Proceedings WARMICE-2012
Sudhir Kumar, et al. (eds)
I.A.H., 2012

V-5

Effect of Two Hydroelectric Projects in Series on the Low Flow Characteristics of Satluj River

[1]Pradeep Kumar, [2]U. C. Chaubey and [2]S. K. Mishra
[1]NIH-WHRC, I & FC Complex, Jammu - 180003
[2]WRDM, IIT Roorkee, Roorkee – 247667

Abstract : A large number of hydropower schemes on the Satluj River are in different stages of development. These river valley schemes will cause flow related impacts due to storage, flow diversion, tunnelling, muck disposal etc. There may be critical reaches in which altered flows are not able to sustain the riverbed ecology and riparian environment existing prior to implementation of the storage and diversion schemes. In this context, the effect of two hydropower projects in series on low flow characteristics of Satluj river has been evaluated in the present study.

As an improvement over the previous hydrological studies of Satluj basin, the methodology proposed in this study is based on correlation between discharges of tributaries having similar catchment characteristics. Distinction has been made on the basis of (i) rainfed and snowfed catchments; (ii) durations with and without snowmelt contribution.

Specific discharge (discharge per unit catchment area) duration curves of Sholding, Gaanvi, Bhaba and Baspa streams are quite similar and hence discharge data of these streams can be used to estimate discharges of other streams on per unit catchment area basis. Difference in the values of Q90/Q50 for tributaries on right bank (Gaanvi, Bhaba) and left bank (Sholding, Baspa) indicate different normalized baseflow contributions from these catchments and it might be attributed to the amount of precipitation varying with the location of these catchments, whether in forward or leeward zones. Therefore, tributaries in the study area are divided into (i) Left bank tributaries having snow melt contribution, (ii) Right bank tributaries having snow melt contribution and (iii) Tributaries having no snow melt contribution.

Estimated tributary discharges have been used in lean season flow mapping of Satluj river from Nathpa to Jhakri. Further, low flow characteristics of Satluj river at three locations i.e. (i) Nathpa, (ii) d/s of confluence of Sholding stream and (iii) Rampur have been analyzed. Flow variability (represented by ratio Q20/Q90) has significantly increased in post-NJHEP condition. The ground water contribution to Satluj flow (represented by ratio Q90/Q50) is relatively higher in post-NJHEP condition compared to pre-NJHEP condition.

Key Words : Nathpa Jhakri Hydroelectric Project, flow duration curve, low flow frequency analysis, specific discharge, river mapping

INTRODUCTION

The flows of the world's rivers are increasingly being modified through impoundments, abstractions, return flows, inter-basin diversions, and flood control structures (Dyson et al., 2003; Postel and Richter, 2003). It is estimated that more than 60% of the world's rivers are fragmented by hydrological alterations (Ravenga et al., 2000). This has led to widespread degradation of aquatic ecosystems (Millennium Ecosystem Assessment, 2005).

Long-term hydrologic data (mainly stream flow) are the main input data in most EFA methods. Such data are usually not available for catchments in many parts of the world particularly in Himalayan mountainous region. Therefore, appropriate methods for assessment of flows in ungauged catchments are needed. Reliability of EFA depends on reliability of low flow assessment. Low flow regional regression models represent a relationship between low stream flow statistics and watershed characteristics. The watershed characteristics are used to describe the various processes that influence streamflow during low flow events. These processes need to be quantified in a way so as to be effectively represented within a regional regression model.

Several hydroelectric schemes on river Satluj and its tributaries are in different stages of implementation. In most of these schemes, river water is diverted for power generation and returned to the river at a downstream location depriving the river of its natural flow in specific reaches. Bhakra, Kol and Suni dams are storage type hydro power schemes. Even if the individual schemes may not be to significantly detrimental the physical and biotic environment, the combined effect of these schemes could be significant on a basin scale. Therefore it is necessary to assess the impact of each scheme. In this context, Nathpa-Jhakri hydro electric project has been selected for the case study.

STUDY AREA

For the purpose of this research work, the study area consists of the Satluj river reaches and interim catchments related with the Nathpa Jhakri Hydroelectric Project (NJHEP) and Rampur Hydroelectric Project (RHEP) as shown in Figure 1. The study reach is part of middle Himalayas also known as lesser Himalayas. It lies between outer Himalayas and the perpetual snow covered ranges of greater Himalayas.

The NJHEP is in operation stage and the diverted water (at Nathpa dam) is released back into Satluj after power generation at Jhakri. RHEP is under construction. The RHEP will make use of the water released in the tail race pool after power generation at Jhakri. Thus, RHEP will cause reduction in Satluj river flow downstream of Jhakri and up to Bael where the water will be released back into Satluj after power generation. The combined effect of NJHEP and RHEP is that the Satluj river will be deprived of the natural flows to the extent of 405 cumec in the reach from Nathpa to Jhakri (34 km) and then from Jhakri to Bael (23 km). Brief details of these projects are given below:

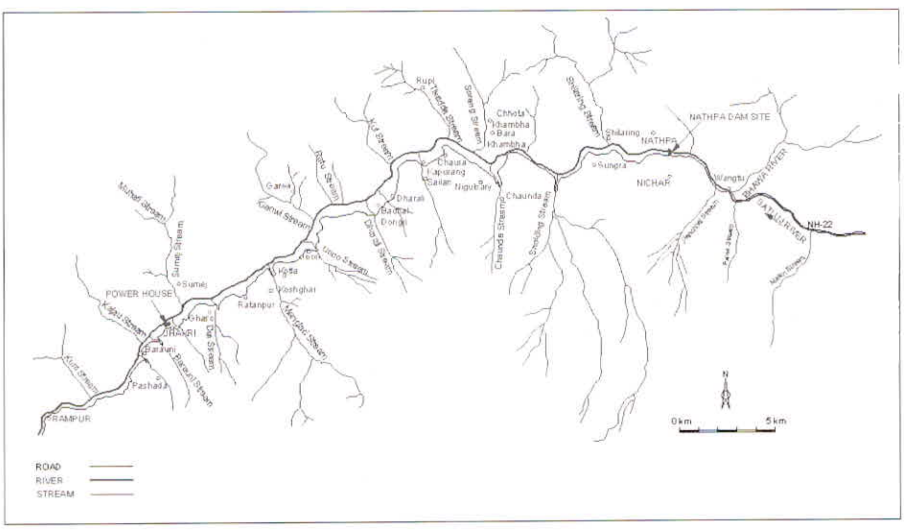

Fig. 1. The study area showing tributaries of Satluj River

Nathpa Jhakri hydroelectric project

The 1500 MW Nathpa Jhakri Hydroelectric Project (NJHEP) is a run-of the river project on the river Satluj with a dam near village Nathpa in district Kinnaur and an underground power house near village Jhakri in district Shimla. The project area is on Hindustan Tibet road NH-22 approximately 150 km from Shimla.

About 405 cumecs of water is required to harness the installed capacity of the project. During monsoon season, the flow of the river varies from 700 to 2500 cumecs, and from 100 to 150 cumecs during the lean months. In the lean period, the entire water in the river at Nathpa is required for power generation. In between Nathpa and Jhakri there are several small streams locally known as streams. Flow of Sholding stream is also diverted into head race tunnel (HRT) during lean period.

The river reach between Nathpa and Jhakri is situated in steep mountain terrain. The study area falls in three tehsils i.e. Rampur tehsil of Shimla district, Nichar tehsil of Kinnaur district and Nirmad tehsil of Kullu district. District and tehsils are administrative units. A district has 3 to 6 tehsils. In elevation, the first 100 m from the river bed is predominantly rocky and do not support much of the vegetation. There is great variation of altitude with rugged terrains and hard climatic conditions in the study area.

Most of the sediment of Satluj river (almost 90%) is contributed by the upper reaches falling in Tibet. Horticulture is almost nil on right bank of Satluj river. There is more forest area on right bank compared to left bank and land holdings are also less. After Jeori, right bank has the green forests. Main face of right bank is overlain by pastures at places, but the back side has dense forests.

Rampur hydroelectric project

The Rampur project is designed to divert 383.88 cumecs of de-silted water of the Satluj from the tailrace pool of NJHEP to the Rampur Intake structure from where the water is conveyed (from left bank to the right bank) through a 484 m HRT and 43.2 m cut and cover conduit. A 10.5 m dia headrace tunnel of 15.08 km conveys the water to a surface power station near Bael. Water is then returned to the Satluj river. The project is under construction stage. On completion, the project would utilise a gross head of 138 m to generate approximately 1969.69 Gwh of design energy in a 90% dependable year. The catchment area of the Satluj upto Nathpa-Jhakri is 49,800 sq. km. and upto Rampur HEP is 50,800 sq. km.

ESTIMATION OF TRIBUTARY DISCHARGES IN THE REACH

Several analysis such as Arihood and Glatfelter (1986), Vogel and Kroll (1992), Ries (1994) have considered drainage area as the important parameter in regional regression studies of low flows.

In the previous hydrological studies of Satluj basin, no attempt was made to consider differences in land use, rainfall, snow area coverage of different tributary catchments. The regional model proposed by Singh et al. (2001) also considers catchment area as the only influencing characteristic.

The proposed methodology is based on correlation between discharges of tributaries having similar catchment characteristics. Distinction has been made on the basis of (i) rainfed and snowfed catchments; (ii) periods with or without snowmelt contribution. Thus, tributaries have been grouped for correlation studies.

The Nathpa-Jhakri reach is only about 34 km in length with 866 sq. km interim catchment area. Long-term discharge data are not available for all the catchments except for Sholding and Gaanvi within Nathpa-Jhakri reach. The short-duration data for some catchments are available but not for concurrent period. However, long-term data for Bhaba and Baspa streams which are upstream of Nathpa dam. The reach can be considered to fall in one hydrometeorological region, which, by definition, covers relatively a large area (McCuen, 1989; Singh et al., 2001; Mishra and Singh, 2003; Bhunya et al., 2004; Bhunya et al., 2006).

Long-term discharge data of four tributaries (Sholding Stream, Gaanvi Stream, Bhaba Stream and Baspa river) of Satluj river upto Rampur is available. The specific discharge (discharge per unit catchment area) duration curves for Sholding Stream, Gaanvi Stream, Bhaba Stream and Baspa river are compared in Figure 2. The figure shows that the specific discharge duration curves of Sholding Stream, Gaanvi Stream, Bhaba Stream and Baspa river are quite similar and hence it may be predicted that flow duration curves of other catchments may be generated using these curves. Hence, discharge data of these tributaries can be used for the estimation of discharges of other tributaries on catchment area basis. Further, tributaries in the study area are divided into three types:

(i) Left bank tributaries having snow melt contribution
(ii) Right bank tributaries having snow melt contribution
(iii) Tributaries having no snow melt contribution

Discharge per unit catchment area of Sholding and Gaanvi Streams and Sailan can be used to represent the discharge per unit area for other sub-catchments in the Nathpa-Jhakri reach. Based on the snow-melt contribution, the analysis is partitioned into two components, viz., December-February and before December and after February, as follows:

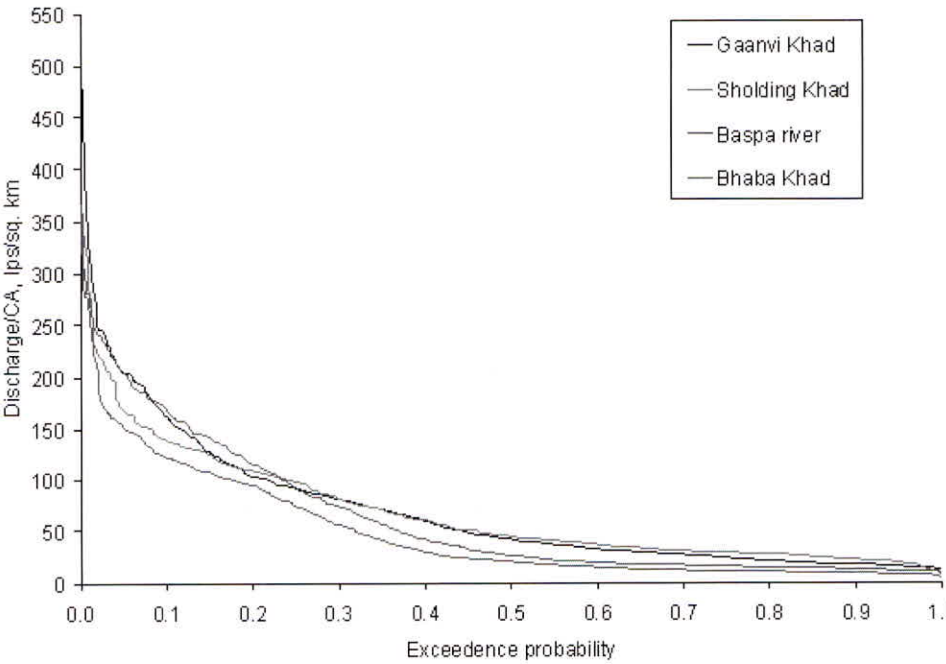

Fig. 2. Specific discharge duration curves for Sholding Stream, Gaaanvi Stream, Bhaba Stream and Baspa River

December-February

During this period, snow melt contribution can be taken to be negligible being it is the period of snowfall at sub-zero temperature. Thus, the rainfall-generated discharge per unit catchment area of Sholding and Gaanvi Streams holds for derivation of discharges occurring in the left and right bank tributaries, respectively.

October-November & March-June

During this period, since the snow-melt contribution is significant, the catchments were divided into two categories, (i) with negligible snow cover area and (ii) with significant snow cover area. For the first type of catchments, discharges were derived using discharge per unit catchment area of Sailan Stream, and for the second type, these were derived using those of Sholding and Gaanvi Streams, respectively, for left and right bank tributaries. The discharges of Sailan stream for the corresponding dry, normal and wet years are taken as derived discharges given in Detailed Project Report of Sailan Small Hydro Power Project.

Satluj River Flow d/s of Nathpa and Sholding Confluence

The average monthly flows of Satluj at Nathpa and Sholding Stream for the period 1970-1996 were used for estimation of time series downstream of Nathpa and Sholding Stream confluence during pre-project and post-project conditions. The discharges of other tributaries meeting Satluj between Nathpa and Sholding Stream confluence were worked out on discharge per unit catchment basis taking Sholding flows as reference. In the estimation, it was considered that if Satluj had discharges more than the tunnel capacity, no water was diverted from Sholding Stream into the tunnel and also that certain minimum flow is being released downstream of Nathpa dam. The Figure 3 depicts the line diagram showing all the terms used in this estimation. The procedure used is as follows:

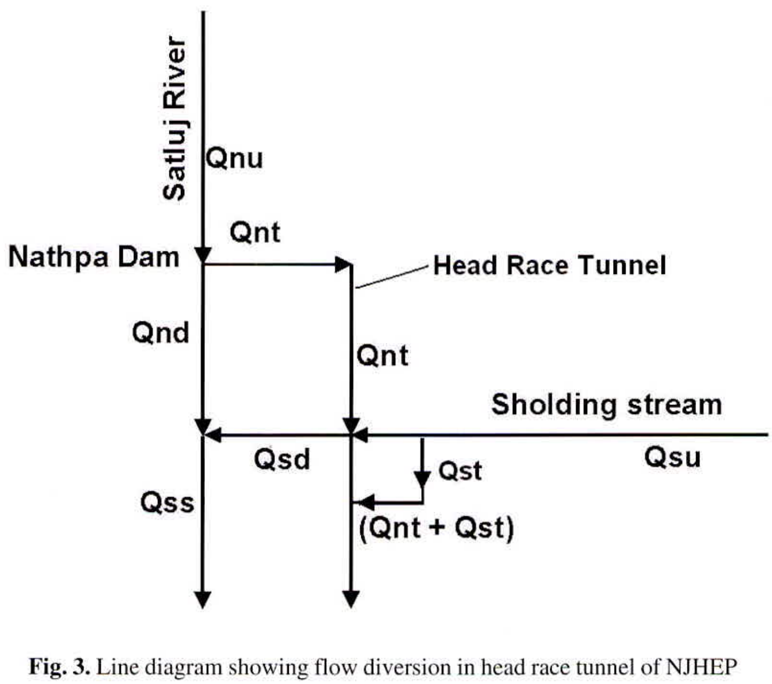

Fig. 3. Line diagram showing flow diversion in head race tunnel of NJHEP

Qnu = Discharge of Satluj river upstream of Nathpa
Qnd = Discharge of Satluj river downstream of Nathpa
Qndm = Minimum required release downstream of Nathpa
Qnt = Discharge of Satluj river going into tunnel
Qsu = Discharge of Sholding Stream upstream of tunnel intake
Qsd = Discharge of Sholding Stream downstream of tunnel intake
Qst = Discharge of Sholding Stream going into tunnel
Qss = Discharge of Satluj river downstream of Sholding confluence

Condition I:

If Qnu > 405 cumec + Qndm,
Qnt = 405 cumec
Qnd = Qnu – 405
Qst = 0
Qsd = Qsu

Condition II:

If Qnu d" 405 cumec + Qndm,
Qnd = Qndm
Qnt = Qnu – Qndm
Qst = lower of (405 – Qnt) and Qsu
Qsd = Qsu – Qst
Qss = Qnd + Qsd + Intermittent tributary discharge

Minimum required release d/s of Nathpa (Qndm) has been taken as 7 cumec based on environmental flow study.

RIVER MAPPING

Mapping of a river reach can be defined as determination of river discharges at different locations in the river reach. This involves: (i) delineation of tributary catchments; (ii) estimation of catchment areas of tributaries and location of confluence with the river and (iii) estimation of tributary discharges. Delineation of catchments, chainage of catchment outlets from Nathpa dam and catchment area have been worked out by ERDAS and ArcGIS using four scanned toposheets covering the study reach.

The river mapping has been done for the wet, dry and normal years by using long-term data. For this purpose Satluj river flow series from 1970 to 2001 was considered and years, in which total annual runoff corresponding to 90%, 50% and 10% exceedance probability occurred, were taken as dry, normal and wet years respectively. Thus, 1993, 1987 and 1983 were found out to be dry, normal and wet years respectively.

Subsequently, discharges of each catchment were computed and cumulated at different chainages. Discharges thus obtained at confluence of various tributaries wet year, normal year, dry year and the observed discharge data have been used to prepare Figure 4 to Figure 6. Relative increase during dry year, wet year, normal year and the year 2005-06 are compared for each of the lean season month separately. Thus, Figures 4 to 6 show Satluj river flow along its course during the month of December, January and February respectively in dry, wet, normal years and in year 2005-06.

The figures show that contributions to lean season flow of Satluj river are mainly from Shilaring stream, Sorang stream, Kut stream, Gaanvi stream, Manglad stream and Sumej stream. The tributary contributions to Satluj river flow start decreasing after monsoon season continuing from October to January and start increasing due to snow melt. There is not much difference in January flows during dry, wet and normal years. Flow contribution from October upto January is mainly from ground water which gets nearly depleted by end of January. Beyond January, flow contribution is mainly from snow melt and winter rain.

Satluj river reach from Nathpa and before confluence of Sorang Stream (about 10.8 km) is a critical reach in the context of environmental flow. Within this reach, contribution is mainly from

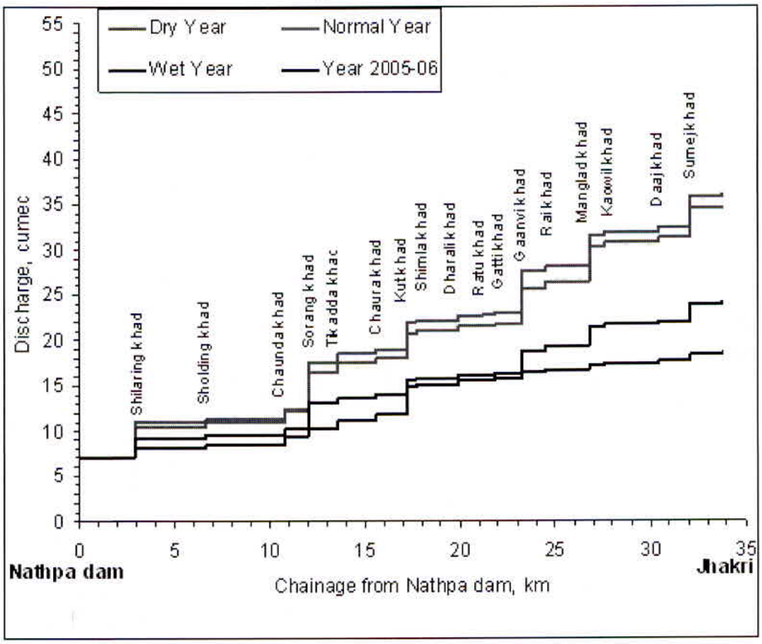

Fig. 4. Discharges of Satluj River at confluence of tributaries for the month of December

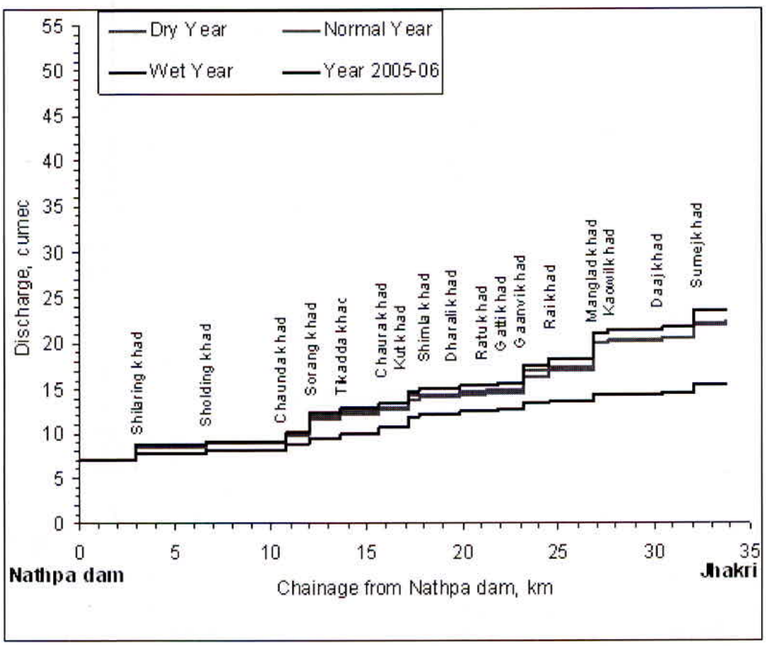

Fig. 5. Discharges of Satluj River at confluence of tributaries for the month of January

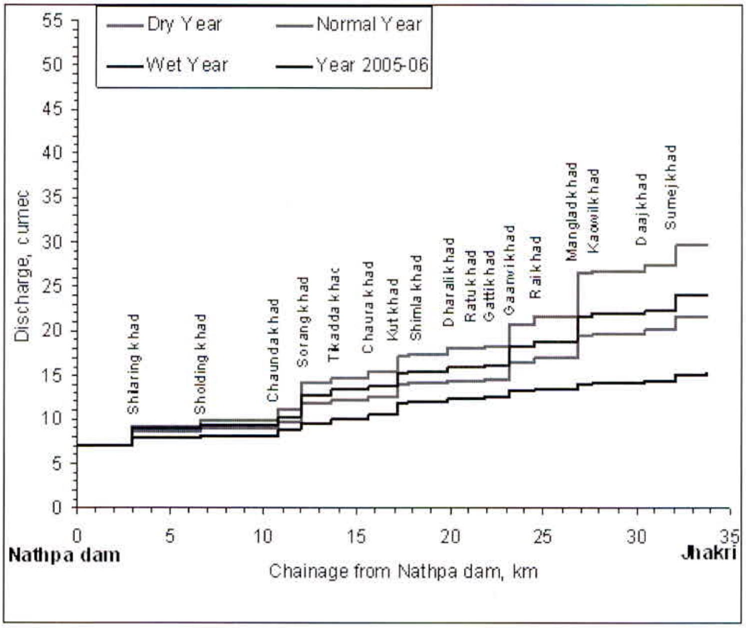

Fig. 6. Discharges of Satluj River at confluence of tributaries for the month of February

Shilaring and Chaunda streams. Flow in this reach is leanest in January, February months and similar in dry, wet, normal years and the year of monitored flow data i.e. 2005-06.

RESULTS AND DISCUSSION

Low Flow Characterisation of Satluj River for Pre and Post Project Conditions

Low flow regime of a river can be analysed in a variety of ways dependent on the type of data initially available and the type of output information required. Consequently there exist a variety of low flow measures and indices. The term 'low flow measure' used here, refers to the different methods that have been developed for analysing, often in graphical form, the low flow regime of a river. The term 'low flow index' is used predominantly to define particular values obtained from any low flow measure.

Flow duration curve

A flow duration curve (FDC) is one of the most informative methods of displaying the complete range of river discharges from low flows to flood events. It is a relationship between any given discharge value and the percentage of time that this discharge is equalled or exceeded, or in other words, the relationship between magnitude and frequency of stream flows discharges.

The flow for the construction of FDC may be expressed in actual flow units, as percentage/ratio of MAR, MDF or some other index flow, or divided by the catchment area. Such normalisation facilitates the comparison between different catchments, since the differences in FDCs caused by the differences in catchment area or MAR. Consequently, the effects of other factors on the shape of FDCs (aridity, geology and anthropogenic factors) may be inspected. Here, the flows are divided by catchment area for the comparison.

FDC may be constructed using different time resolutions of stream flow data: annual, monthly, m-day or daily. In the present case, ten daily flows are available, hence these are used for the derivation of FDC.

A FDC is constructed by reassembling the flow time series values in decreasing order of magnitude.

m = order of event
N = total number of events
Probability, P = m/(N+1)

The flow duration curves for Satluj river (d/s of Nathpa and Sholding confluence) during pre-project and post-project conditions of NJHEP and at Rampur during pre-project and post-project conditions of RHEP are shown in Figures 7 and 8.

Low flow domain

The arbitrary 'upper bound' to low flow hydrology may be given by the Mean Annual Runoff (MAR), which is a mean value of the available flow time series of annual flow totals. Dividing MAR by the number of seconds in a year gives the long-term Mean Daily Flow (MDF).

The lowest recorded ten daily discharge may be referred to as Absolute Minimum Flow (AMF). The information content of this index varies with the length of record and depends upon the measuring limits of streamflow gauges. The values of low flow indices for the tributary catchments and for Satluj river during pre and post-project conditions of NJHEP and RHEP are given in Tables 1 to 3, respectively,

Q20 = discharge corresponding to 20% exceedance probability
Q50 = discharge corresponding to 50% exceedance probability
Q90 = discharge corresponding to 90% exceedance probability
Q20/Q90 = measure of stream flow variability
Q50/Q90 = measure of variability of low flow discharge
Q90/Q50 = index representing proportion of flow originating from ground water storage

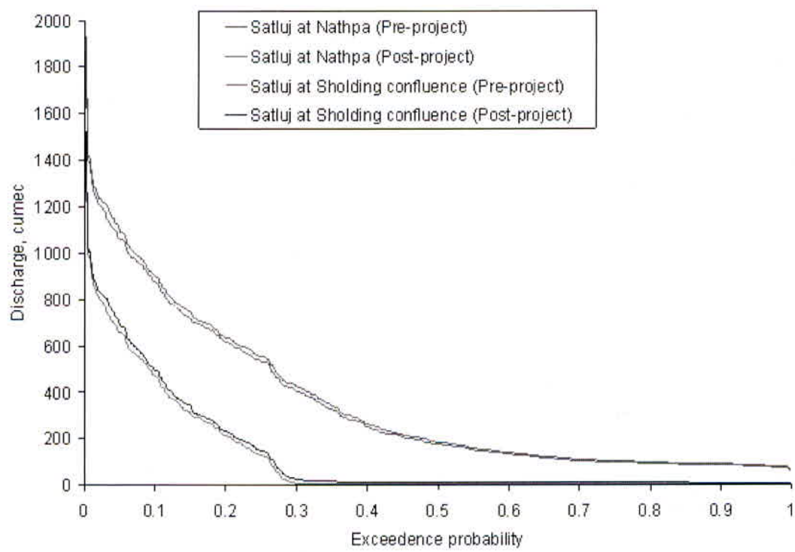

Fig. 7. Flow duration curves for Satluj River (d/s of Nathpa and Sholding confluence during pre and post-NJHEP conditions)

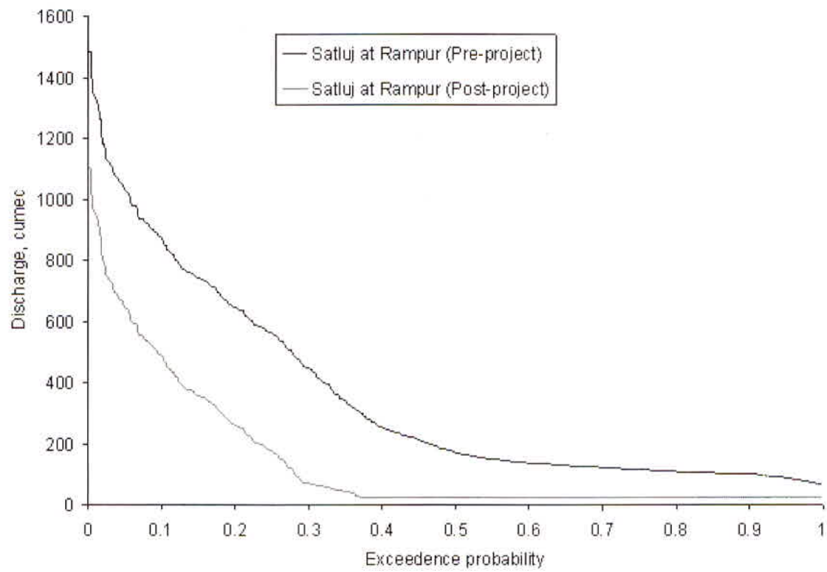

Fig. 8. Flow duration curves for Satluj River (at Rampur) during pre and post-RHEP conditions

Low flow frequency analysis

A low flow frequency curve (LFFC) shows the proportion of years when a flow is exceeded or equivalently the average interval in years (return period or recurrence interval) that the river falls below a given discharge. LFFC is constructed on the basis of a series of annual flow minima (daily or monthly minimum discharges or flow volumes), which are extracted from the available original continuous series (one value from every year of record. Some of the indices obtained from LFFC are as follows.

Table 1 shows that variability of low flow discharges (Q50/Q90) is almost same for Gaanvi, Sholding, Baspa and Bhaba streams placing confidence in consistency and reliability of data. Q20/Q90 is a measure of stream flow variability. Flows of Bhaba and Baspa are highly variable. Values of Q20/Q90 parameter for Bhaba and Baspa are significantly higher than (almost twice of) the values for Sholding and Gaanvi. The ratio Q90/ Q50 is interpreted as an index representing proportion of stream flow originating from ground water storage excluding the effects of catchment area. Secondly, the values of Q50/Q90 or Q90/Q50 of those catchments lying on a particular side of the Sutluj river are quite close to each other, indicating a similar hydrologic character. For example, Gaanvi and Bhaba catchments which are on the right side indicate Q90/Q50 values as 0.49 and 0.48, respectively. Similarly, Sholding and Baspa catchments which are on the left side indicate values as 0.41 and 0.44, respectively. Significant difference between the values for right and left catchments indicate different normalized baseflow contributions from these catchments and it might be attributed to the amount of precipitation varying with the location of these catchments, whether in forward or leeward zones (Singh and Singh, 2001).

Tables 2 and 3 show that changes in Q20/Q90 from pre to post project conditions are more prominent for NJHEP than for RHEP. It is also noted that flow

Table 1. Low flow indices of Sholding stream, Gaaanvi stream, Bhaba stream and Baspa River

Indices	Sholding Stream	Gaanvi Stream	Bhaba Stream	Baspa river
MAR, MCM	244.19	181.69	547.35	1450.68
MDF, m^3/s	7.74	5.76	17.36	46.00
AMF, m^3/s	1.21	0.67	2.06	3.70
Q20/Q90	5.95	4.98	9.05	10.51
Q50/Q90	2.42	2.05	2.07	2.26
Q90/Q50	0.41	0.49	0.48	0.44
MAM10	1.72	1.77	3.35	8.04
10Q2	1.69	1.80	3.66	8.23
10Q10	2.11	2.42	3.96	11.00

Table 2. Low flow indices of Satluj River at Nathpa and at Sholding confluence during pre and post-NJHEP conditions

Indices	Satluj d/s of Nathpa		Satluj d/s of Sholding confluence	
	Pre-project	Post-project	Pre-project	Post-project
MAR, MCM	10800.00	3740.00	11300.00	4080.00
MDF, m^3/s	343.88	118.68	357.07	129.38
AMF, m^3/s	62.00	7.00	67.31	7.99
Q20/Q90	18.395	165.077	17.795	128.151
Q50/Q90	2.058	1.000	2.024	1.263
Q90/Q50	0.486	1.000	0.494	0.792
MAM10	80.14	7.00	85.22	9.42
10Q2	83.50	7.00	88.15	9.44
10Q10	91.33	7.00	96.86	10.24

Table 3. Low flow indices of Satluj River at Rampur during pre and post-RHEP conditions

Indices	Pre-project	Post-project
MAR, MCM	11074.40	4438.87
MDF, m^3/s	349.23	139.69
AMF, m^3/s	65	25
Q20/Q90	6.46	10.48
Q50/Q90	1.70	1.08
Q90/Q50	0.59	0.93
MAM10	88.84	25
10Q2	105	25
10Q10	93.5	25

variability decreases towards downstream of Nathpa dam. The ratio Q90/Q50 represents proportion of stream flow originating from ground water storage. Increase in this value shows that proportion of ground water contribution to flow have increased after project implementation. This is due to the fact that main contribution to flow during lean season is from tributary catchments.

MAM10: The average of annual series of minimum 10-day average flows is known as Dry Weather Flow or Mean Annual 10-day Minimum Flow (MAM10).

10Q10 = 10-day minimum flow corresponding to 10 year return period
10Q2 = 10-day minimum flow corresponding to 2 year return period

CONCLUSIONS

The SDDCs of Gaanvi and Sholding are almost same particularly in the low flow range. Therefore, these SDDCs are considered as representative of SDDC for other tributaries between Nathpa and Jhakri. The ratio Q90/Q50 is interpreted as an index representing proportion of stream flow originating from ground water storage excluding the effects of catchment area. The values of Q90/Q50 of catchments lying on a particular side of the Satluj river are found to be close to each other, indicating a similar hydrologic character.

Contributions to lean season flow of Satluj river are mainly from Shilaring stream, Sorang stream, Kut stream, Gaanvi stream, Manglad stream and Sumej stream. The tributary contributions to Satluj river flow start decreasing after monsoon season continuing from October to January and start increasing due to snow melt.

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