

SUMMER INTERNSHIP REPORT ON

DEVELOPMENT OF FLOW DURATION CURVES AND ECO-FLOW METRICS FOR THE TAWI RIVER BASIN

Minor Project Thesis

Submitted by

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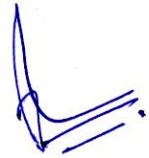
**National Institute of Hydrology (NIH)
Roorkee**

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CERTIFICATE

I hereby certify that the project work entitled “Development of Flow Duration Curves and Eco-Flow Metrics for the Tawi River Basin” carried out by Miss. Aditi Vasishtha, B.Tech. (Civil Engineering), Meerut Institute of Technology, Meerut is an authentic record of work carried out by her during June 13, 2016 to August 12, 2016 under my guidance.

We appreciate the sincerity and hard work put by Miss. Aditi Vasishtha for completing the task in two months period. I wish her success in her future endeavour.



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(Aditi Vasishtha)

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ABSTRACT

Flow Duration Curves (FDCs) are important tools, which are essential for water resource planning and management. These can condense a lot of hydrological information into a single graphic image, are often used to summarize the impacts of potential climate change scenarios on water resource systems. Results derived from the flow duration curves are needed by hydrologist and engineers involved in planning and designing of various water resources projects. And many other significant uses of this curve prevail such as evaluating the characteristics of the hydropower potential of a river, design of drainage systems, flood-control studies, computing the sediment load and dissolved solids load of a stream, and comparing the adjacent catchments with a view to extend the streamflow data. Apart from these classical uses the FDCs can also be used to assess the health of the river in terms of its ecological status. The present study has been undertaken with an objective to identify the status of ecological health of the Tawi River, based on the eco-flow metrics. The daily streamflow data at *Gulab Singh Bridge*, Jammu from the Hydrological Data Centre of the Central Water Commission (CWC), Jammu, has been used to develop the Flow Duration Curves (FDCs) for different periods like daily, monthly, annual etc. Finally, the 10-daily time series have been used to identify the ecosurplus and the ecodeficit years and their respective magnitudes. Further, an eco-flow metric for the Tawi River was prepared for the 30 years daily discharge data from the period 1977 to 2007. The study was undertaken during the two months Summer Internship program at National Institute of hydrology (NIH), Roorkee. The results of the study conclude that Tawi River is an ecosurplus river for most of the years for the study period. The results of the study confirm that the ecology of Tawi River is at par for the study period except for the years of 1999 and 2000 particularly. Although the ecology is under sustaining condition but the metric has falling due course of time, which can be a signal of ecological deterioration in the future.

Keywords: Flow Duration Curve (FDC), Ecosurplus, Ecodeficit, Eco-Flow Metric, Tawi River, River Ecology.

1. INTRODUCTION

Changes in flow regime and river discharge are commonly observed in a large number of rivers worldwide as a response to environmental changes. However, the characteristics and the attribution of such changes are not fully understood. River discharge is given the most attention among all the components of the hydrological cycles for its close relation to water resources. Moreover, river flow regimes are critical components of the ecological integrity of the river systems (*Poff et al., 1997; Hart and Finelli, 1999*). River discharge and flow regime changes are well recognized by ecologists as the primary drivers of a number of fundamental ecological processes in riverine ecosystems (*Poff and Zimmerman, 2010*). Understanding the characteristics of changes in river discharge and flow regime and analyzing the reasons for these changes are important for river management and river ecosystem protection.

The literature has suggested that climate change would accelerate the global water cycle, thereby resulting in an increase of extreme events (*Arnell, 1999; Trenberth et al., 2003*). As a consequence, the regional river discharges and flow regimes will be significantly altered under the changing climate. Hydrological systems have become more and more complicated as a result of human activities, such as the construction of reservoirs. Intensified human activities, including land use change, artificial water intake, and dam construction, also have directly changed the streamflow and altered the natural river flow regimes for the past few decades.

Changes in river discharges and flow regimes were examined by more and more researchers in many regions worldwide, (*Richter et al., 1996; Magilligan and Nislow, 2005; Mathews and Richter, 2007; Piao et al., 2010; Poff and Zimmerman, 2010; Sabater and Tokner, 2010; Suen, 2010; Kim et al., 2011; Zhang et al., 2011; Fernandez et al., 2012; Gao et al., 2012; Lian et al., 2012; Zhao et al., 2012*). Accordingly, researchers have developed and applied a number of statistical tools and methods to characterize the various aspects of flow regimes to assess and quantify the ecological effects from hydrologic alterations. To evaluate the ecological effect of flow regime and to support river management, indicators are needed for evaluating the ecological health of the river and degree of hydrologic alteration. To date, numerous hydrologic metrics have been published to analyze various aspects of the flow regime. These multiple hydrologic

metrics enable researchers and policy makers to investigate the multiple effects of hydrological changes on the river ecosystems. However, large numbers of metrics are sometimes too complicated to use, and many metrics are inter-correlated, resulting in statistical redundancy (*Olden and Poff, 2003*).

The most widely used metrics are the “Indicators of Hydrologic Alteration” (IHA), developed by the Nature Conservancy in the United States (*Richter et al., 1996*), which includes the Range of Variability (RVA) method to evaluate changes of the river flow regime (*Richter et al., 1998*). Flow Duration Curves (FDCs), which can condense a wealth of hydrological information into a single graphic image, are often used to summarize the impacts of potential climate change scenarios on water resource systems (*Vogel and Fennessey, 1995*). Flow Duration Curves have been in general use since about 1915; their theory has been discussed by Foster and others.

The concept of eco-flow statistics, proposed by *Vogel et al. (2007)* is another way to represent generalized index of hydrologic alterations of streamflow time series. *Gao et al., (2009)* developed a few statistics to capture the key components of ecologically relevant flow variations using an eco-flow metrics (ecosurplus and ecodeficit) calculated from FDCs. Eco statistics is a good method for understanding the flow change at different flow frequencies. The eco-statistics method allows for the use of the period flow record and for median flows. It is suggested that median flows be used to avoid the impact from extreme events.

Based on the previous studies, the present study is an attempt to understand and analyze the basic concept of FDCs and the changes in the eco-flow metrics of respective water bodies, as they provide a convenient means for studying the flow characteristics of streams and for comparing one basin with another and for various other such significant purposes. This study has been undertaken under the two months Summer Internship program at National Institute of hydrology (NIH), Roorkee with the following objectives:

- To develop the flow duration curves for the flow regimes in the Tawi River basin using the available data for the period of 1977 to 2007.
- To identify the 25th and 75th dependable years.
- To examine and quantify flow regime changes in the Tawi River basin using the eco-flow metrics (ecosurplus and ecodeficit).

2. REVIEW OF LITERATURE

For various significant purposes such as planning of water resources engineering projects, evaluating the hydro power potential of any river and designing of drainage systems and, to know the different essentials of these studies a detailed analysis of the Flow Duration Curve (FDC) and the change in the Eco-Flow Metrics of the respective water bodies is proven to be very helpful. Comprehensive attempts have been made by many for the assessment of FDC and the change in the Eco-Flow metrics of different streams. Some major contributing studies are delineated infra:

1. **Subramanya (2013)** defined the flow duration curve (FDC), as a cumulative frequency curve representing the percent of time during which the average discharge (flow rate) equaled or exceeded a particular value at a given location. The curve is also called Discharge-Frequency Curve. The FDC may be created based on daily, weekly or monthly values of discharge. The discharge data are usually plotted on a logarithmic scale as on arithmetic, semi-log, log-log paper depending upon data range and use of data or as percentages of total discharge. If N number of data points are used in this listing, the *Weibull (1986)* plotting of any discharge (or class value) Q is

$$P_p = \frac{m}{(N+1)} \times 100 \% \quad \dots(1)$$

Where, P_p = Percentage probability

m = Order number of the discharge

The plot of discharge Q against P_p is the Flow Duration Curve which represents the cumulative frequency distribution and can be considered to represent the streamflow variation of an average year. The ordinate Q_p at any percentage probability P_p represents the flow magnitude in an average year that can be expected to be equaled or exceeded P_p per cent of time and is termed as P_p % dependable flow. In a perennial river $Q_{100} = 100\%$ dependable flow is a finite value. On the other hand in an intermittent or ephemeral river the streamflow is zero for a finite part of a year and as such Q_{100} is equal to zero.

2. **Gao et al. (2012)** attempted towards working on detailed analysis of Flow Regime Changes in the Upper Yangtze River using the eco-flow metrics (ecosurplus and ecodeficit) and the “*Indicators of Hydrologic Alteration*” (IHA) parameters. Results showed that annual streamflow decreased in the period from 1961 to 2008. Autumn

streamflow evidently decreased after the 1980s, which resulted from the decrease in precipitation and water storing by reservoirs. Summer flow decreased after the 1980s which was also primarily attributed to the decrease in precipitation. Winter streamflow increased in the two most recent decades, which resulted from the reservoir release. Results of the study showed that the Three Gorges Reservoir (TGR) elevated low flow in the dry season and reduced peak flow in the summer since 2003. The decrease in the autumn precipitation since 1990s, suggests that TGR is facing a serious challenge in maintaining water storage in the reservoir and releasing the water to the downstream ecosystem. Therefore, to mitigate the negative effects on the river ecosystem in the downstream and to maintain its water storage capacity, TGR should start storing water earlier than its designed schedule to meet the requirements for both power generation and ecosystem protection. A comparison between the eco-flow metrics and the IHA metrics demonstrated that combination of two groups of metrics provided a sufficient measure of the changes in the flow regime.

3. The change trends and change points of flow at three main gauging stations in the Dongjiang River were analyzed by *Kairong et al (2014)* using the nonparametric Mann-Kendall test and Pettitt-Mann-Whitney change-point statistics. Flow regime changes in the Dongjiang River were quantified by using both the *Indicators of Hydrologic Alteration (IHA)* parameters and eco-statistics, such as ecosurplus and ecodeficit. It was found that the change trend for annual median flow in the Dongjiang River increased over the past 60 years, with the major change occurring sometime between 1970 and 1974. IHA analyses showed that the magnitude of monthly flow decreased during the flood period, but increased greatly during the dry period. The median date of the one-day minimum flow moved ahead, and the duration of low pulse for the Dongjiang River was reduced significantly because of reservoir construction and operations. The IHA-based Dundee Hydrological Regime Alteration Method analysis indicated that all three stations have experienced a moderate risk of impact since 1974. The eco-statistical analyses showed that the majority of the flows appeared to be ecosurplus at all three locations after 1974, while flows with less than 30%, or higher exceedance probability, had ecodeficit in the summer flood period due to heavy reservoir operations.
4. The hydrologic effect of replacing pasture or other short crops with trees was studied by *Lane et al. (2005)*. A method to assess the impact of plantation establishment on

FDCs was developed. The starting point for the analyses was the assumption that rainfall and vegetation age are the principal drivers of evapotranspiration. A key objective was to remove the variability in the rainfall signal, leaving changes in the streamflow solely attributable to the evapotranspiration of the plantation. A method was developed to:

- i.) Fit a model to the observed annual series of FDC percentiles; i.e. 10th percentile for each year of record with annual rainfall and plantation age as parameters,
- ii.) Replace the annual rainfall variation with the long term mean to obtain climate adjusted FDCs, and
- iii.) Quantify changes in FDCs percentile as plantations age.

Data from 10 catchments from Australia, South Africa and New Zealand were used. The model was able to represent flow variation for the majority of percentiles at eight of the 10 catchments, particularly for the 10-50th percentiles. The adjusted FDCs revealed variable patterns in flow reductions with two types of responses (groups) being identified. Group 1 catchments show a substantial increase in the number of zero flow days, with low flows being more affected than high flows. Group 2 catchment show a more uniform reduction in flows across all percentiles. The differences may be partly explained by storage characteristics. The modeled flow reductions were in accord with published results of paired catchment experiments. An additional analysis was performed to characterize the impact of afforestation on the number of zero flow days (N_{zero}) for the catchments in group 1. This method performed particularly well, and when adjusted for climate, indicated a significant increase in N_{zero} . The zero flow day method could be used to determine change in the occurrence of any given flow in response to afforestation. The methods used in this study proved satisfactory in removing the rainfall variability, and have added useful insight into the hydrologic impacts of plantation establishment. This approach provides a methodology for understanding catchment response to afforestation, where paired catchment data is not available.

5. The construction of Flow Duration Curves is a fundamental task for several activities related to water resources management. The scarcity of observed streamflow data is a diffuse problem in the real world, and Flow Duration Curves often need to be constructed for ungauged basins. We address this problem by regionalizing the

stochastic index-flow model of Flow Duration Curves proposed by *Castellarin et al (2007)*. The index-flow model differ from any other stochastic model of Flow Duration Curves proposed in the literature because it can be used for deriving long-term as well as annual Flow Duration Curves. The former are constructed on the basis of several years of streamflow data, whereas the latter refer to a given water or calendar year (a typical hydrologic year or a particularly wet or dry year). We apply an extensive cross-validation procedure to quantify the uncertainty of the proposed regional model and to compare it with the uncertainty of traditional regional models of Flow Duration Curves proposed in the literature. The results of the study indicate that the regional index-flow model is as reliable as or more reliable than traditional regional models for estimating long-term Flow Duration Curves. Also, the proposed model is more versatile than previous regional models for estimating long-term and annual Flow Duration Curves and for reproducing the variance of annual Flow Duration Curves.

6. The study executed by *Sauquet et al (2011)* aims at estimating Flow Duration Curves (FDC) at ungauged sites in France and quantifying the associated uncertainties using a large dataset of 1080 FDCs. The interpolation procedure focuses here on 15 percentiles standardized by the mean annual flow, which is assumed to be known at each site. In particular, this paper discusses the impact of different catchment grouping procedures on the estimation of percentiles by regional regression models. In the first step, five parsimonious FDC parametric models are tested to approximate FDCs at gauged sites. The results show that the model based on the expansion of Empirical Orthogonal Functions (EOF) outperforms the other tested models. In the EOF model, each FDC is interpreted as a linear combination of regional amplitude functions with spatially variable weighting factors corresponding to the parameters of the model. In this approach, only one amplitude function is required to obtain a satisfactory fit with most of the observed curves. Thus, the considered model requires only two parameters to be applicable at ungauged locations. Secondly, homogeneous regions are derived according to hydrological response, on the one hand, and geological, climatic and topographic characteristics on the other hand. Hydrological similarity is assessed through two simple indicators: the Concavity Index (IC) representing the shape of the dimensionless FDC and the Seasonality Ratio (SR),

which is the ratio of summer and winter median flows. These variables are used as homogeneity criteria in three different methods for grouping catchments:

- i.) According to an a priori classification of French Hydro-Eco Regions (HERs),
- ii.) By applying regression tree clustering and
- iii.) By using neighborhoods obtained by canonical correlation analysis.

Finally, considering all the data, and subsequently for each group obtained through the tested grouping techniques, we derive regression models between physiographic and/or climatic variables and the two parameters of the EOF model. Results on percentile estimation in cross validation show that a significant benefit is obtained by defining homogeneous regions before developing regressions, particularly when grouping methods make use of hydro geological information.

7. Predictions of hydrological responses in ungauged catchments can benefit from a classification scheme that can organize and pool together catchments that exhibit a level of hydrologic similarity, especially similarity in some key variable or signature of interest. Since catchments are complex systems with a level of self-organization arising from co-evolution of climate and landscape properties, including vegetation, there is much to be gained from developing a classification system based on a comparative study of a population of catchments across climatic and landscape gradients. The study conducted by *Coopersmith et al. (2012)* on climate seasonality and seasonal runoff regime, as characterized by the ensemble mean of within-year variation of climate and runoff. The work on regime behavior is part of an overall study of the physical controls on regional patterns of Flow Duration Curves (FDCs), motivated by the fact that regime behavior leaves a major imprint upon the shape of FDCs, especially the slope of the FDCs. As an exercise in comparative hydrology, the paper seeks to assess the regime behavior of 428 catchments from the MOPEX database simultaneously, classifying and regionalizing them into homogeneous or hydrologically similar groups. A decision tree is developed on the basis of a metric chosen to characterize similarity of regime behavior, using a variant of the Iterative Dichotomiser 3 (ID3) algorithm to form a classification tree and associated catchment classes. In this way, several classes of catchments are distinguished, in which the connection between the five catchments' regime behavior and climate and catchment properties becomes clearer. Only four similarity indices are entered into the algorithm, all of which are obtained from smoothed daily regime curves of climatic

variables and runoff. Results demonstrate that climate seasonality plays the most significant role in the classification of US catchments, with rainfall timing and climatic aridity index playing somewhat secondary roles in the organization of the catchments. In spite of the tremendous heterogeneity of climate, topography, and runoff behavior across the continental United States, 331 of the 428 catchments studied are seen to fall into only six dominant classes.

8. Flow Duration Curves (FDCs) display streamflow values against their relative exceedance time. They provide critical information for watershed management by representing the variation in the availability and reliability of surface water to supply ecosystem services and satisfy anthropogenic needs. FDCs are particularly revealing in seasonally dry climates, where surface water supplies are highly variable. While useful, the empirical computation of FDCs is data intensive and challenging in sparsely gauged regions, meaning that there is a need for robust, predictive models to evaluate FDCs with simple parameterization. A process-based analytical expression for FDCs in seasonally dry climates was derived by *Muller et al. (2014)*. During the wet season, streamflow is modeled as a stochastic variable driven by rainfall, following the stochastic analytical model of *Botter et al. (2007)*. During the dry season, streamflow is modeled as a deterministic recession with a stochastic initial condition that accounts for the carryover of catchment storage across seasons. The resulting FDC model is applied to 38 catchments in Nepal, coastal California, and Western Australia, where FDCs are successfully modeled using five physically meaningful parameters with minimal calibration. A Monte Carlo analysis revealed that the model is robust to deviations from its assumptions of Poissonian rainfall, exponentially distributed response times and constant seasonal timing. The approach successfully models period-of-record FDCs and allows inter-annual and intra-annual sources of variations in dry season streamflow to be separated. The resulting median annual FDCs and confidence intervals allow the simulation of the consequences of inter-annual flow variations for infrastructure projects. They had presented an example using run-of-river hydropower in Nepal as a case study.
9. Flow Duration Curves (FDCs) are a useful tool for characterizing hydrological regimes and flow variability. FDCs observed at 379 gauging stations located across New Zealand were analyzed by *Booker et al. (2012)* with the aim of investigate how parameterization and generalization combine to influence the accuracy of empirically

predicted FDCs at ungauged sites. The appropriateness of four strategies for estimating FDCs was compared:

- (a) Parameterize then generalize;
- (b) Parameterize then regionalize then generalize;
- (c) Parameterize and generalize together; and
- (d) FDC substitution.

These strategies were deployed using various combinations of methods for calculating parameters that describe the shape of FDCs (polynomial expressions and probability distribution functions) and then methods for estimating these parameters at ungauged sites using available catchment characteristics (stepwise linear regression and random forests). A parameterize and generalize together strategy was devised by applying a mixed-effects approach. A jack-knife cross-validation procedure was used to provide an independent test of each method for estimating the FDC at ungauged sites. For parameterize then regionalize strategies, it was found that the combination of parameterization method and generalization method together, rather than either in isolation, was important in determining overall performance. Results indicated that predictive capability varied between methods and across exceedance percentiles. The mixed-effects approach provided the most parsimonious method for estimating FDC at ungauged sites. A method using the generalized extreme value probability distribution that was generalized using random forests was the most accurate method of estimating flow duration curves at ungauged sites across New Zealand.

10. Paired catchment studies have been widely used as a means of determining the magnitude of water yield changes resulting from changes in vegetation. This review pursued by *Brown et al. (2005)* focuses on the use of paired catchment studies for determining the changes in water yield at various time scales resulting from permanent changes in vegetation. The review considers long term annual changes, adjustment time scales, the seasonal pattern of flows and changes in both annual and seasonal flow duration curves. The paired catchment studies reported in the literature have been divided into four broad categories: afforestation experiments, deforestation experiments, regrowth experiments and forest conversion experiments. Comparisons between paired catchment results and a mean annual water balance model are presented and show good agreement between the two methodologies. The results

highlight the potential underestimation of water yield changes if regrowth experiments are used to predict the likely impact of permanent alterations to a catchment's vegetation. An analysis of annual water yield changes from afforestation, deforestation and regrowth experiments demonstrates that the time taken to reach a new equilibrium under permanent land use change varies considerably. Deforestation experiments reach a new equilibrium more quickly than afforestation experiments. The review of papers reporting seasonal changes in water yield highlights the proportionally larger impact on low flows. Flow duration curve comparison provides a potential means of gaining a greater understanding of the impact of vegetation on the distribution of daily flows.

3. STUDY AREA

3.1 General Topography

The Tawi River basin is a small part of Western Himalayan and is contained in between 32° - 35° to 33° - 35° North Latitude & 75° - 45° to 75° - 45° East Longitude. At its upper part the basin is narrow and elongated while it broadens down along lower part. The upper portion of the basin is characterized by rugged mountainous topography, whereas lower basin consists of low hills and a gradational plain. The average height of basin is about 2200 meter above mean sea level. The basin ground elevation varies from 4000 meter to 400 meter above mean sea level. The slope of basin is from east to west in the upper part, while North-East to south –West in the lower part. The river, at its upper reaches is fed by melting of snow and ice of *Kali- Kundi Glaciers* at its origin and by rain. In the lower catchment it is predominantly rain fed. A small area of about 200 square meters is snow bound. The upper part of the basin is covered by hard granite intrusive rocks and the lower part by loose and soft Siwalik rocks.

The Tawi river basin falls mostly within the districts of Jammu, Udhampur, and small portion of Doda districts. In the present study, the area of about 1885sqkm. upto Jammu has been considered.

3.2 Climate

In the Tawi Basin, July and August are generally the wettest months with about 55% rainfall and November is the least rainy month with about 2-3% of total rainfall. Tawi experience heavy flood in July & August. Monsoon starts from first July with heavy thunder showers and up to mid-September. The North-Eastern catchment area comprising of Baderwah and adjoining area have climate like extra tropical mountain type. The mountain type climate has wide variation in temperature and rainfall depending upon the location and direction of the land features. In this area winter is very severe and influence of South-West monsoon is negligible. Central territory consisting of Udhampur districts where also climate is of mountain type but having sufficient influence of monsoon. The South–Western zone consisting of Jammu district where climate is warm with strong monsoon influence, can be described as similar to tropical wet & dry climate during certain part of the year. The River Tawi is snow fed at its origin from the *Kali-*

Kundi glacier. The Kali-Kundi and Seoj-Dhar start experiencing snowfall in November. Snow is very deep and in some years continuous till May.

3.3 Water Resources

The River Tawi is endowed with vast water resources potential for irrigation, domestic water supply and power Generation. A study on assessment of water availability has been done by the *NIH regional centre (NIH Report CS-86)*. The river is of about 141 km length up to the point it enters Pakistan, from its origin at Himalayan Kali-Kundi glacier. It has nine major tributaries, carrying discharge of Tawi was 4.3 lakhs cusec in September, 1988 at Jammu and minimum discharge was about 300-400 cusecs. Low water flow is experienced during the month of October, November and December. But there is occasional rises of water level during winter due to rains and on the early summer due to snow melt from the seasonal snow cover in the upper catchment.

3.4 Soil

Comprehensive soil survey for Tawi basin has not yet been done. However the soil classification of Tawi basin exhibits zonal properties as follows:

In *Doda districts*, of which a very small portion is lying with in the basin, the soils are mainly alluvial in nature. Whereas in the midlands or foots hills, the process of colluviation seems predominant. Generally the silt or other material, brought down by the action of water gets deposited at the foot hill and give rise to soil formation. The texture, in general varies from sandy loam, sandy, to silty clay loam.

In *Udhmapur part*, the soils are moderately deep to deep on the mid hills and plateaus whereas deep to very deep at the foothills. The texture in general is coarse to medium.

Soils of district *Jammu* are alluvial subtropical having a texture varying between sandy loams to silty clay loam. The lower part is recent alluvium whereas the outer plains are Pleistocene. The foothills of Siwaliks are moderately deep to deep soils with coarse texture having stony face in general and due to lack of irrigation; these are left as uncultivated fallows.

3.5 Geology

Western Himalaya is geologically described as lying within moving belt of earth's crest. Like other parts Tawi basin mainly consists of Siwaliks, Murree and granite intrusion. Tawi basin has three *Meso geomorphic regions*:

Kaplas Granite zone: from Kaplas range to Panjal Thrust. Kaplas granite associated with Bhaderwah slate, Sewa para gneiss etc. are the main features of the area. Maximum elevation of Kaplas range is 400 m.

Thrust Zone: from Panjal thrust to Udhampur thrust having same tectonic structures like Panjal thrust. The height of this region is from 700 m to 1900 m.

Siwalik Zone: lies between Udhampur thrust and Jammu. Most of the Region consists of hilly as well as plain areas.

3.6 River Profile

From origin to outfall the long section of Tawi River exhibits wide degree of variations. The variations in Slopes along different river reaches are as follows:

R.L. 4000m–1600m = Steep gradient of 1:10:42

R.L. 1600m–900m = Slight changes in slopes

Below 800m = Slope is decreasing

However, variation is not linear. The gradient changes from very steep at upper part to concave and flat in the lower courses. The reason may be there is *degradational process* in upper stage and *aggradational process* in lower stages. Based on field investigations it has been reported that flood plains, meander, meander core and other depositional landforms are formed at the lower course of the river. There are all indicative of non regime nature of the river.

3.7 Tributaries of the River Tawi

Nine predominant tributaries of the river Tawi have been identified as follows:

Kali Kundi: About 4 kms long this tributary has a long profile, concave. Its level varies from 4000 m to 3200 m.

Pich: It is 2.0 km long and predominantly degrading in nature. Its level varies from 3600 m to 3200 m.

Magri: The stream profile indicates two breaks; first at 3200 m and second on 2600 m elevation. It is 9.5 km long and elevation varies from 3600 m to 2000 m.

Chenani: This left bank tributary flows between altitude of 1100 m to 1700 m and is 7.5 km long.

DhakNalla: The profile of this river also shows steepness varying from 900 m to 800 m. R.L. Its length is about 2.5 km.

Naddal Khud: The profile represents small breaks due to the tectonic structure of the area. Its R.L. varies from 1200 m to 700 m and is about 5.8 km long.

Calari: The profile of this Sewalik stream shows a straight line without any break. The aggradational process is predominant in the basin of Calari because of the absence of high slope. It is about 15 km long and R.L. is from 900m to 700 m.

Pharos: Its profile presents a steep gradient with high degradational processes. The 5.25 km long river course is between elevations 3600 m to 2400 m.

Gamhi: The course of river is generally straight with small breaks at places. Its length is about 19 km while elevation varies from 700 m to 400 m.

4. DATA AND METHODOLOGY

In order to achieve the study objectives, the data used and methodologies adopted in the current study have been described in subsequent sections:

4.1 Data

FDCs and eco-flow metrics assessment requires huge amount of flow data. The data used in the present study is the daily river discharge data of the Tawi River from the year 1977 to 2007. This data was collected from the *Hydrological Data Centre of the Central Water Commission in Jammu*, (website: www.cwc.nic.in). Since, the observed data for this site is not that accurate and the correctness of the data used in this study is not known. Therefore, the results given here may be considered to be indicative.

4.2 Flow Duration Curve

The Flow Duration Curve is a cumulative frequency curve that shows the percent of time during which specified discharges were equaled or exceeded in a given period. An example of flow duration curve of a river for natural and regulated Flow has been shown in the Fig. 1.

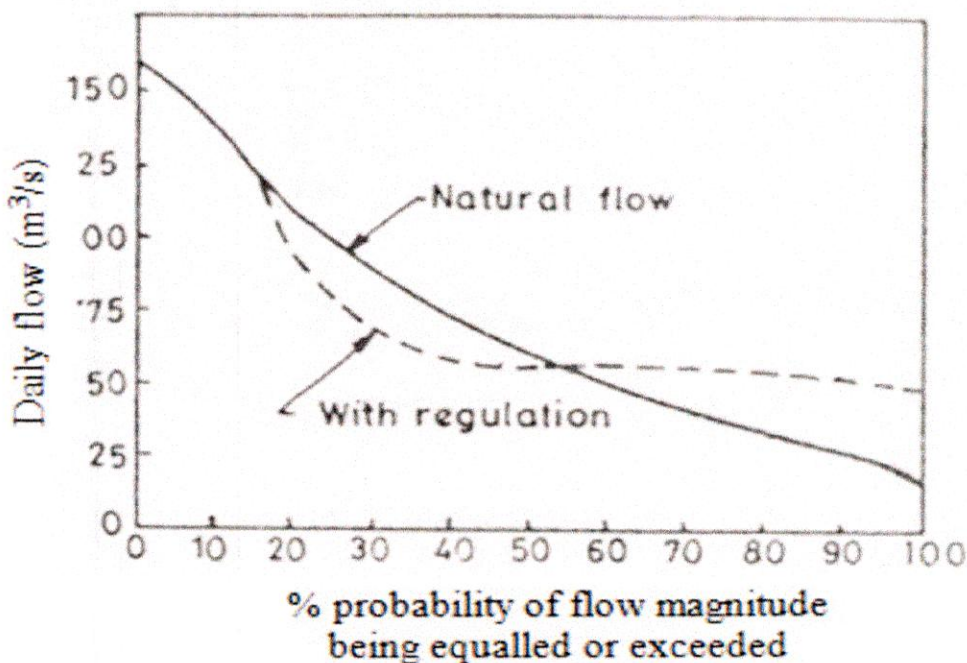


Fig. 1- Flow Duration Curve of a river for natural flow and regulated Flow

The Flow Duration Curve is the integral of the frequency diagram. Perhaps a simpler concept of the Flow Duration Curve is that it is another means of representing streamflow data combining in one curve of the flow characteristics of a stream throughout the range of discharge. Although the Flow Duration Curve does not show the chronological sequence of flows, it is useful for many studies. To prepare a Flow Duration Curve, the daily, weekly, or monthly flows during a given period are arranged according to magnitude, and the percent of time during which the flow equaled or exceeded the specified values is computed. The curve, drawn to average the plotted points of specified discharges versus the percent of time during which they are equaled or exceeded, thus represents an average for the period considered rather than the distribution of flow within a single year. Flow Duration Curves find considerable use in water-resources planning and development activities and provides a convenient means for studying the flow characteristics of streams and for comparing one basin with another.

4.3 An Idle FDC

An FDC simply plots Q as a function of its corresponding exceedance probability

$$P_p = \frac{m}{(N+1)} \times 100 \% \quad \dots (2)$$

Where, P_p = Percentage probability

m = Order number of the discharge

n = Number of data points used in the listing

The ordinate Q_p at any percentage probability P_p represents the flow magnitude in an average year that can be expected to be equaled or exceeded P_p percent of time and is termed as P_p % *dependable flow*. In a perennial river Q_{100} = 100% dependable flow is a finite value. On the other hand, in an intermittent or ephemeral river the streamflow is zero for a finite part of a year and as such Q_{100} is equal to zero.

The presence of a reservoir in a stream considerably modifies the virgin-flow duration curve depending on the nature of flow regulation. Fig. 1 clearly depicts the effects of regulation on the FDC.

4.4 Eco Flow Metrics

In the present study, recently introduced metrics viz. ecosurplus and ecodeficit were analyzed for detecting the change of the river ecology. The ecosurplus and

ecodeficit metrics are based on 25th and 75th percentile flow duration curves (FDCs). FDCs are constructed from streamflow data over a time interval of interest and provide a measure of the percentage of time duration that streamflow equals to or exceeds a given value. In the current study, annual ecosurplus and ecodeficit values were calculated using daily streamflow data.

In the current study, the annual, monthly, and daily FDCs were constructed for the available flow data (1977-2007). These FDCs were used to check the status of river ecology. Based on the 30 years of annual, monthly, and daily FDCs, the 25th percentile FDC and the 75th percentile FDC were obtained. But the obtained 25th and 75th percentile years were not that accurate and the results obtained were not so correct for the said time steps. Therefore, to get the desired 25th and 75th percentile years we opted for the *10 daily average FDC* for the current 30 years daily data.

The 25th and the 75th percentile FDCs pertaining to the 10-daily flow data were then used as the upper and the lower limits of the river ecology to justify its status. The range from the 25th to 75th percentiles could be considered the normal range for the river ecology. If the 10 daily averages FDC of a given year are located below the 25th percentile FDC, the area between the 25th percentile FDC and the 10 daily average FDC is defined as *ecodeficit*. This value represents how bad the condition of river ecology is. Conversely, if the 10 daily average FDC of a given year is located above the 75th percentile FDC, the area between the 75th percentile FDC and the 10 daily average FDC is called *ecosurplus*, which represents how good is the condition of river ecology (**Fig. 2**).

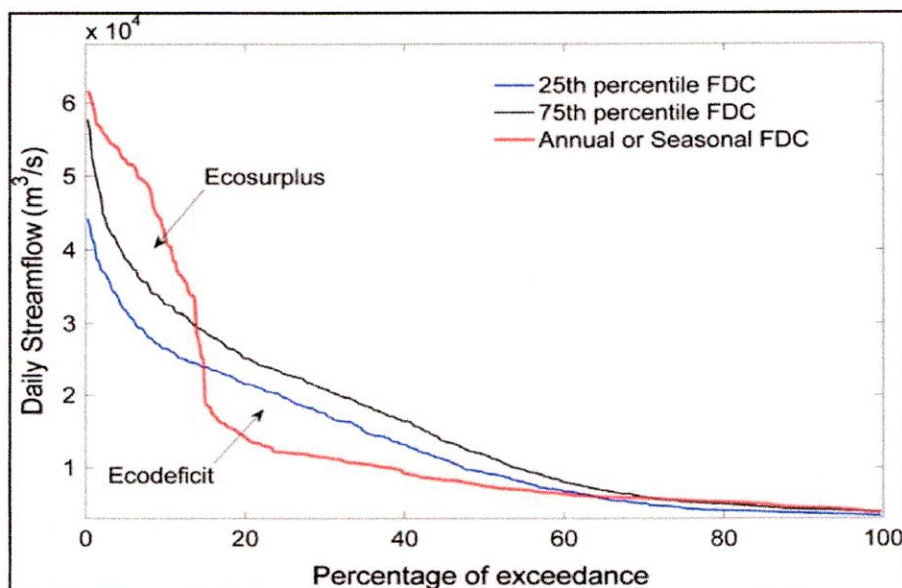


Fig. 2- Definition of ecosurplus and ecodeficit in the flow duration curve.

Later, the eco-values of all the years and the 10 daily average discharge data for the 25th and the 75th percentile years were averaged individually. All the positive averaged eco-values were divided by the sum of the averaged 25th percentile year and the maximum positive averaged eco-value. Similarly, all the negative averaged eco-values were divided by the sum of the averaged 75th percentile year and the minimum negative averaged eco-value. In the present study, the fractions of eco-values were termed as *eco-flow metrics*.

5. RESULTS AND DISCUSSIONS

5.1 FDCs for different periods (Annual, Monthly, Daily & 10Daily):

The method described in the chapter 4 was used to develop daily, weekly and annual FDCs for the given period of data. The 25th and the 75th percentile years are then obtained, but these years were not so accurate and the results obtained were not good. So we opted for 10 daily averages FDC and the 25th and 75th percentile years were then obtained.

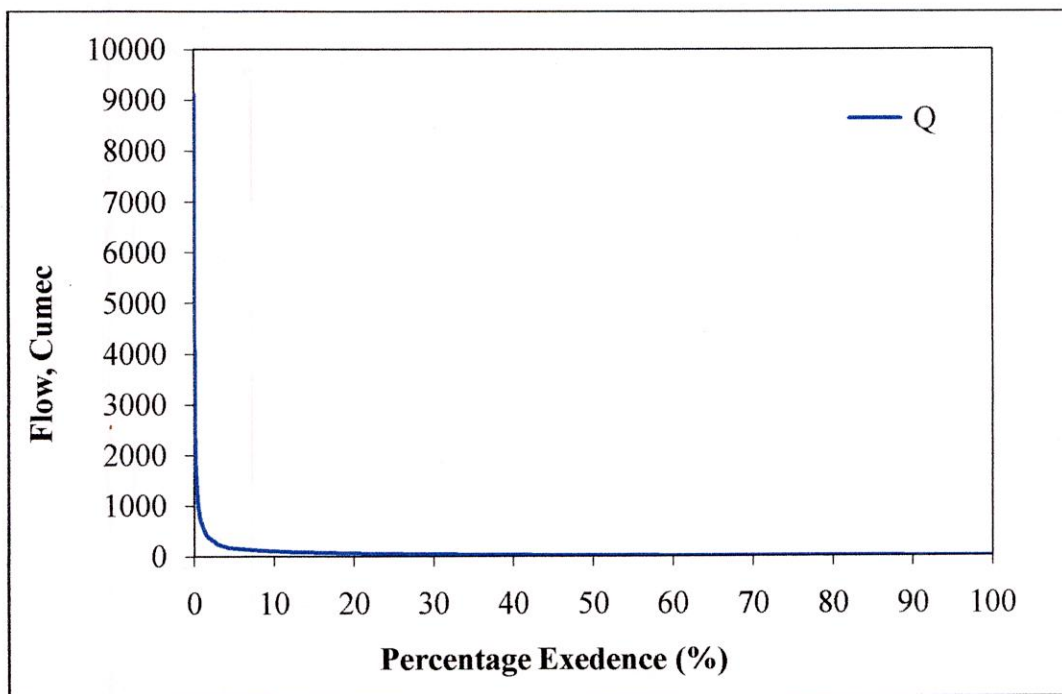


Fig. 3- Daily FDC, 1977-2007.

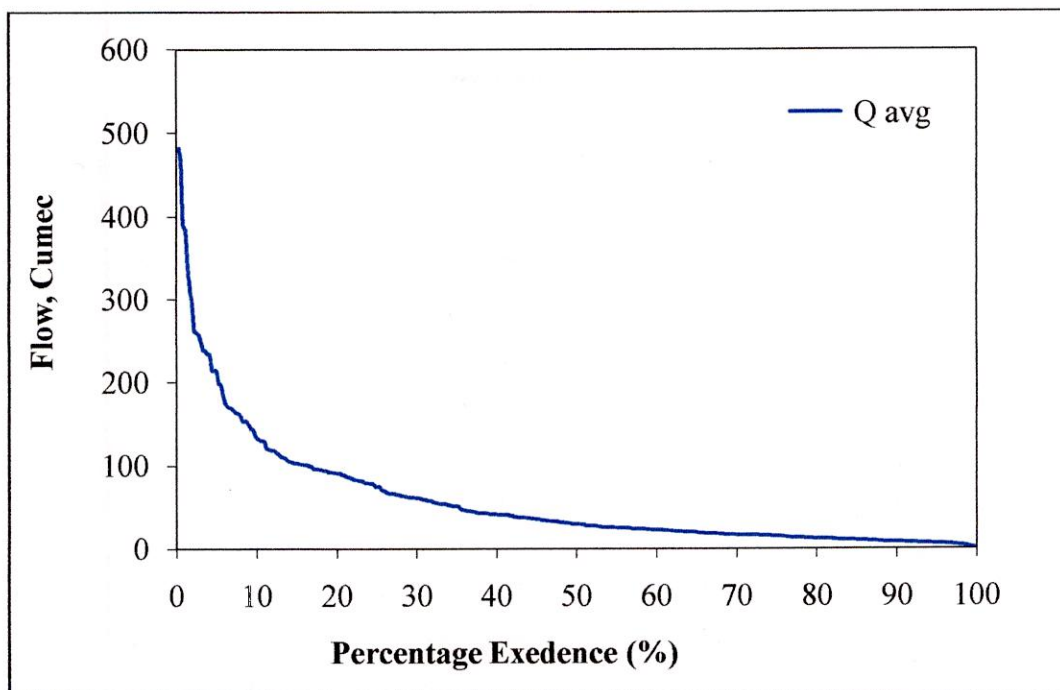


Fig. 4- Weekly FDC, 1977-2007.

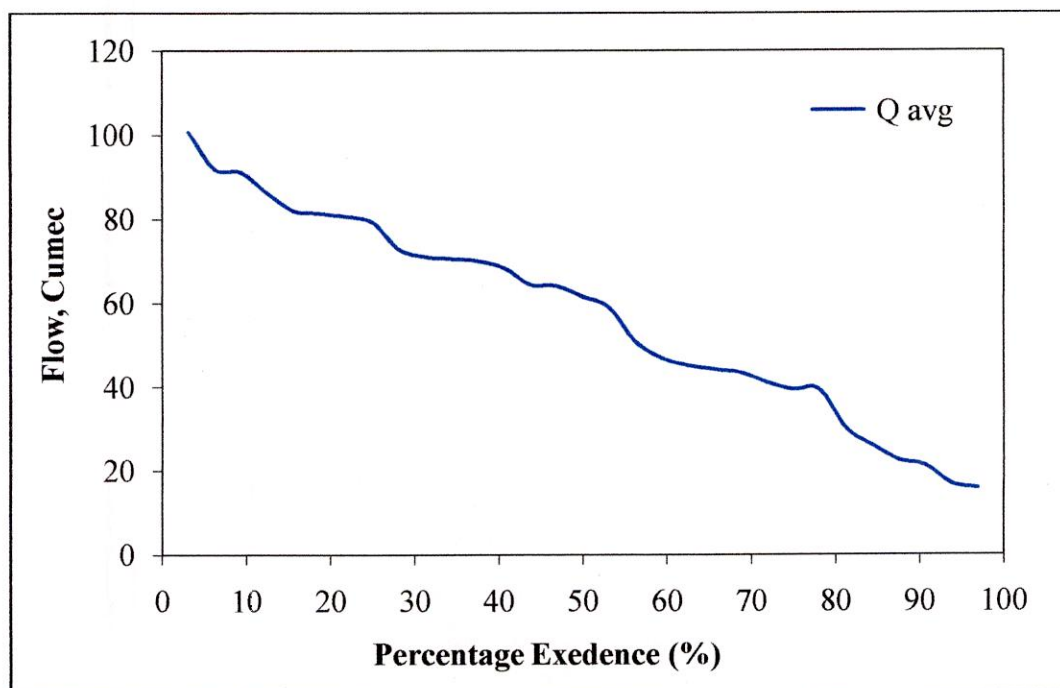


Fig. 5- Yearly FDC, 1977-2007.

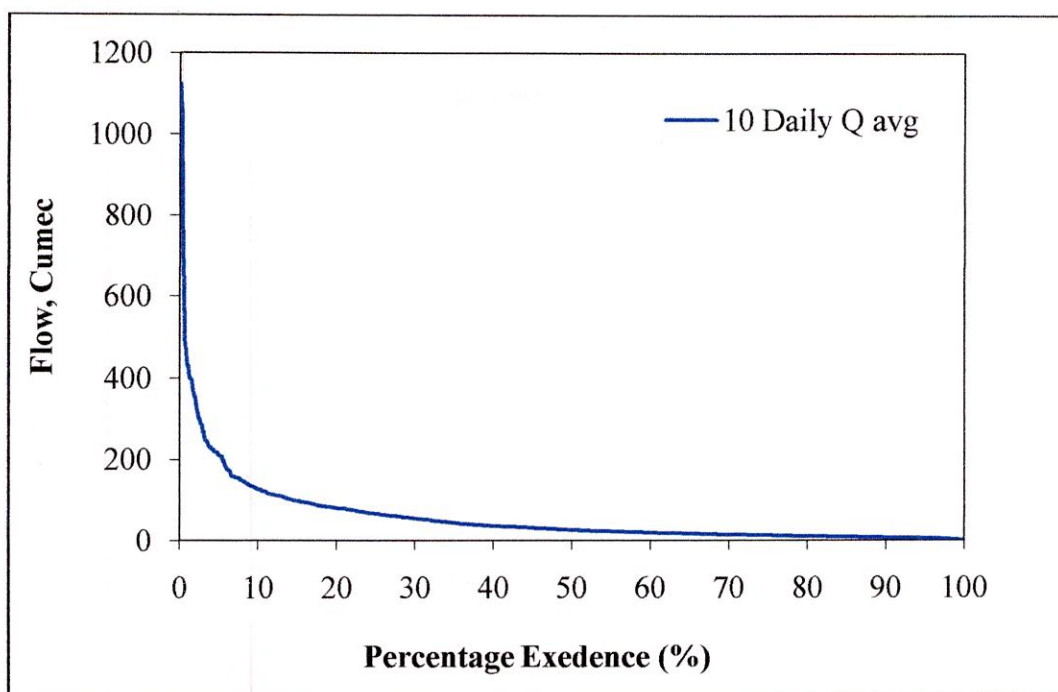


Fig. 6- 10Daily Average FDC, 1977-2007.

5.2 25th and 75th Percentile FDCs for 10-daily average data:

The 10 daily average FDC was drawn and the 25th and the 75th percentile years were obtained which were more accurate than the previous FDC's 25th and 75th percentile years. And the results obtained were now more précised and satisfying.

Table 1: Flow values for 25th, 75th, 1991 and 2002 year for different percentile probabilities of exceedance.

p%	Q25 1991	Q75 2002	Q 1980	Q 2001
2.63	248.10	99.10	331.60	115.70
5.26	155.33	90.00	224.90	113.30
7.89	101.59	84.20	181.40	79.20
10.53	85.14	82.20	116.70	67.30
13.16	79.90	38.60	100.90	52.00
15.79	71.21	36.40	98.60	37.40
18.42	68.11	27.60	60.60	32.10
21.05	66.59	19.80	51.10	29.30
23.68	66.14	18.60	45.30	22.50
26.32	63.40	18.30	39.40	22.00
28.95	61.77	16.60	33.00	21.00
31.58	59.76	15.20	30.60	18.50
34.21	58.73	14.00	29.10	18.40
36.84	52.02	13.40	28.30	18.00
39.47	48.24	13.00	21.50	13.09

42.11	47.96	12.90	20.90	12.90
44.74	47.09	12.50	19.20	12.60
47.37	45.47	12.10	18.70	10.40
50.00	45.13	12.00	16.70	10.40
52.63	42.55	11.90	16.50	9.20
55.26	41.45	10.90	14.70	8.35
57.89	38.52	10.10	14.40	8.20
60.53	38.00	10.10	13.00	7.70
63.16	20.94	10.00	11.40	7.23
65.79	20.64	8.80	9.50	7.13
68.42	19.05	8.50	9.40	7.11
71.05	14.88	7.20	8.80	6.79
73.68	13.75	7.20	7.40	6.70
76.32	13.70	7.20	6.50	6.49
78.95	12.46	7.00	6.00	6.46
81.58	8.96	6.70	5.90	6.20
84.21	8.69	5.90	5.50	6.02
86.84	8.62	5.70	4.90	6.01
89.47	8.30	5.00	4.90	5.98
92.11	8.24	4.80	4.30	5.97
94.74	8.13	4.80	4.20	5.86
97.37	8.00	4.80	3.70	5.10
AVERAGE	48.83	20.89	43.77	22.39

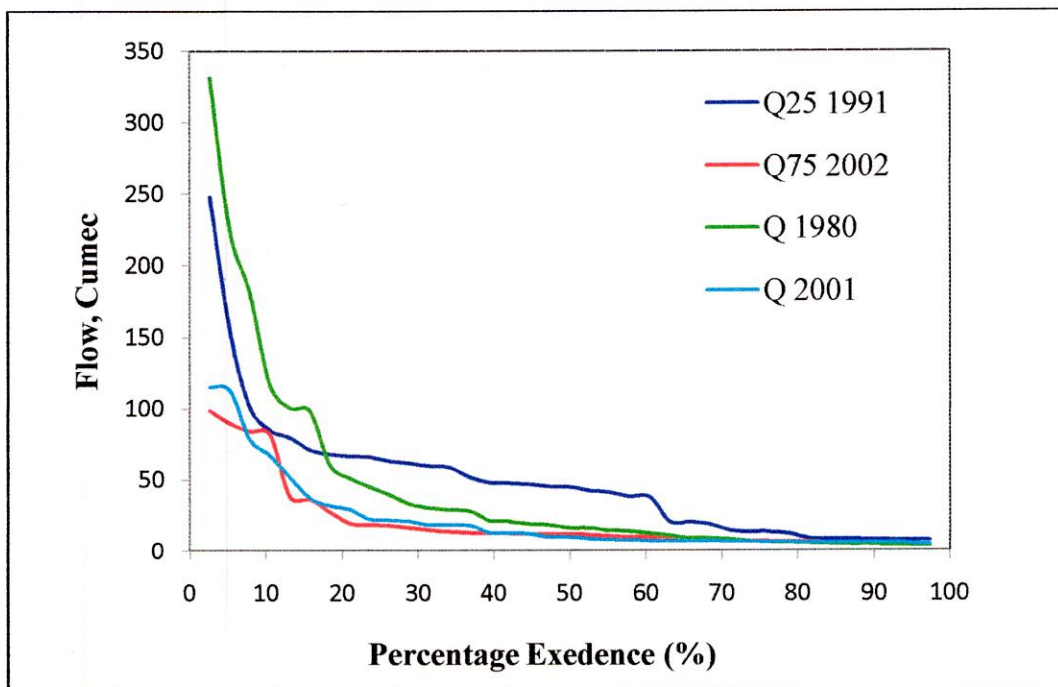


Fig. 7- 25th and 75th percentile FDC, 1977-2007.

5.3 Ecosurplus and Ecodeficit Flows:

The ecosurplus and ecodeficit metrics are based on Flow Duration Curves (FDCs). Now the obtained 25th and the 75th percentile years were used for determining the ecosurplus and the ecodeficit flow. If the discharge value is greater than 25th percentile value, then the flow is *Ecosurplus*. And if the discharge value is greater than 25th percentile value, then the flow is *Ecodeficit*. And if the discharge value lies within the 25th and 75th percentile values, then the flow is normal.

Table 2: The Eco-values and the Eco-flow metric values for each of the year for the Tawi River.

Year	Eco Values	Eco Flow Metric
1977	51.34	0.47
1978	25.49	0.23
1979	29.17	0.27
1980	8.29	0.08
1981	35.02	0.32
1982	16.80	0.15
1983	24.41	0.22
1984	5.73	0.05
1985	4.84	0.04
1986	5.02	0.05
1987	1.75	0.02
1988	60.48	0.55
1989	-1.80	-0.12
1990	35.67	0.33
1991	48.83	0.45
1992	17.99	0.16
1993	22.46	0.21
1994	35.06	0.32
1995	23.10	0.21
1996	37.95	0.35
1997	12.56	0.11
1998	-0.14	-0.01
1999	-6.23	-0.43
2000	-5.12	-0.35
2001	-1.11	-0.08
2002	20.89	0.19
2003	17.63	0.16
2004	36.57	0.33
2005	37.08	0.34
2006	5.33	0.05
2007	-0.86	-0.06

5.4 Eco-Flow Metric:

Now the ecosurplus and the ecodeficit flow data so obtained is further used to create an Eco-flow Metric for the given data period. The Eco-flow Metric gives a clear indication of the flow type which in result tells us about the River Ecology. The eco flow metric for the study period i.e. 1977-2007 for Tawi river basin is depicted in the figure 8. It can be seen that the ecology of Tawi River is at par during the study period expect for the years of 1999 and 2000 particularly. Although the ecology is under sustaining condition but the metric has falling due course of time, which can be a signal of ecological deterioration in the future.

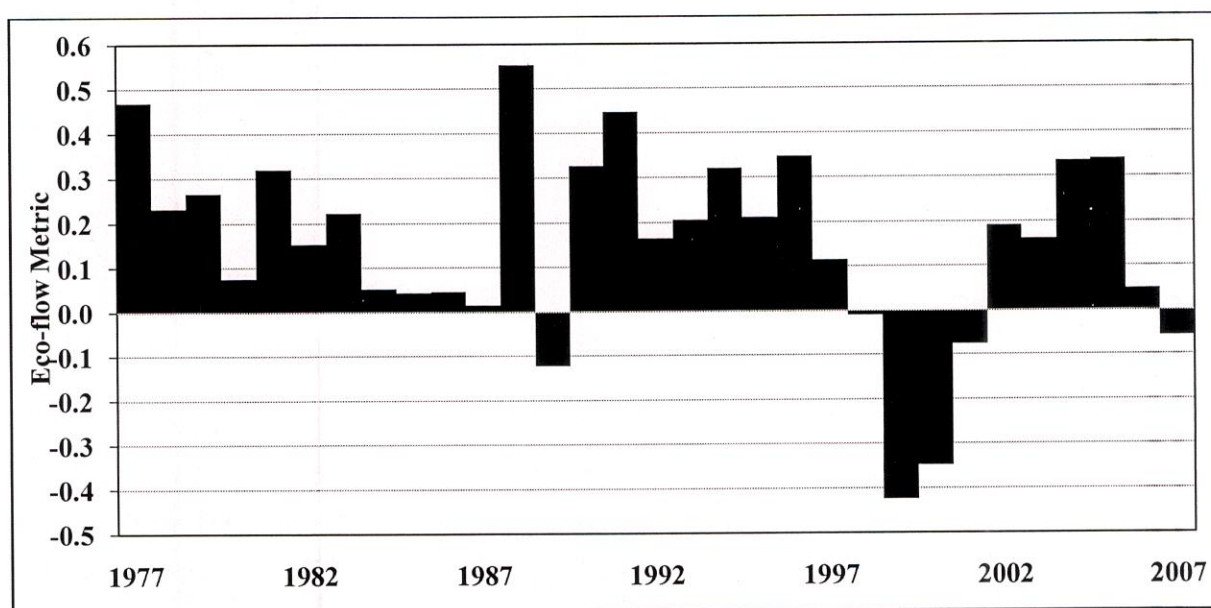


Fig. 8- Eco-Flow Metric of the Tawi River for the study Period

6. SUMMARY

Flow Duration Curves (FDCs), which can condense a wealth of hydrological information into a single graphic image, are often used to summarize the impacts of potential climate change scenarios on water resource systems (*Vogel and Fennessey, 1995*). Results derived from the flow duration curves are needed by hydrologist and engineers involved in planning and designing of various water resources projects. And many other significant uses of this curve prevail such as evaluating the characteristics of the hydropower potential of a river, design of drainage systems, flood-control studies, computing the sediment load and dissolved solids load of a stream, and comparing the adjacent catchments with a view to extend the streamflow data. Apart from these classical uses the FDCs can also be used to assess the health of the river in terms of its ecological status.

In the present study, the flow duration curves for different time spans were abstracted from the daily discharge data for the Tawi River Basin for the period 1977 to 2007 (i.e. 30 yrs.) collected from the *Hydrological Data Centre of the Central Water Commission in Jammu*. The FDCs so created were not that appealing so 10 daily average FDC was used for the research to precede. Then the 25th and the 75th percentile years were obtained with the help of this FDC, which in further were used to find the recently introduced metrics viz. ecosurplus and ecodeficit were analyzed for detecting the change of the river ecology. As a final result, the Eco-flow Metric was constructed from the flow data so derived to know the status of the Tawi River and the effect on its ecology. The results of the study confirms that the ecology of Tawi River is at par for the study period expect for the years of 1999 and 2000 particularly. Although the ecology is under sustaining condition but the metric has falling due course of time, which can be a signal of ecological deterioration in the future.

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