Sagar Reservoir

The reservoir storage capacity loss consequent upon sedimentation deposition in Gobind Sagar reservoir is given in Table 3. The dead storage is reducing by an alarming rate of 0.73% annually and this number is going to increase. Live and Gross storage are also decreasing by 0.28% and 0.39% per year and these values increase every year.

Table 3 : The reservoir storage capacity loss consequent upon sedimentation deposition in Gobind Sagar Reservoir

Capacity	Original designed capacity in million m^3at 1690 feet	Balance capacity of reservoir in million m^3 ending 2018	% capacity loss ending 2018	Balance capacity of reservoir in million m^3ending 2050	% capacity loss ending 2050
Dead storage	2431.81	1388.07	42.92%	821.78	66.21%
Live storage	7436.03	6208.34	16.51%	5542.19	25.47%
Gross storage	9867.84	7596.26	23.02%	6363.65	35.51%

The above table depicts that the sediments deposited up to year 2018 is 2272.73million cubic meters. Average sedimentation rate of 38.41 million cubic meters (31141acre feet) per year which is more than the designed figure of 33.61 million m^3 (27250 acre feet) per year.

B. MAHARANA PRATAP SAGAR RESERVOIR OF BEAS DAM

The storage dam on River Beas was a vital necessity to provide perennial irrigation supplies to the Thar Desert of Rajasthan and areas of Punjab & Haryana besides generating sizable hydroelectric power, flood control, though incidental is an added advantage. The Beas Dam, located at Pong in District Kangra of Himachal Pradesh in the Himalayan foot hills, across Beas River, is an earth core-gravel shell dam, 132.6 m (435 ft) high from the deepest foundation level. The Pong Power Plant has generating capacity of 6 x 66 MW i.e. 396 MW. Pong reservoir has a water spread areas of 260 square kilometer at full reservoir level at EL. 426.72 m (elevation 1400 feet.) to impound 8579 MCM of water and its extreme point extends to a distance of about 42 km.

River Beas and its tributaries carry large quantities of sediments, gravel and boulders etc. along with its flow. With the construction of the dam and creation of the vast reservoir behind it, the silt, gravel and boulders have hardly any exit from it; rather only a small fraction of suspended sediment is passed down through the penstock tunnels and other discharging facilities under operation. The rest of the sediment load gets deposited in the reservoir.

Annual suspended silt load of about 43 million tones (29260 acre feet) at average density of 1.24gm per cc (77.5 lbs per cubic ft) has been assumed on the basis of actual silt observations. The bed load carried by the river could not be assessed and has been taken as 15% of total suspended silt load. For working out the volume of deposits, an estimate of the probable density of the deposit was made. Available data indicates large amount of variation in the densities observed at various reservoir places and the lower and upper values as about 1.04 gm per cc (65lbs per cubic ft) and 1.44 gm per cc (90 lbs per cft) respectively were assumed for the preliminary studies. The rate of loss of storage capacity is worked out for these extreme values. The actual density of deposits may be somewhere between these limits. Figure 10 shows original and modified L-section of river after sedimentation of reservoir.

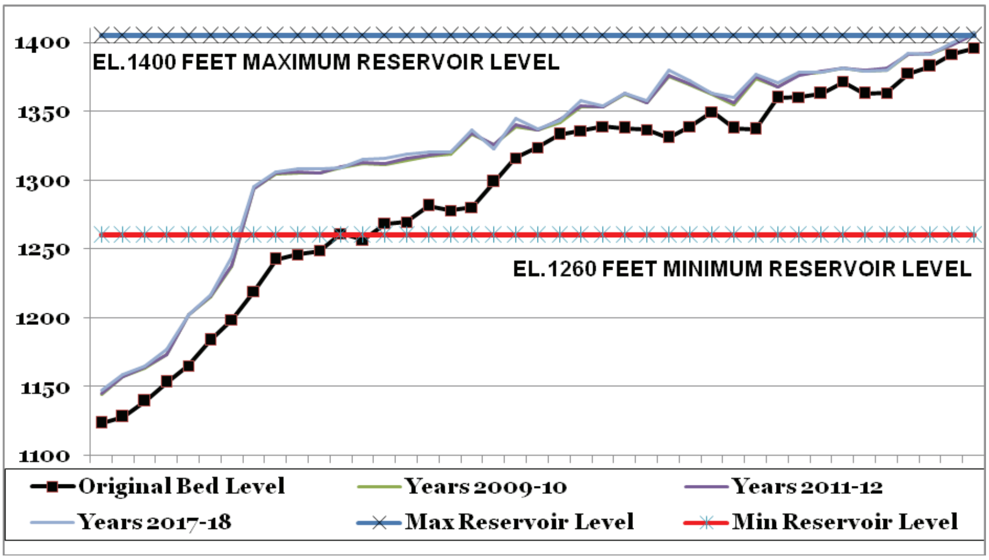

Fig. 10 : L-Section of Maharana Pratap Sagar Reservoir

The sediment observation data observed at the different stations for the period 1974-2018 has revealed that during pre-construction period of Pandoh Dam, the river had contributed about 72 % of the total sediment load brought into the reservoir, whereas the remaining 28 % was the combined contribution of streams. With the construction of Pandoh Dam, the sediment contribution of river reduced to about 64% as a part of sediment load in the river upto Pandoh gets deposited in the Pandoh reservoir and also passes through Pandoh Baggi tunnel of the Beas Satluj link Project. With the sedimentation of Pandoh reservoir, the sediment contribution by the river has now risen to about 77% of the total sediment load brought into the reservoir up to the end of 2017-18. It is also evident from soil erosion index that the sub catchment areas entrapped by Baner stream, Gaj stream and Dehar stream yield huge quantity of sediment, which necessitates immediate soil conservation measures in the sub catchment area of these streams. The sediment concentration and discharge relationship at sediment measuring station provides a measure of the sediment load carried out by the river/streams. It is revealed that sediment load normally increases with the increase in discharge which generally happens during monsoon period. Average sediment yield per annum during the period from 1974 to 2018 per thousand hectares of catchment area is worked out to be 19338m3 as compared to sediment yield of 19368 m3 during the year from 1959 to 2016 which depicts decrease in rate of sedimentation.

Loss of Storage Capacity Maharana Pratap Sagar Reservoir

The reservoir storage capacity loss consequent upon sedimentation deposition in Maharana Pratap Sagar reservoir is given in Table 4. The dead storage is reducing by an alarming rate of 0.50% annually and this number is likely to increase. Live and Gross storage are also decreasing by 0.25% and 0.28% per year and these values increase every year.

The reservoir storage capacity loss consequent upon sedimentation deposition in Maharana Pratap Reservoir is shown in Table 4.

Table 4 : The reservoir storage capacity loss consequent upon sedimentation deposition in Maharana Pratap Reservoir

Capacity	Original designed capacity in million m^3at 1400 ft.	Balance capacity of reservoir in million m^3ending 2018	% capacity loss ending 2018	Balance capacity of reservoirin million m^3 ending 2050*	% capacity loss ending 2050
Dead storage	1287.7	1005.31	21.93%	842.25	34.59%
Live storage	7291.2	6504.48	10.79%	6023.37	17.39%
Gross storage	8578.9	7509.97	12.46%	6865.62	19.97%

The above table depicts that the Silt deposited up to year 2018 is 2495 million cubic meters.Average sedimentation rate of 24.29 million m^3 (19695 acre feet) per year which is nearby to the designed figure of 25.29 million m^3 (20500 acre feet) per year.

6. STUDY OF HYDROLOGICAL CYCLE FOR WATER YEAR

Inflow into Bhakra Dam during a water year starting from 01st October to 30th September, last two and current water year inflows are shown below in Figure 11. In the starting of a water year the inflow remains in the range of 11000 cusecs to 6500 cusecs so there is no much variation in the inflow pattern. During the water year, inflow remains almost straight line with downward gradient from 01st October to 31st March. The inflow forecasting for this period, BBMB uses statistical methods like matching year pattern, percentage exceedance method. Normally, the inflow pattern remain between 40 and 60% limit, in average year and in dry and wet year may sometime goes upto 30% and 70% range but not much fluctuations has been observed.

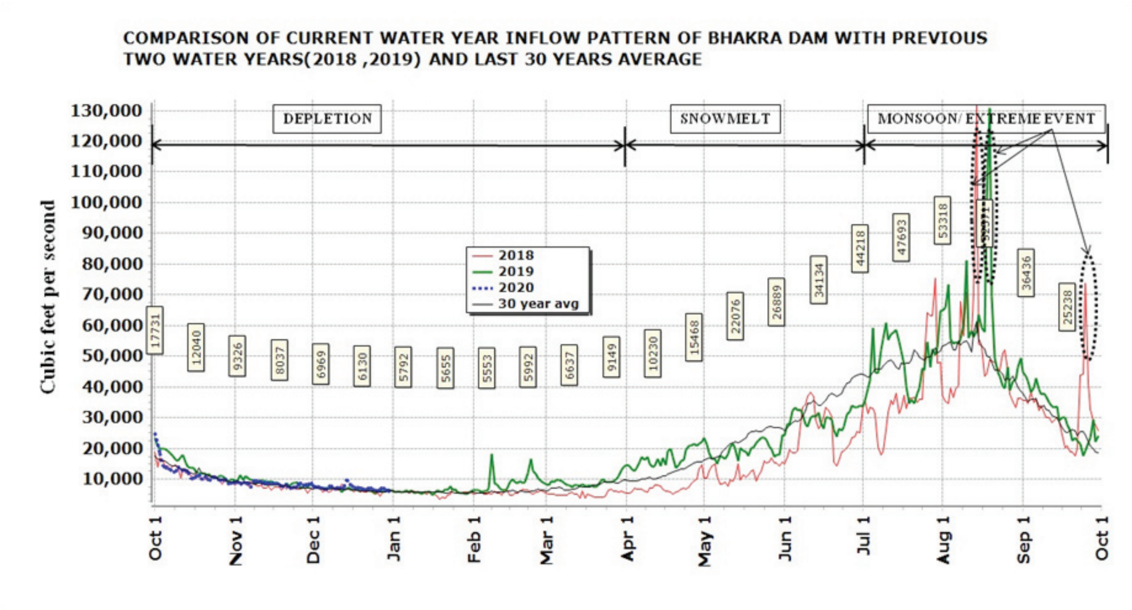

Fig. 11 : Comparison of current water year inflow pattern of Bhakra Dam during the last two water years (2018 & 2019)

Inflow into Pong Dam during a water year starting from 01st October to 30th September, last two and current water year inflows are shown below in Figure 12. Inflow remains constant averaging 6500 cusecs to 3000 cusecs in the starting of a water year the so there is no much variation in the inflow pattern. The inflow remains straight line with gradient in downward side upto the 15th of May. The inflow forecasting for this period, BBMB uses statistical methods like matching year pattern, percentage exceedance method. Normally, the inflow pattern remain between 40 and 60% limit, in average year and in dry and wet year this may sometime goes upto 30% and 70% range but not much fluctuations has been observed.

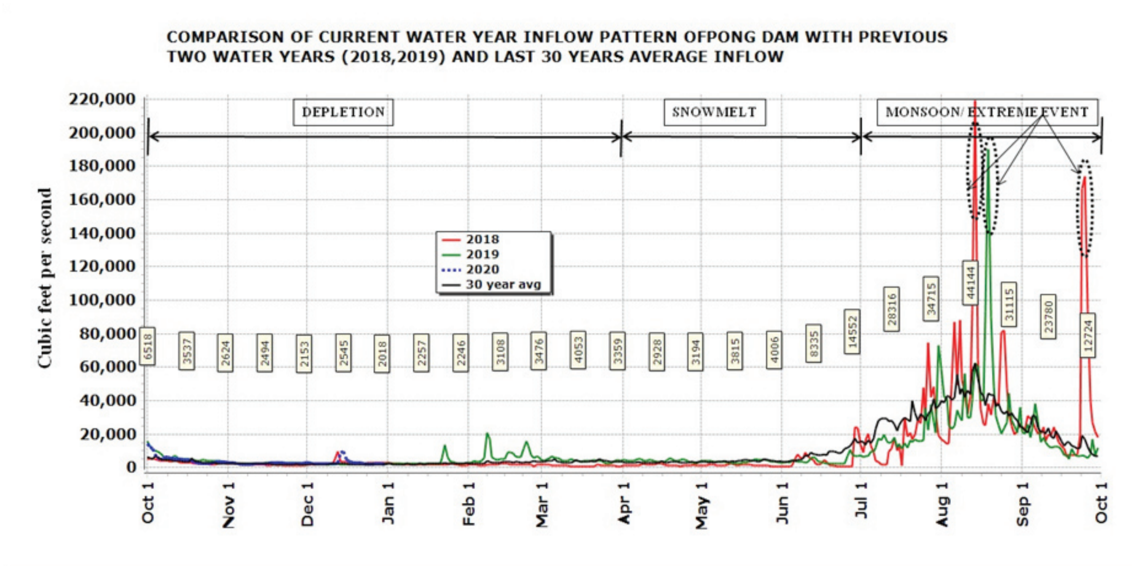

Fig. 12 : Comparison of current water year inflow pattern of Pong Dam with Last two water years (2018 & 2019)

7. SEASONAL FORECASTING

Snow accumulation due to winter precipitation from October to March and melting during summer from April to June plays a vital role in the inflow of BBMB reservoirs. The 50% of total volume received in water year is due to snowmelt. Last three year witnessed, historically minimum inflow 3.2 billion cubic meter (BCM) in water year 2018 (due to average SWE 120 mm) and historically maximum 6.5 BCM (due to average SWE 200mm).The air temperature alongwith precipitation during accumulation and melting plays an important role. Snow water equivalent of deposited snow fall in the catchment vis a vis run-off is shown below in Table 5. Comparison of average depth of snow water equivalent available in snow bound sub basins in the catchment area of rivers Beas and Satluj and temperature in snow bound sub-basins of the river Satluj is shown in Figure 13 & 14 respectively.

Table 5 : Snow Accumulation in last three years in the Satluj and Beas Catchments

S. No.	Volume in BCM during 2017	Volume in BCM during 2018	Volume in BCM during 2019	Volume in BCM during 2020 (till December 2019)
Snow accumulation in BCM	8.65	4.58	10.21	11
Runoff in BCM	5.1	3.2	6.5	Expected more than 6.5 BCM

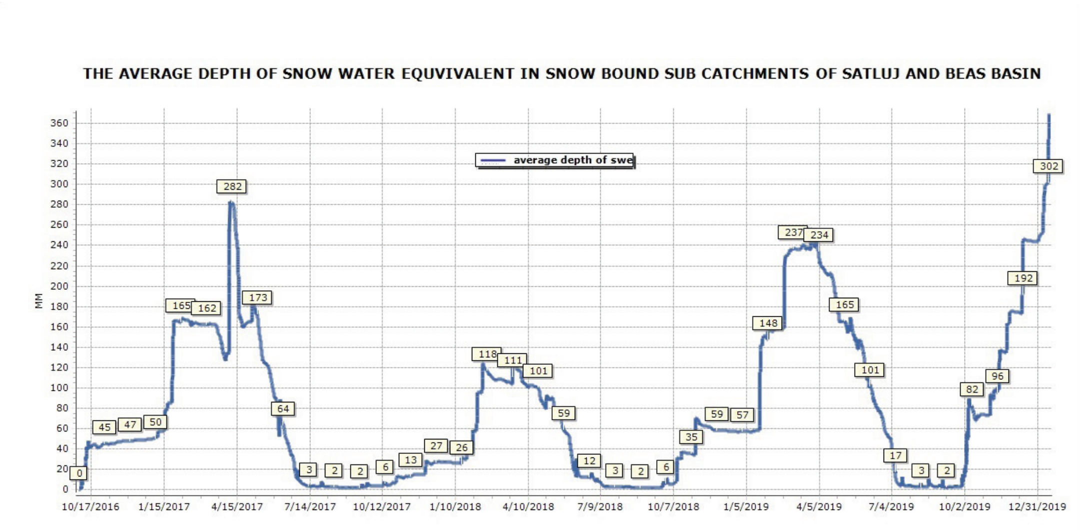

Fig. 13 : Comparison of average depth of snow water equivalent available in snow bound sub basins of the Satluj basin

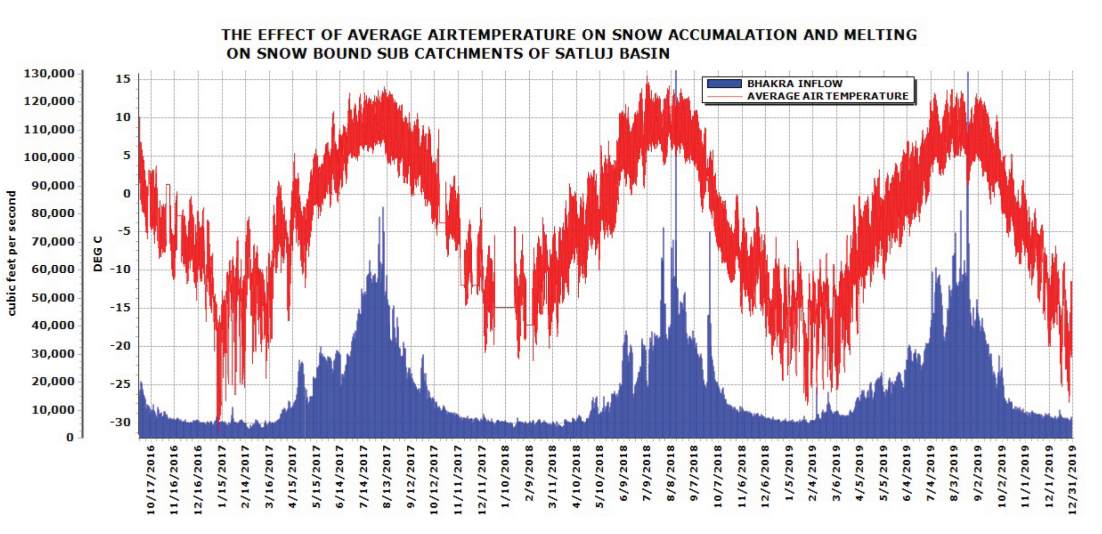

Fig. 14 : Comparison The effect of average temperature of snow bound sub basins of the Satluj catchment on inflow of Bhakra Dam

8. EXTREME EVENT ANALYSIS

On 16th of August, 2019, a forecast of heavy rain fall event was received and it was anticipated that as per model forecast the level of 1684 ft. would be reaching by 24th of August, 2019.On evening of 17th August, 2019, a fresh forecast with very heavy rainfall event in next 9 to 12 hours in the periphery of Bhakra reservoir and just downstream area of Bhakra Dam was received.

An unprecedented hydrological event occurred in the intervening night of 17/18 August, 2019, which generated around 3,11,134 cusecs of inflows into Bhakra Dam. This water inflow was more than 1988 considering that inflows of 8400 cusec into the river Satluj from the river Beas through Beas Satluj Link Project were stopped completely. Comparison of real time and forecasted rainfall during an hydrological event of 17th – 18th August 2019 is shown in Figure 15. Operation of Bhakra reservoir during this event is shown in Figure 16.

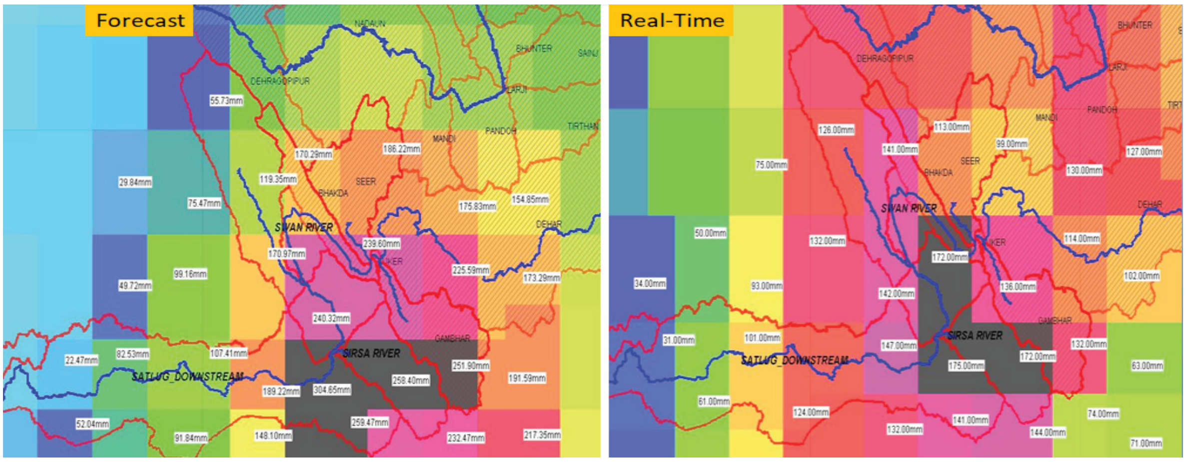

Fig. 15 : Comparison of Real time and forecasted rainfall during an hydrological event of 17th – 18th August 2019 in Govind Sagar reservoir.

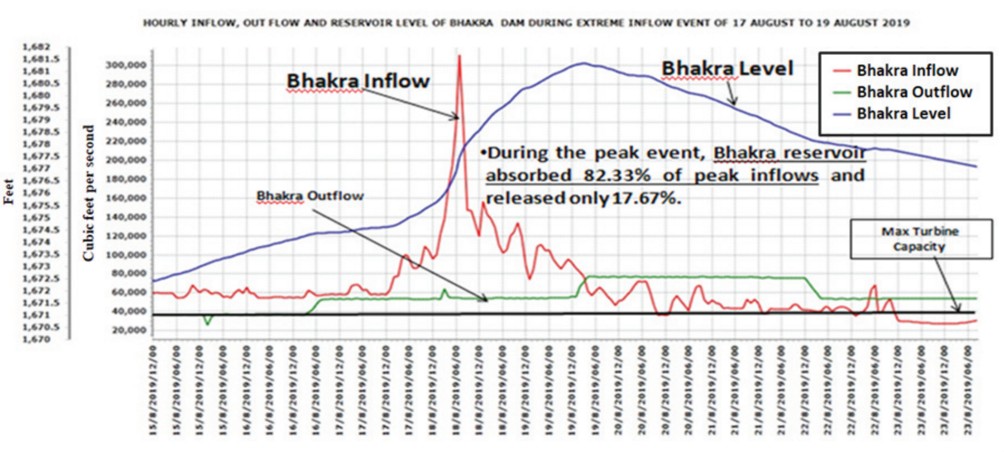

Fig. 16 : Operation of Govind Sagar Reservoir of Bhakra during the event of 17th – 18th August 2019

Inflows of 8400 cusec into the river Satluj from the river Beas through Beas Satluj Link Project were stopped completely to control the rise of water level in Bhakra Dam. These inflows along with flood discharge from the catchment entered into Pong reservoir. Comparison of Real time and forecasted rainfall alongwith hourly inflow, outflow and level of Pong Dam showing operation of Pong Reservoir during the hydrological event of 17th – 18th August 2019 is shown in Figure 17 & 18 respectively.

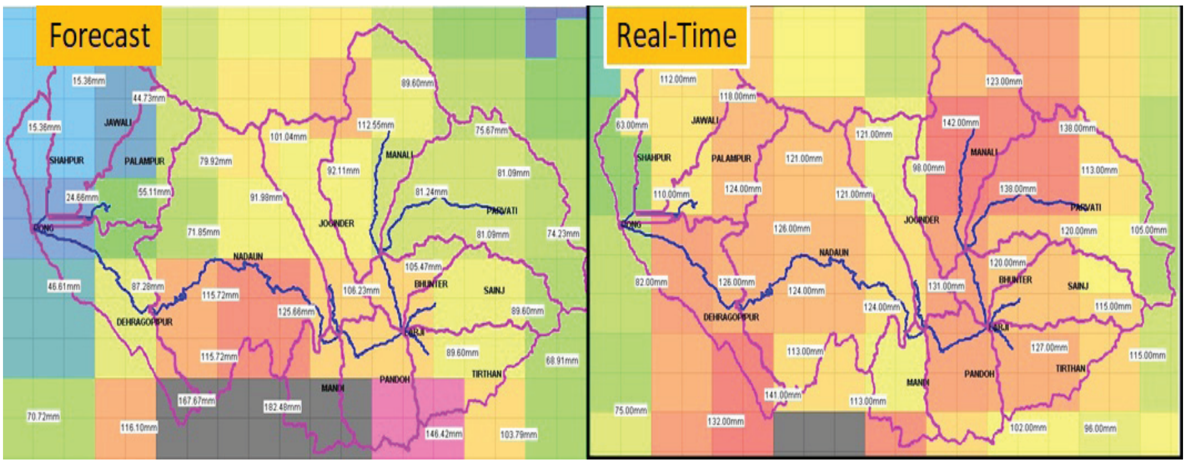

Fig. 17 : Comparison of Real time and forecasted rainfall during an hydrological event of 17th – 18th August 2019 in Maharana Pratap reservoir

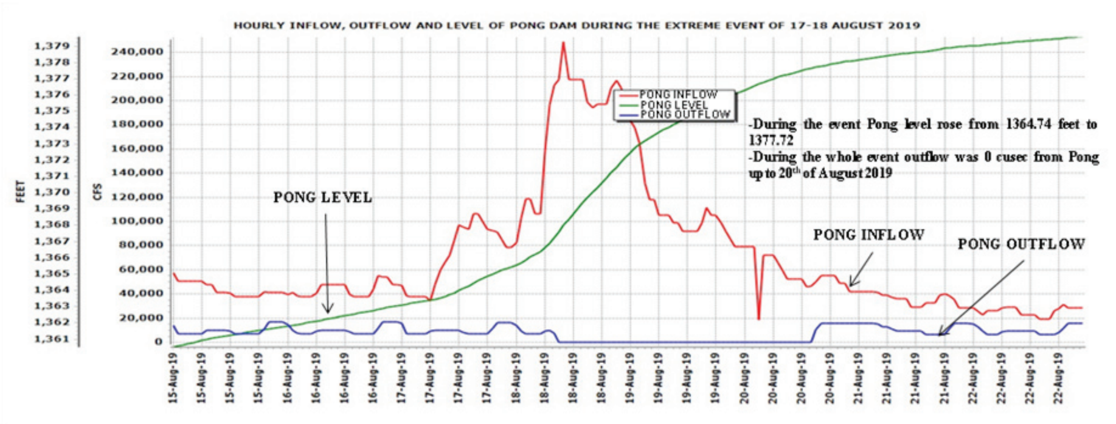

Fig. 18 : Operation of Maharana Pratap Sagar Reservoir during the event17th – 18th August 2019

Further, during the event, the deflection of Bhakra Dam was observed to be all time high i.e. 1.1467 inches which was 22% more than the highest observed so far. The total seepage in the dam body also increased from 169 liter per minute on 17.08.2019 to 825 liter per minute on 18.08.2019.The rain fall event in the intervening night of 17/18th August, 2019 was historically high for the last 70 years.

High flood inflows were absorbed in the reservoir by allowing the level to rise even beyond the permissible storage level of 1680 feet and release of excess water in a controlled manner. This has been possible due to forecast of inflows and precipitation in the catchment area.

The extreme events were well forecasted prior to their arrival by the system accurately. The western disturbances, monsoon clash were forecasted in advance by the real time decision support system. Quantitative analysis of snow cover and temperature position in the catchment area were a great advantage in deducing the reduced inflows in months of April-May. The generated multiple scenarios act as guidelines for management in reservoir operation.

9. CONCLUSION

Due to climate change, the occurrence of extreme rainfall events having high intensity and high frequency is being witnessed over the years. Forecast of these extreme hydrological events due to climate change is becoming a challenge. These extreme events resulted in sudden increase in reservoir level causing floods (2019) and droughts (2018) as witnessed during the last two water years. Reduction of storage capacity of Bhakra (23%) and Pong reservoirs (12%) due to sedimentation is diminishing flood retention capacity and has led to adverse impact on areas downstream in eventuality of occurrence of such events. Filling of natural drainage system for human usage, encroachment of flood plains of main rivers/streams has resulted in reduction in water carrying capacity of the rivers downstream of these dams has aggravated the problem of tackling floods in such like extreme hydrological events.

Keeping in view the climatic change scenario, sedimentation of both Bhakra and Pong dams and increase in PMF (Probable maximum flood) of these dams, water carrying capacity of the rivers and streams in the areas downstream of the dams need to be restored. Removal of encroachments in natural drainage system requires immediate attention. Complete Hydro-dynamic Model with 2D flood mapping of downstream areas with precise elevations need to be done on urgent basis so that vulnerable areas be identified and emergency disaster plan could be implemented. Embankment and Levees need to be strengthened/ repaired to sustain the designed floods along with river training works. Hydrological modelling (forecasting and real time monitoring) of downstream catchment areas is required so that flash floods in sub-basins are identified. Small storage dams are required to be constructed and also channelization of main rivulets/streams like Sirsa and Swan is required to be done. Desilting and restoration of storage capacity of barrages Ropar and Harike downstream of Bhakra dam, need to be taken up immediately.

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