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Research Article

Development of Flow Duration Curves and Eco-Flow Metrics for the Tawi River Basin - (Jammu, India)

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Abstract A Flow duration Curve (FDC) and eco-metrics are one of the principal techniques employed to study the changes in flow regimes and flow discharge in any river basin. Stream flows vary widely over a year and this variability can be assessed by using FDC's which is a curve plotting stream flows (Q) on the vertical axis and the percent of time the flow is equalled or exceeds (P) a critical discharge threshold on the horizontal axis for a particular river basin. Flow Duration curves (FDCs) are imperative instruments which are fundamental for water asset distribution and administration, which can further be analysed to get a great deal of hydrological data to understand the impact of climate changes on water asset frameworks. Results got from the flow duration curves are required by hydrologists and specialists associated with various water asset ventures such as assessing the hydropower capabilities of a waterway, stream health, surge control examines such as recurrence outlines, runoff estimations, figuring the dregs stack and broken down solids of a stream, and contrasting the adjacent catchments. Apart from these classical uses, the FDCs can also be used to survey the health status of the streams in terms of its ecological status. The present study has been undertaken with an objective to identify the ecological health status of the Tawi River, based on eco-flow metrics. Eco-surplus and eco-deficit are known as the indicators of Hydrologic Alteration (IHA) and are used to study intra and inter annual variations in river flows. The daily stream flow 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 Curve (FDCs) for the different periods like daily, monthly, annual etc. Finally, 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 results of the study conclude that Tawi River is an ecosurplus river, in most of the years of the study period. The ecology of Tawi River is at par for the study period except for the years 1999 and 2000. Although the ecology is under sustaining conditions, but the metric has been falling in course of time, which can be a signal of ecological deterioration in the future.

Keywords *Flow duration curve (FDC); Ecosurplus; Ecodeficit; River ecology; Tawi river*

1. Introduction

Changes in stream administration, stream health and waterway releases are usually seen in a substantial number of streams worldwide as a result of natural and environmental changes. However, the qualities and the results occurring from such changes are not completely comprehended. River discharge or stream flow is the most important part of the hydrological cycle for its very close connection to water assets. River flow characteristics such as flow discharge and duration, and eco-statistics are critical parts to understand the ecological integrity, processes and changes taking place in these river ecosystems. Many earlier studies have suggested that climatic changes would deeply influence the water cycle resulting in expansion of extreme climatic events worldwide. The resulting climatic variations will significantly modify the regional river discharges and seasonal flow regimes. Escalated human activities such as modified land use patterns, artificial water intake, and construction of dams and reservoirs, have also directly impacted the stream flow and altered the natural river flow regimes for the past few decades.

Changes in river and stream discharges and flow regimes have been analysed by an ever-increasing number of analysts in various parts around the world. To date many researchers and scientists worldwide, have developed methods to relate flow statistics to ecological health in order to quantify and characterize the effects of hydrologic modifications on river ecosystem integrity. To assess the impact of flow statistics on ecosystem integrity various indicators or hydrological metrics have already been developed. The indicators of Hydrologic Alteration (IHA) which were developed by Richter, Baumgartner, Powell, and Braun (1996) are one of the most widely used metrics to assess the changes on flow regimes due to different flow regulations. Eco-deficit and eco-surplus can be calculated for any time period and indicates the overall loss or gain in stream flows due to flow regulation imposed during that period (Vogel et al., 2007). Based on the previous studies such as the Detailed analysis of Flow regimes changes in the Upper Yangtze river by Gao et al. (2012), Assessment of environmental flow requirements in Damodar river basin using flow duration indices by Mitra et al. (2018), Design flow duration curves for environmental flows estimation in Damodar river basin, India, by Verma et al. (2017); the present study is carried out to understand and analyze the basic concept of FDCs and study the changes in the eco-flow metrics of respective water bodies, to provide a meaningful insight into the flow characteristics of streams and contrasting the contiguous catchments in terms of their ecological integrity. Therefore, the study has been undertaken considering three broad objectives (a) Development of flow duration curves for the flow regimes in the Tawi River basin using the available data for the period 1989 to 2000 (b) Identification of 25th and 75th dependable years and (c) Examining and quantifying the changes in flow regime in the Tawi River basin Based on the eco-flow metrics (ecosurplus and ecodeficit).

2. Literature

2.1. Flow Duration Curve

The Flow Duration Curve is a cumulative frequency curve that demonstrates the percent of time amid which indicated releases equalled or surpassed a critical discharge threshold in a given period. They demonstrate how the flow is distributed during a time period (calculated usually once a year).The vertical axis shows the flow, and the horizontal axis gives the probability percentage of flow magnitude that exceeds or equals the given threshold. For example, the FDC demonstrates the level of flow that charges for at least 50% of the year (known as Q50). The flow exceeding 95% of the year (Q95) is often a characteristic value for minimum river flow (Ian Bostan, 2013). The FDC is a medium to study the flow characteristics of rivers and streams and to make inter and intra comparisons for different basins.

An example of flow duration curve of a river for natural and regulated flow is shown in the Figure 1 below.

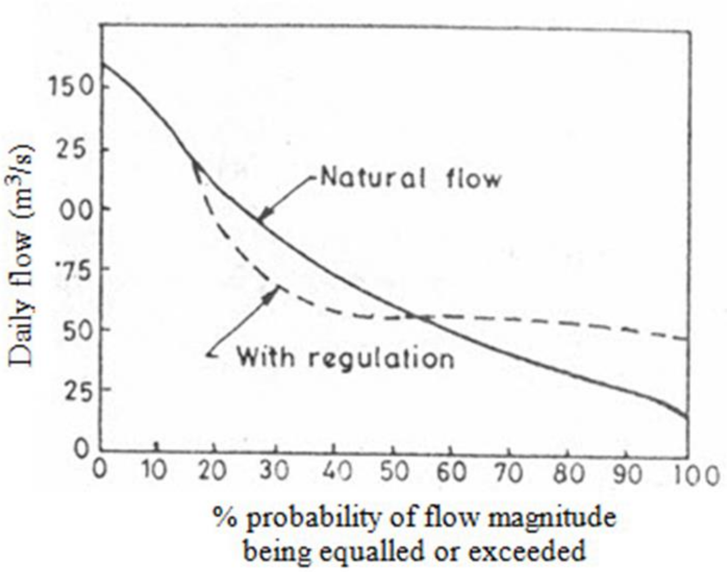

Figure 1: *Flow duration curve of a river for natural flow and regulated flow* (Source: Subramanya, 2009)

To create a Flow Duration Curve, daily, weekly, or monthly flows are organized by magnitude for a given period of time, and the percent of time during which the stream equalled or surpassed the predetermined threshold is derived. The plotted curve indicates discharge versus the percent of time amid which they equalled or surpassed a specific threshold subsequently represents an average for the considered period as opposed to the flow distribution within a single year (Searcy, 1959).

2.2. An Ideal FDC

An FDC plots Q (discharge) as a function of its corresponding exceedance probability:

$$P_p = \frac{m}{(N+1)} \times 100\% \ldots \text{(Weibull plotting formula)}$$

Where, Pp = Percentage probability (the probability that a given flow magnitude will be equalled or exceeded (% of time); m = Order number or Rank of the discharge with 1 being the largest possible value; N = Number of data points used in the listing

The ordinate Q, at any percentage probability P_p, represents the magnitude of flow in an average year that can be expected to be equalled or exceeded P_p percent of time and is termed as P_p% dependable flow. In a perennial river Q100=100% dependable flow whereas for an intermittent or ephemeral river, the streamflow is zero for a finite part of a year and therefore Q100 is equal to zero (Subramanya, 2009). The plot between discharge Q and Pp is the flow duration curve.

2.3. Eco Flow Metrics

Eco-surplus and eco-deficit are amongst the various other Indicators of Hydrologic Alteration (IHA) and are used to examine intra and inter annual variations in flows and can reveal significant changes if present in the streamflow time series. The eco-surplus and eco-deficit measurements depend on the 25^{th} and 75^{th} percentile flow duration curves (FDCs). FDCs are developed from stream flow data over a period of interest and give a measure of the percentage of time that stream flow equalled or exceeded a given value. The range from the 25^{th} to 75^{th} percentiles could be considered as the normal flow range for the river ecosystem. If the annual or seasonal FDC for a given year is below the 25^{th} percentile FDC, the area between the 25^{th} percentile FDC and the annual or seasonal FDC is defined as Eco-deficit. This value represents the amount of water insufficiency or how bad is the state of river ecology. On the other hand, if the annual or seasonal FDC of a given year is located above the 75th percentile FDC, the area between the 75th percentile FDC and the annual or seasonal FDC is called Eco-surplus, and indicates the goodness level of the river ecosystem The values of the eco-surplus and eco-deficit are divided by the annual mean or seasonal mean flow amount to quantify the fractions of eco-surplus and eco-deficit, respectively (Gao et al., 2012). These fractions of Eco-surplus and Eco-deficit are termed as the Eco-flow Metrics. Figure 2 below shows a general definition of eco-surplus and eco-deficit areas derived from a FDC.

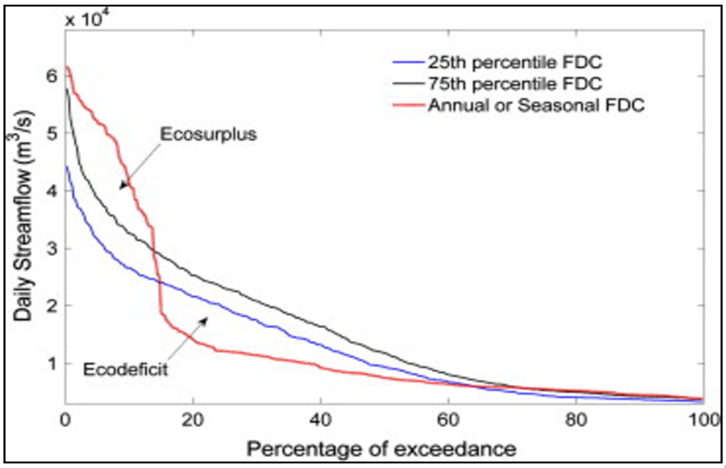

Figure 2: *General definition of eco-surplus and eco-deficit in a flow duration curve* (Source: Gao et al., 2012)

3. Study Area

3.1. General Topography

The Tawi River basin is a small part of Western Himalayas and is contained between 32°35' to 33°35' North Latitude & 75°45' to 75°45' East Longitude. At the upper part the basin is narrow and elongated; 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 400 meter to 4000 meter above mean ocean level. Figure 3 below shows the location map of Tawi river basin.

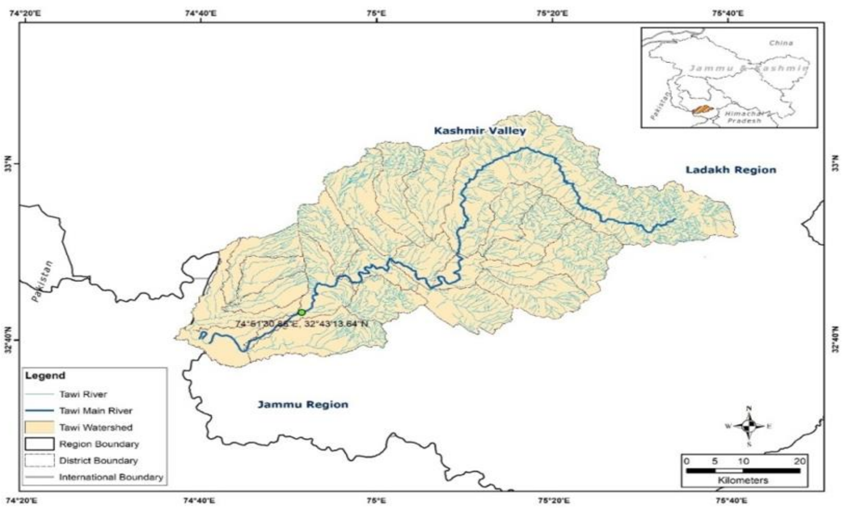

Figure 3: *Location map of the study area*

The slope of the basin is from east to west in the upper part and NE to SW in the lower part. The river, at its upper scopes is nourished by liquefying of snow and ice of Kali-Kundi Glacier at its origin and by rain. In the lower part, the catchment is dominatingly rain nourished. A little region of around 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 Jamrnu has been considered.

3.2. Climate

In the Tawi Basin, July and August are for the most part the wettest months with around 55% rainfall and November is the month with least rainfall with around 2-3% of aggregate rainfall. Tawi encounters substantial floods in July and August. Monsoon begins from first July with heavy thunder showers that lasts up to mid-September. The North-Eastern catchment area comprising of Bhaderwah and adjoining area have extra tropical mountain type climate. 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 consists of Udhampur district where again climate is of mountain type but has sufficient influence of monsoon. The South-Western zone consisting of Jammu district has a warm climate with strong monsoon influence, and can be described as similar to tropical climate during certain parts 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 it continues till May.

3.3. Water Resources

The Tawi River is gifted with enormous water resource 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 stream is of around 141 km length up to the point where it enters Pakistan, from its origin at Himalayan Kali-Kundi glacier. It has nine major tributaries carrying 4.3 lakhs cusec water release of Tawi in September 1988 at Jammu, with minimum discharge around 300-400 cusecs. Low water flow is experienced during the long stretch of October, November and December. But there are also occasional rises of water level during winters because of downpours and during early summers due to snow melting from the seasonal snow cover in the upper catchment.

3.4. 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 represents the River Length)
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 because there is degradation in the upper stages and aggradation in the 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.

4. Data and Methodology

In order to achieve the project objectives, the data used and the 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, (*www.cwc.nic.in*). Since the accuracy of the collected data used for this project is not known, the outcomes given here might be thought to be indicative.

4.2. Methodology

In the present investigation, Indicators of hydrologic alteration (IHA) namely Ecosurplus and Ecodeficit were examined to study the changes in river ecology. Yearly eco-surplus and eco-deficit values were computed utilizing daily stream flow data.

Annual, monthly and daily FDCs were built for the available stream flow data for the period (1977-2007). These FDCs were utilized to check the status of river ecology. Based on the 30 years of annual, monthly and daily FDC's, the 25th percentile FDC and the 75th percentile FDC were calculated. But the obtained 25th and 75th percentile years were not that accurate, and the results obtained were not satisfactory for the said time stamps. Therefore, to get the desired 25th and 75th percentile years, we opted for the 10 daily averaged FDC for the 30-year daily data.

The 25th and the 75th percentile FDCs relating to the 10-daily (Ten days cumulative flow in a month) stream flow data were then used as the upper and the lower limits of the river ecology to justify its ecological status. The range from the 25th to 75th percentile was considered as the normal range for the river ecology. If the 10-daily averaged FDC of a given year are located below the 25th percentile FDC, the area between the 25th percentile FDC and 10-daily averaged FDC is defined as Eco-deficit, which represented the bad state of river ecology. Conversely, if the 10-daily averaged 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 termed Eco-surplus and represented the level of goodness of the river ecosystem.

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. These fractions of eco-values were termed as Eco-flow metrics.

5. Results and Discussion

5.1. FDCs for Different Periods (Annual, Monthly, Daily & 10 Daily)

The method described in section 4 was used to develop daily, weekly and annual FDCs for the given period of data showing the flow discharge vs the percentage of time. Figure 4, 5 and 6 below show the daily, weekly and annual FDC's for the Tawi river basin.

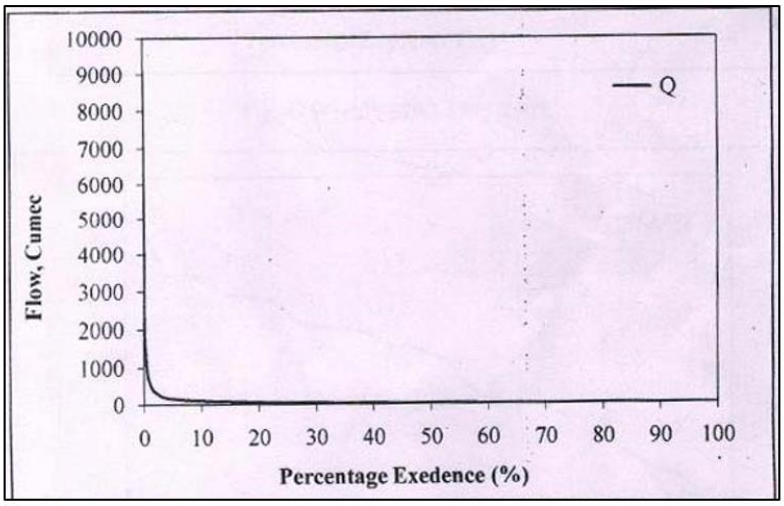

Figure 4: *Daily average FDC showing the discharge values from (1977-2007)*

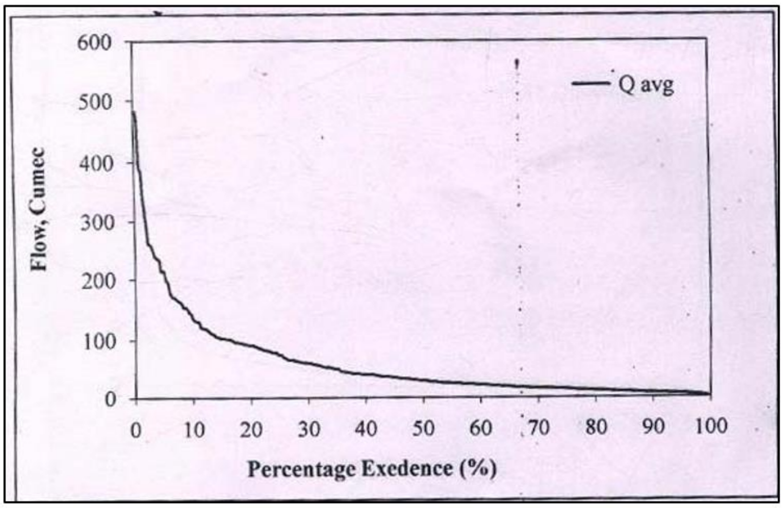

Figure 5: *Weekly averaged FDC (1977-2007)*

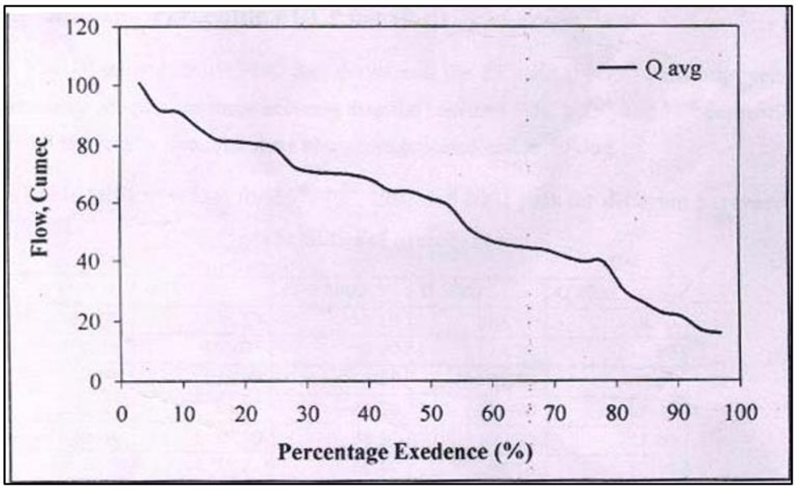

Figure 6: *Yearly FDC (1977-2007)*

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

The 25th and the 75th percentile years were obtained, but these years were not so accurate and the results obtained were not satisfactory. Therefore, 10 daily averaged FDC was chosen, and the 25th and 75th percentile years were then obtained. Figure 7 below shows the 10-daily average FDC for the Tawi basin.

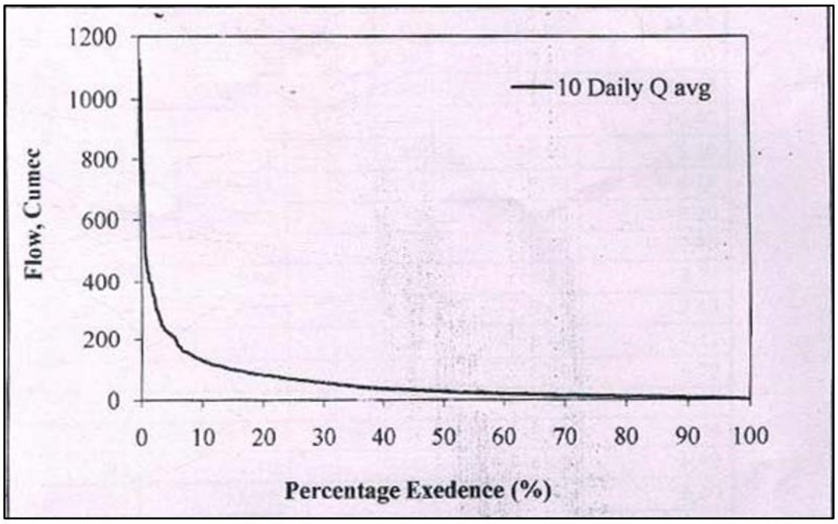

Figure 7: *10-daily average FDC (1977-2007)*

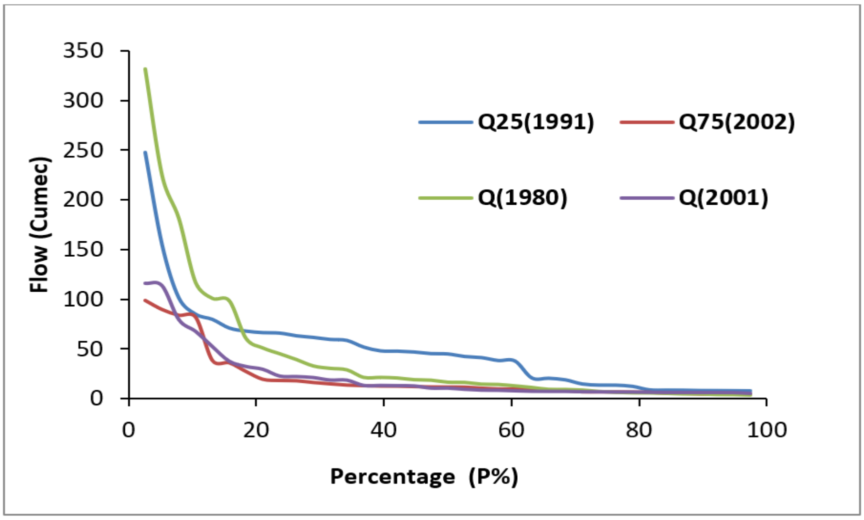

Figure 8: *25th and 75th percentile FDC (1977-2007)*

Figure 8 below shows the 25th and 75th percentile years for 10-daily averaged FDC. During the study period 1977-2007, Q25 was achieved in the year 1991 and Q75 was achieved in the year 2002. Q1980 shows the discharge curve when the value was nearest to Q25, which suggests that there was a major drawdown in water flow between 1980 and 1991, which had resulted into lesser Q values between 1980 and 1991. Q75 was achieved in 2002 and the nearest year where the value was close to Q75 was 2001. The range from the 25th to 75th percentile was considered as the normal range for the river ecology.

Table 1 below, shows the Flow values for 25th, 75th percentile probabilities of exceedance for 1991 and 2002, and also shows the discharge values at the nearest years 1980 and 2001.

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

p%	Q25Percentile (1991)	Q75 percentile (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	21.50	13.09
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**

5.3. Ecosurplus and Ecodeficit Flows

The obtained 25th and the 75th percentile years were used for determining the ecosurplus and the ecodeficit flow. The Figure 9 below shows the Eco-deficit areas where the discharge value is less than 25th percentile value and the Eco-surplus areas where the discharge values is greater than 75th percentile value. The area between the 25th and 75th percentile values is the area with normal flow.

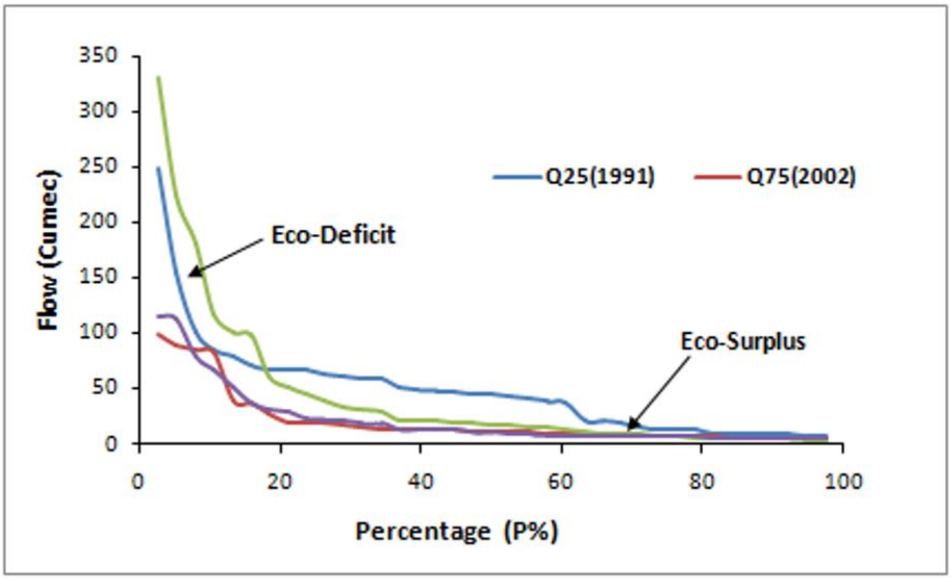

Figure 9: *Eco-surplus and eco-deficit areas for the study period*

5.4. Eco-Flow Metric

The eco-surplus and the eco-deficit flow data obtained was further used to create an Eco-flow Metric for the given data period. The Ecoflow Metrics provides a clear indication of the flow type which tells us about the river ecology. Table 2 below shows the eco-flow metrics calculated for each year during the study period 1977 to 2007.

Table 2: *The eco-values and the eco-flow metric values for each year (1977-2007)*

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	-6.12
1990	35.67	0.33
1991	48.83	0.45
1992	17.99	0.16
1993	22.46	0.21
1994	35.06	032
1995	23.10	O.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	005
2007	-0.86	-006

Figure 10 below shows a graphical representation of the eco flow metrics for the study period as calculated from Table 2. The figure clearly shows that Tawi River is an ecosurplus river, in most of the years of the study period and that the ecology of Tawi River is at par except for the years of 1999 and 2000 where the eco flow metrics are falling down and suggest some extreme changes in the flow regime during those years.

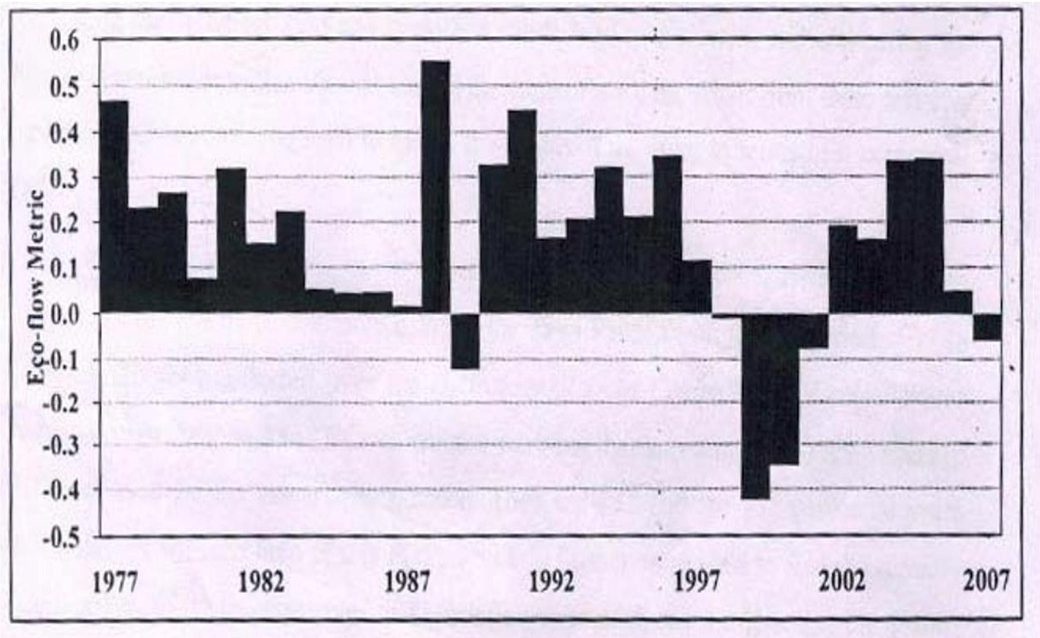

Figure 10: *Eco-flow metrics for the study period*

The results indicate that although the ecology of Tawi basin is under sustaining condition but the metric has been falling in due course of time, which can be a signal of ecological deterioration in the future.

4. Conclusion

Changes in the flow regime of the Tawi River Basin were analyzed based on recordings of daily river discharge data during the period from 1977 to 2007. Eco-surplus and eco-deficit areas were identified based on the Flow duration curves which showed the spatial and temporal changes in the Tawi river flow during the study period. Eco-metrics were derived and plotted for the entire period which indicated that the metrics in the river basin has been gradually falling down over the years suggesting ecological deterioration in the area. The eco flow metrics were quite low for the years of 1999 and 2000, which suggest some hydrologic extremes during those years. Thus Flow duration curves coupled with eco flow metrics provide a good framework to study the flow regimes in a river basin and its impact on the ecological health in the catchment. Our results indicate that although the ecology of Tawi basin is under sustaining condition but the metric has been falling in due course of time, which can be a signal of ecological deterioration in the future.

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