

Changes in Streamflow Regime Due to Anthropogenic Regulations in the Humid Tropical Western Ghats, Kerala State, India

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Abstract: Regulation of streamflow by a reservoir creates a flow regime much different from the pre-impoundment period flow regime. Hydro-Electric Projects (HEPs) commissioned in the Western Ghat regions of the Kerala State, India during the last four decades caused considerable changes in the flow regimes of the rivers of the Kerala State in southwest India. In this paper, the Indicators of Hydrologic Alteration (IHA) approach proposed by Richter et al. (1996) is used to analyze flow regime changes in the Periyar and Muvattupuzha Rivers, due to the construction of the Idukki (1976), Idamalayar (1987) and Lower Periyar (1997) HEPs in the high ranges of the Western Ghats. Normal rainfall years (annual rainfall values within mean \pm 0.75 standard deviation limits) are only considered in the analysis to focus on hydrologic alterations due to human activities. The mean hydrologic alteration in the Periyar River (deviation from the pre-development hydrologic indicator values) after commissioning of three HEPs is 35%. Inter-basin water transfer after power generation from the Idukki HEP resulted in a higher discharge in the adjacent Muvattupuzha River, leading to considerable changes in the hydro-environment (mean hydrologic alterations varying between 57 to 63%). IHA parameters showing hydrologic alterations above the 67th Percentile were

further analyzed. For each of the pre-construction hydrologic parameters \pm 1 standard deviation from the mean is set as the upper and lower management target limits. The values of each IHA parameter beyond these targets are considered as non-attainment. Considerable hydrologic alterations are observed, especially for low flows in both basins. Inter-basin transfer induced larger changes in flow parameters compared to intra-basin regulations. The study shows that under a proper water release and diversion scheme, the non-attainment of IHA parameters (values fall beyond the target limits) can be reduced. The findings of the study will be greatly beneficial to regional water management and restoration of an eco-environmental system in the humid tropical region.

Keywords: Range variability approach; Hydro-electric projects; Humid tropics; Flow regime changes; Inter-basin regulation; Intra-basin regulation

Introduction

The humid tropical climate is characterized by season-long precipitation. The rainy season lasts at least six months in a year and creates a humid climate, in which more water falls than can

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evaporate. The annual precipitation usually ranges between 2000 to 4000 mm on slopes exposed to wind. Some areas in the humid tropics receive more than 4000 mm of rain annually. About 85% of the total annual rainfall in the humid regions is received during the monsoon season spread over a period of six months. The remaining six months is usually dry, receiving sparse summer rains. Because of this rainfall pattern, which considerably varies between seasons, the rivers of the humid tropics experience high variability in flow over a year.

Temperature in humid tropics generally varies in a very narrow range annually. The daily maximum temperature varies between 28°C-34°C during warm months and between 22°C-24°C during cool months. The humid tropics have the greatest biodiversity, while the biodiversity decreases towards the north and south poles as the temperatures decrease. As these regions are characterized by a wide range of species diversity of aquatic biota and riparian vegetation including several endemic species, they are considered as bio-diversity hot spots. The loss of bio-diversity in such bio-diversity rich regions could be attributed to the expanding human population activity by way of habitat destruction through fragmentation and degradation and overexploitation of species for human use and many other complex unexplored factors.

A streamflow hydrograph describes the magnitude and timing of river discharge at a single location. Streamflow is one of the key driving forces in river eco-systems (Stanford et al. 1996; Poff et al. 1997). Any alterations from the natural streamflow conditions can cause disturbances in the habitat conditions and subsequently negatively impact the sustainability of aquatic/riparian biota.

Earlier instream flow studies were mainly focused on determining the low flow conditions required to maintain particular instream values. This is because fresh water demand is higher and the river ecosystem is under the most stress during low flow periods. However, several aspects of a river's flow regime may also influence its ability to maintain particular instream values, which are detailed below.

Large floods (magnitudes \geq mean annual flood) maintain the overall form of an alluvial river channel. Smaller floods and freshets, with a

frequency of a few times each year, are contained within the channel, and therefore have a more restricted effect than large floods. Nevertheless, they are able to mobilize sediment on at least some areas of the riverbed, remove periphyton and other aquatic vegetation, and often assist fish passage. They generally 'flush' and 'refresh' the riverbed by removing silt and algal coatings, and inhibit vegetation from colonizing the riverbed gravels that are not covered by flowing water and, in terms of flow requirements, are known as 'flushing flows'. Low flows are particularly important because as detailed above, they are the times at which there is the greatest competition for water, the total wetted area of aquatic habitat is smallest, and the aquatic ecosystem is likely to be under greatest stress. On the other hand, stable low flows offer periods of high biological productivity, which permit recolonization of the riverbed by macro-invertebrates and fish after a flood, and re-establishment of periphyton and macrophyte vegetation (Jowett et al. 2006).

The seasonal variation of flows may also have an important biological function. For example, the monsoon floods that open a river mouth and enable the migration of fish from the sea. It is known that flow variations are an essential element of the regime that should be maintained, and that long periods of constant flow, which could result from adherence to a minimum flow, should be avoided. Determining the river flows required to maintain particular instream values may present significant challenges, particularly if there are several stakeholders with conflicting interests. Depending on specific proposals for use of the river (e.g., damming, large-scale run-of-river abstraction, minor abstractions), it may be necessary to develop what might be called a 'designer flow regime', that considers the need to maintain floods, freshets, low flows, and aspects of flow variability, thus mimicking the natural flow regime which existed before regulations (Jowett et al. 2006).

Man-made storage and diversion structures considerably alter the flow regime in the downstream lowlands and through analysis of historical records; these alterations to hydrologic regimes can be evaluated. Comparison of flow records at a downstream flow gauging site during pre- and post-project period would be helpful in such evaluation of changes to flow regime (Richter

et al. 1996, 1997). Studies by researchers show that eco-system oriented water allocation planning is important and such plans are usually evaluated based on instream flow evaluation methods (Poff et al. 1997; Jowett 1997).

Several useful indices have been developed by researchers. These indices are useful in assessing the flow regime changes due to human interventions. Many of the earlier studies were focused on individual indices such as mean daily flow variability, maximum and minimum flows etc., (Irina 1995; Ramon et al. 2004). A multivariable approach is generally adopted to quantify hydrologic alterations (Julian DO et al. 2003; Poff et al. 2009). The multivariable approach helps in investigating the multi-impacts of hydrological changes which are difficult to assess using a single variable approach (Shiau et al. 2004).

The hydrologic changes due to inter-basin (from one river basin to another) and intra-basin (within a river basin) regulations of streamflow are reflected in the shape and characteristics of hydrographs and/or flow duration curves. Flood moderation by the HEPs (Hydro-Electric Projects) is one of the dominant impacts, which can significantly alter aquatic life cycles (Brian et al. 1998; Kingsolving and Bain 1993) and contribute to adjustments in riparian community promoting dominance of invasive exotics (Johnson 1994). Along with moderated floods, other components of the hydrograph such as the timing and duration of low/high flows, the rate of change and the frequency of rises and falls in the hydrograph also contribute to the alterations in the aquatic life cycle (Richter et al. 1996; Poff et al. 1997; Dugger et al. 2002). The magnitude, frequency, duration, timing and rate of change of flow conditions are the five major components which control the ecological processes in a river (Poff et al. 1997).

Richter et al. (1996) developed a method referred to as the 'Indicators of Hydrologic Alteration' (IHA) to assess the degree to which human disturbance impacts the hydrologic regime within an ecosystem and proposed the Range of Variability Approach (RVA) as a tool for evaluating alterations caused by human interventions in a naturally flowing river. In this approach 32 hydrologic parameters were used to assess the hydrologic alterations (Richter et al. 1997). The application of RVA in assessing hydrologic

alterations from a river basin perspective is demonstrated by evaluating the impacts of dam construction on hydrologic variability of two major rivers in the upper Colorado river basin in Colorado and Utah, USA (Richter et al. 1998). IHA analysis was used by Galat et al. (2000), to study the impact of reservoirs on the flow regime of Missouri river. The study results show that river flows are considerably impacted by the reservoirs. The Range Variability Approach to investigating pre- and post-diversion conditions of a weir on Chou-Shui Creek, Taiwan, suggesting that restoration of natural flow is expected to promote the natural stream biota (Shiau et al. 2004).

The objective of the RVA is to guide efforts to restore or maintain the natural streamflow regime of a river, using the range of natural variability in different ecologically relevant flow parameters, as a basis for setting management targets. The values of these parameters for undisturbed flow can be a guiding factor, to maintain the flow regime within a threshold limit of natural flow variability. These parameters are used to assess hydrologic alterations.

The RVA has proved to be a practical and effective approach facilitating river restoration planning. However availability of sufficient flow records for the pre- and post-impact periods is a major problem in many cases. Since there is usually more than one dam in a river, it is hard to distinguish which dam plays a major role in causing hydrologic alterations downstream.

The HEPs in the highlands of Western Ghat region, Kerala, is the major source of Electric power. The storage structures commissioned under the HEPs considerably altered the flow regime in the rivers, which are major sources of fresh water for the midland and lowland regions. The majority of the HEPs in Kerala, India are located in the Periyar River basin, central Kerala. A major inter-basin diversion to the adjoining Muvattupuzha River basin exists under the Idukki HEP located in the Periyar River basin. Exploring the extent to which anthropogenic activities in these river basins affected the hydrologic regime is crucial for better understanding of human-induced hydrologic alterations and will aid in water resources management of such river basins.

Construction and operation of reservoirs for hydro-power generation, flood moderation and fair

weather period flow augmentation inevitably induce high hydrologic alterations in the system, which considerably affects the natural flow regime. This will be one of the main threats to aquatic and riparian biota. In this paper, an attempt was made to use data from normal years, with the aim of focusing attention on the influence of reservoir operations on streamflow regimes. However, with the method used in this paper, it is almost impossible to exactly differentiate individual roles of climatic variability and human activities in hydrological alterations. Complicated climatic changes along with intensive human activities (e.g. urban development, soil and water conservation measures, irrigation, groundwater extraction, water supply for industrial and domestic use etc.) have the potential to affect the hydrological regimes, which introduces uncertainties into assessments of hydrologic changes.

The objectives of this work were

(1) to compare the pre- and post-impact flow regimes and evaluate the impacts of

- inter-basin transfer of water due to Idukki HEP (1976) from the Periyar River basin to the Muvattupuzha River basin

- intra-basin regulations within the Periyar River basin due to the Idamalayar (1987) and Lower Periyar (1997) HEPs

- diversion at Malankara diversion dam (1994) in the Muvattupuzha River basin, after partially commissioning of the Muvattupuzha Valley Irrigation Project(MVIP) in 1994

(2) to quantify and characterize the flow regime in the main stream of the Muvattupuzha River once the MVIP is fully commissioned to irrigate 19,237 ha.

(3) to study the hydrologic alterations, if excess water is diverted from the Muvattupuzha River basin for other uses.

1 Study Area

The Kerala State in southwest India is located in the humid tropical zone with an average annual rainfall of 3000 mm. The monsoon period in the state starts with the onset of southwest monsoon by 1 June every year. Northeast monsoon rainfall is received from September to November, three months after the start of the southwest monsoon.

About 85% of the total annual rainfall is received during these two monsoons spread over a period of six months. The remaining six months is usually the fair weather period, is divided into two periods of equal lengths, locally designated as the post-monsoon (December-February) and the pre-monsoon (March-May). Because of considerable changes in rainfall, rivers of the state experience high flow variability over a year.

The 244 km long Periyar River is the longest river in Kerala. The Periyar River basin (catchment area: 5398 km²) is flanked by the Chalakudy river basin on the north and the Muvattupuzha and Pamba river basins on the south (Figure 1). The study area falls between 09°15' to 10°30' N latitude and 76°00' to 77°30' E longitude. From its source at 1850 m above the mean sea level (m asl), the Mullayarflows down traversing 48 km, and joins the Periyar from its right at an elevation of 850 m amsl. The Periyar River continues to flow towards the west for another 16 km and passes through a narrow gorge, where the Mullaperiyar dam was constructed in 1896, which gave birth to the Periyar lake, famous for its wildlife. The impoundment is 41.45 m high. Water from this reservoir is diverted to the adjoining Tamil Nadu State mainly for irrigation. The spillover is received in the Idukki reservoir of the Idukki HE project located further downstream at an elevation of 540 m amsl. The tail race discharge (i.e. water released from the powerhouse after power generation) from the Idukki project, is diverted to the Muvattupuzha River basin located on the southern side of the Periyar River basin. Because of these two inter-basin transfers, the catchment of the Periyar River basin supplying water downstream is virtually 3665 sq. km, where as the unaltered (natural) Periyar River basin catchment is 5398 km² (Report on Periyar River basin (2003)). Several small HEPs were developed in the Periyar River basin before the commissioning of Idukki HEP, the details of which are given in Table 1. After the Idukki HEP, two projects were commissioned in the Periyar River basin. They are (1) the Idamalayar HEP (Idamalayar River, a branch of the Periyar River), with an effective storage of 1017.8 million cubic meters and (2) the Lower Periyar HEP (Periyar Main Stream) with an effective storage of 4.55 million cubic meters. Both of them are within basin (intra-basin) regulations.

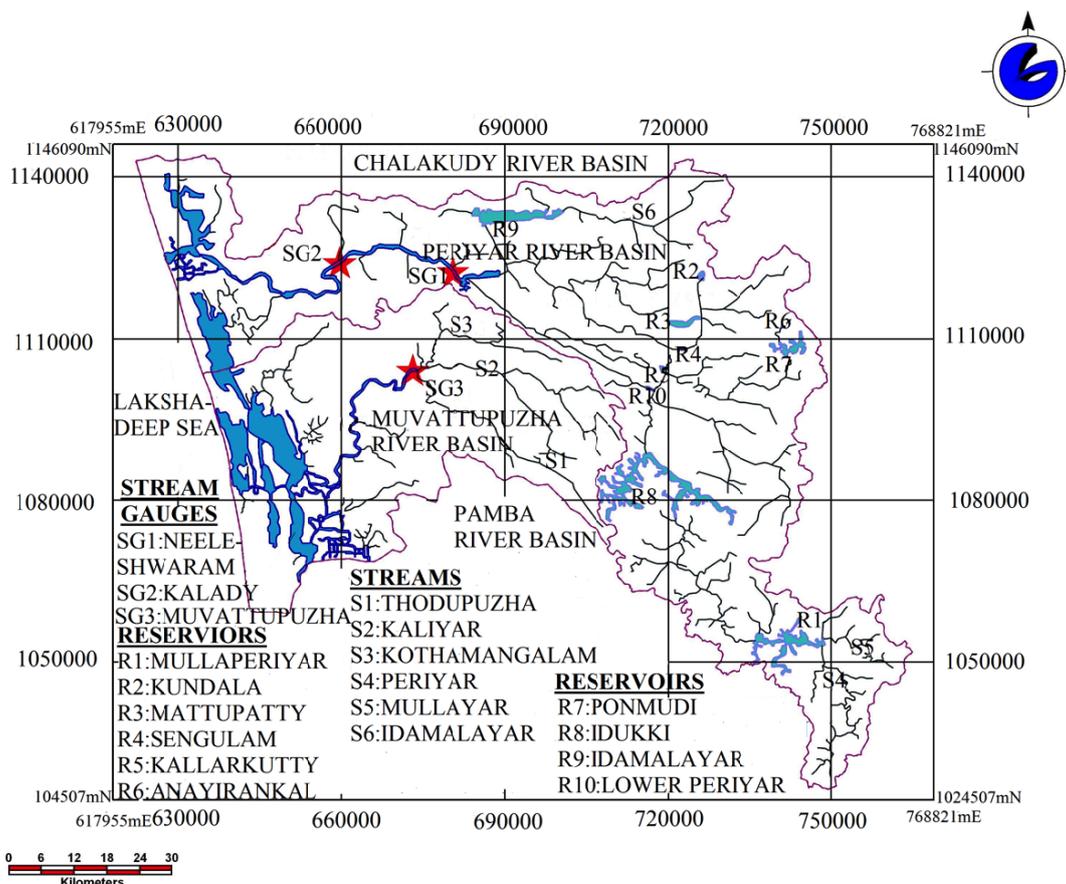


Figure 1 Location Map of Periyar-Muvattupuzha System.

Table 1 Hydro-Electric Projects (HEP) in the Periyar River basin					
HEP	Dam	Year*	F-Catchment	E-Storage	Power generation*
-	Mullaperiyar	1896	624	443.23	4 × 35
	“Kundala”		36.26	7.78	3 × 5
Pallivasal	“Mattupatty”	1947	67.34	55.21	3 × 7.5
	“C.P.R Headworks”	1957	129.75	-	-
Sengulam	Sengulam	1954	5.18	0.70	4 × 12
Neriyamangalam	Kallarkutty	1961	81.6	5.49	3 × 15
	“Ponmudi”	1963	221.445	47.4	2 × 15
Panniyar	“Anayirankal”	1965	64.75	48.98	-
Idukki	“Idukki”, “Cheruthoni”, “Kulamavu”	1976	649.31	1459.43	6 × 130
Idamalayar	Idamalayar	1987	380.73	1017.80	2 × 37.5
Lower Periyar	Lower Periyar	1997	181.3	4.55	3 × 60
Idukki (Augmentation)	“Kallar”	1989	187	79.6	-
	“Erattayar”	1989	67	508.2	-

Notes: HEP-Hydro-Electric Projects; Year* - Year of Commissioning; F-Catchment - Free catchment (km²); E-S storage - Effective storage (M m³); Power Generation* - No. of units × Capacity of each unit in Mega Watts

The Idamalayar River emerges at an elevation of 2520 m amsl. The river is dammed at a place named Ennackal (Idamalayar reservoir) and then joins the Periyar. The total length of the Idamalayar River up to the confluence point with

the Periyar River is 74 km. The Periyar barrage at Bhoothathankettu is about 1.5 km downstream of the confluence of the Idamalayar with the Periyar. The Periyar then flows through the midland and lowland and finally joins the Vembanad wetland

system.

The Muvattupuzha River is formed by the joining of three tributaries (i) the Kothamangalam, (ii) the Kalyar and (iii) the Thodupuzha. The longest of these tributaries is the Kaliyar which originates from Taragamkanam at an elevation of 1094 m amsl. The basin area is 1554 km². The Thodupuzha is the receptor of the tail water from the Moolamattom power house of the Idukki HEP, the largest HE project in Kerala. Since the power production from the Moolamattom power house is continuous throughout the year, a medium flow of clean and clear water is maintained in the river, even in summer. Even though only surplus water is received in this river, the flow pattern of the river was changed considerably as the current pattern of flow is to a great extent is dependent on the water released after power generation from the Idukki HEP.

The Periyar and Muvattupuzha River basins are the fresh water sources for three major irrigation projects (Periyar Valley Irrigation Project (PVIP, 1967), Muvattupuzha Valley Irrigation Project (MVIP, 1994) and Idamalayar irrigation Project (IIP, under construction)). These two rivers are sources of water for the major industrial belt of Kerala, several domestic water schemes and play a major role in sustainability of Vembanad wetland system downstream of these rivers. These two basins are rich in aquatic and riparian biodiversity with several endemic species. Surveys on the aquatic flora and fauna indicate that several species are in endangered condition (James et al. 1997). A study on hydrologic changes due to human interventions in these Rivers is important because of these factors.

2 Data

Daily flow time series from three stream gauging sites were analyzed in this study (Figure 1 and Table 2). These records were provided by the Central Water Commission, Government of India and Kerala State Water Resources Department. Even though streamflow is monitored at other

locations in the river basins under consideration, data in most of the cases are not continuous with several missing records. The daily data used for the study are given in Table 3.

In the Periyar River daily streamflow data at two downstream gauging stations (Central Water Commission station at Neeleshwaram for 1971-2011 and Water Resources Department station at Kalady for 1963-1971) was used for the analysis. These stations are located just downstream of all large impoundments and diversion schemes in the basin. Between the Neeleshwaram and Kalady gauging sites no major tributaries join the Periyar River. Major withdrawal schemes were also absent in this stretch of the river course during the period 1963-1971. The daily streamflow data at the Kalady and Neeleshwaram gauging sites (before the construction of the Idukki HEP) showed good correlation (r^2 value +0.931) in the linear regression analysis. This correlation is used to simulate flow data at Neeleshwaram for a part of the pre-project period (June, 1963- May, 1971), since stream gauging at the Neeleshwaram was initiated in the year 1971. For the remaining period of analysis (1971-2006), the actual streamflow at the Neeleshwaram gauging site is used.

In the Muvattupuzha River basin, major change in the streamflow regime occurred when the tailrace water from Idukki HEP was transferred to this basin in 1976. The alterations were analyzed using daily flow data for the 1963-2009 period recorded at the Muvattupuzha stream gauge station, which is maintained by the Water

Table 2 Location of steam gauge stations

Station	Location		River	C-area
	Lat	Long		
Neeleshwaram	10°11'00" N	76°30'00" E	Periyar	3824.68
Kalady	10° 10'00" N	76°27'00" E	Periyar	3833.15
Muvattupuzha	09°59'00" N	76°35'00" E	Muvattupuzha	1109.75

Notes: C-area= Catchment area (km²)

Table 3 Data used for the study

River-gauging station	Daily data availability (yyyy-mm-dd)	Missing records
Periyar- Neeleshwaram	1971-06-01 to 2011-05-31	1999 (Jun-Nov)
Periyar- Kalady	1963-06-01 to 1971-05-31	Nil
Muvattupuzha -Muvattupuzha	1963-06-01 to 2009-05-31	1972(Jan-Dec); Jun 1987-May 1988; Jun 1989-May 1990

Resources Department, Government of Kerala. This gauge is located downstream, of the confluence of three major tributaries: (i) the Thodupuzha (receiving tailrace water from Idukki HEP), (ii) the Kaliyar and (iii) the Kothamangalam rivers. The Muvattupuzha Valley Irrigation Project (MVIP), a major irrigation project proposed to utilize the tailrace release from Idukki HEP was partially commissioned in 1994. The water diversion is done at Malankara using a diversion dam (Figure 1). The impact of partial diversion was analyzed using the daily flow data for the Muvattupuzha River during the period 1995-2009.

3 Methods

The flow regime that existed in the Periyar and Muvattupuzha Rivers before 1976 is considered as the pre-project (undisturbed) condition. Daily streamflows of the Periyar and Muvattupuzha Rivers for undisturbed and regulated conditions are studied to evaluate the impact of HEPs.

3.1 The ‘Range Variability Approach’

The IHA is a suite of statistics developed by The US Nature Conservancy (<http://www.nature.org/>) to assess the degree of hydrologic alteration caused by human activities. It consists of 67 parameters, which are subdivided into two groups- 33 IHA parameters and 34 EFC (Environmental Flow Component) parameters. These hydrologic

parameters were developed based on their ecological relevance and their ability to reflect human-induced changes in flow regimes across a broad range of influences including dam operations, water diversions etc. The Range Variability Approach (RVA) uses daily streamflow data to compute 33 hydrological parameters used to evaluate hydrologic alterations, which are categorized into five groups addressing the magnitude, timing, frequency, duration, and rate of change (Table 4) (refer IHA User's Manual, The Nature Conservancy, 2006 for definition of the parameters). Hydrologic Alteration (HA) is defined as the degree to which the RVA target range is not attained. $HA = (\text{observed frequency} - \text{expected frequency}) / \text{expected frequency}$, which is usually expressed in percentage values.

Group-1: At any given time the magnitude of monthly mean flows is a measure of availability or sustainability of a habitat for aquatic and riparian biota.

Group-2: Daily discharge data are used in IHA to evaluate the minima and maxima, which are synthesized and grouped in to several temporal scales, for each year. (1-day, 3-days, 7-days 30-days and 90-days). These parameters describe the magnitude and duration of annual extreme flows. Base flow index (defined as: 7-day minimum flow/ mean flow for the year) and number of days with almost zero flow are also included in this group. The mean magnitudes of high and low water extremes provide measure of environmental stress during the year. The inter-annual variation in the

Table 4 Summary of 33 hydrologic parameters used in Indicators of Hydrologic Alteration (IHA) Software (The US Nature Conservancy 2006)

General group	Flow regime features	Hydrologic parameters
Group 1: Magnitude of monthly water conditions	Magnitude; Timing	Mean value for each calendar month
Group 2: Magnitude and duration of annual extreme conditions	Magnitude; Duration	A min and A max of 1-day means, 3-day means, 7-day means, 30-day means and 90-day means; Number of zero flow days; Base flow Index
Group 3: Timing of annual extreme water conditions	Timing	Julian date of each annual; 1-day max & 1-day min
Group 4: Frequency and duration of low and high pulses	Magnitude; Frequency; Duration	Number of high pulses each year; Number of low pulses each year; Mean Duration of high pulses and low pulses within each year
Group 5: Rate and frequency of water condition change	Frequency; Rate of change	Number of rises; Number of falls; Number of Reversals

Notes: A min = Annual minimum, A max = Annual maximum

magnitude of these extremes provides another expression of contingency.

Group-3: Mean value of Julian dates of annual 1-day maxima and minima indicate the timing of annual extreme flows, which determines whether certain life cycle requirements are met or can determine the degree of stress or mortality associated with extreme events such as floods or droughts.

Group-4: Four parameters included in this group refer to the frequency and duration of low and high pulses. The high pulses are the periods within the year when the daily flows are above the 75th percentile of the pre-dam period. The low pulses correspond to periods when daily flows are below 25th percentile of the pre-dam period. The duration of time over which a specific water condition exists may determine whether a particular life cycle phase can be completed or the degree to which stressful effects such as inundation or desiccation can accumulate.

Group-5: Three parameters (rise rate, fall rate and number of reversals) indicate the number and mean rates of both positive (rise) and negative (fall) changes of flow on two consecutive days. The rate of change in water condition may be tied to the stranding of certain organisms along the edge of the water or the ability of the plant roots to maintain contact with the phreatic water supplies. For these parameters, the IHA software can perform a Range of Variability Analysis. For each of the parameters, IHA calculates a HA factor, as follows:

- For each parameter, IHA software divides the full range of 'pre-impact data' into three different categories, generally percentiles (i) 0–33% (low alteration) (ii) 34–67% (moderate alteration) and (iii) 68–100% (high degree of alteration)

- The program then analyzes the 'post-impact' data and compares the observed distribution of data with the distribution from the pre-impact data. Hydrologic Alteration (HA) is defined as the degree to which the RVA target range is not attained.

- It is expressed as a percentage, which can be calculated as:

HA factor = (observed frequency-expected frequency)/expected frequency (1)

- A positive HA factor means that the frequency of values in the category (percentile

grouping) has increased in the post-impact period, while a negative HA factor means that the frequency of values in the category (percentile grouping) has decreased in the post-impact period.

The calculations of hydrologic alterations are done at individual stream gauges based on daily streamflow records. Thus the hydrologic alterations assessed are point based temporal information. These results are representative of a larger stretch of the stream, where the downstream flows are not subjected to other major changes.

3.2 Selection of normal years for analysis

Analyses of alterations in flow regime caused by human structures require a longer data period. Hence, the frequency of occurrence of wet and dry years during the pre- and post-project periods varies in many cases and may influence the hydrological alteration values.

To identify the influence of such changes on the analysis of IHA, (Chulsang Yoo 2006) recommended that the years in which annual basin precipitation is more than $P_{\text{mean}+0.75\text{stdv}}$ ($P \geq P_{\text{mean}+0.75\text{stdv}}$) can be considered as the wet years, whereas, periods with annual basin precipitation less than $P_{\text{mean}-0.75\text{stdv}}$ are considered as the dry years ($P \leq P_{\text{mean}-0.75\text{stdv}}$). Periods with annual basin precipitation values between wet and dry year thresholds can be considered as the normal years ($P_{\text{mean}-0.75\text{stdv}} \leq P \leq P_{\text{mean}+0.75\text{stdv}}$).

Data from rain gauges in the Periyar and Muvattupuzha basin were used to compute the mean annual precipitation using isohyetal method. The above method was used to classify water years as wet, normal and dry years for the Periyar-Muvattupuzha River basin (Figures 2-3).

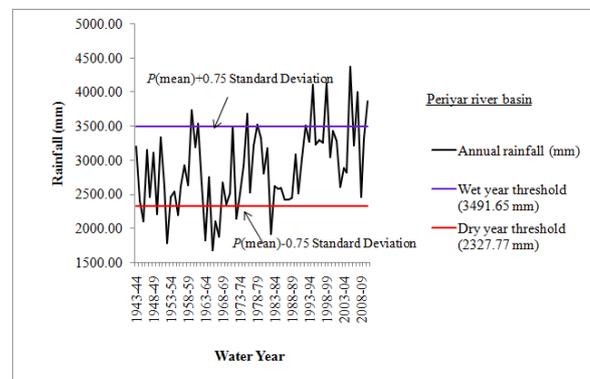


Figure 2 Periyar River basin- wet, dry and normal rainfall years.

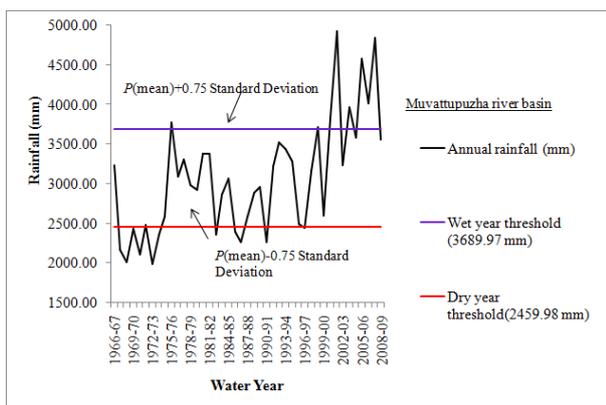


Figure 3 Muvattupuzha River basin-wet, dry and normal rainfall years.

Wet and dry years were eliminated from the available daily streamflow records. The remaining records were used in parametric comparison of pre- and post-periods flow regime using the IHA software.

3.3 IHA Factors used in the Periyar and Muvattupuzha Rivers

Normal years were used to arrive at the hydrologic alterations in the Periyar and Muvattupuzha Rivers for different degrees of regulation (Table 5). The different periods considered for analysis are named as follows; AB-Period before construction of Idukki HEP (before 1976); BC-Period after construction of Idukki HEP and before Idamalayar HEP (1977-86); CD-Period after construction of Idamalayar HEP and before Lower Periyar HEP (1986-1996); DE-Period after Lower Periyar HEP (after 1997). Similarly the data for the Muvattupuzha River was also divided into three periods (PQ, QR and RS); the divisions being based on Idukki HEP (1976) and Partial commissioning of MVIP (1994). Considering the influence of most of the IHA indicators on the total degree of hydrologic alterations with percentile values greater than 67%, it is not necessary to determine the degree of hydrologic alterations for all the 33 indicators calculated using the IHA software. Herein, the ranked mean absolute values of 33 IHA parameters for different degrees of regulation in the Periyar and Muvattupuzha Rivers are provided to detect statistically significant contributions to IHA factors. Then the HA factors

are singled out according to whether the mean value of IHA factor exceeds the 67th percentile (IHA = 40.78 (Periyar River) IHA = 100 (Muvattupuzha River), which is different from the test used by Richter (1998) in the Upper Colorado river basin, USA, wherein six IHA factors (i.e. annual maxima, 30-day low flows, high pulse duration, date of annual maximum and minimum and number of reversals) were the factors used to decide the degree of hydrologic alterations. Factors (exceeding the 67th percentile) used in the current study for the Periyar and Muvattupuzha Rivers are detailed in Tables 6 and 7. The means, standard deviations and ranges of the 33 hydrologic parameters before regulation in the Periyar and Muvattupuzha Rivers are also detailed in these Tables. The non-attainment of IHA parameters (number of values falling beyond the threshold limits expressed as percentage of total number in the data set) for different degree of regulations in both the rivers are detailed in Tables 8 and 9.

4 Results and Discussion

Flow regime changes in the Periyar and Muvattupuzha Rivers due to commissioning of three HEPs in the Periyar River basin are analyzed. Inter-basin and intra-basin regulations of different magnitudes cause alterations in the array of hydrologic indices discussed above. Analysis is done for different periods, so as to bring out the impact of regulations by HEPs.

4.1 HA prior to regulations in the Periyar and Muvattupuzha Rivers

The means, standard deviations and ranges of thirteen parameters above 67th percentile before regulations are detailed in Tables 6 and 7, where the RVA management targets are based on one standard deviation from the mean. The last column of each of the IHA parameter is the non-attainment (%) of IHA, defined as the percentage of time the hydrologic parameter is outside the RVA target ranges. The non-attainment range for the period prior to regulation, in the Periyar River ranges from 8.33% to 50% whereas for the Muvattupuzha River it is from 22.22% to 44.44 %. This non-attainment values show that even for the

unregulated conditions, flow regime does not attain the RVA target every year. For example, the low pulse duration during pre-construction period in the Periyar River was 58.33% (Table 6) indicating

that for more than half the years the values are outside the RVA target range. In the Muvattupuzha River all the thirteen parameters selected show more than 22% of non-attainment.

Table 5 Statistics for 33 indicators of hydrologic alteration (IHA) for different degree of regulations in the Periyar and Muvattupuzha Rivers

IHA Factor	Absolute value of Hydrologic Alteration (%)						
	Neeleshwaram stream gauge*				Muvattupuzha stream gauge+		
	AB-BC	AB-CD	AB-DE	Average	PQ-QR	PQ-RS	Average
Jun	14.29	40	45.45	33.25	88.33	100	94.17
Jul	33.33	0	39.39	24.24	5	44	24.5
Aug	14.29	0	51.52	21.94	28.33	12	20.17
Sep	23.81	33.33	15.15	24.10	16.67	44	30.33
Oct	33.33	33.33	33.33	33.33	6.667	40	23.33
Nov	80.95	33.33	75.76	63.35	2.083	40	21.04
Dec	31.43	40	85.45	52.29	30	12	21
Jan	42.86	75	27.27	48.38	100	100	100
Feb	31.43	20	16.36	22.60	100	100	100
Mar	31.43	20	16.36	22.60	100	100	100
Apr	31.43	20	16.36	22.60	100	100	100
May	31.43	60	30.91	40.78	100	100	100
1-day min	54.29	20	1.818	25.37	100	72	86
3-day min	54.29	60	1.818	38.71	100	100	100
7-day min	77.14	60	1.818	46.32	100	100	100
30-day min	31.43	60	30.91	40.78	100	100	100
90-day min	31.43	40	30.91	34.11	100	100	100
1-day max	14.29	20	12.73	15.67	45.83	30	37.92
3-day max	14.29	20	41.82	25.37	6.667	16	11.33
7-day max	37.14	0	27.27	21.47	5	16	10.5
30-day max	14.29	0	27.27	13.85	60.42	5	32.71
90-day max	14.29	16.67	39.39	23.45	18.33	12	15.17
Number of zero days	0	0	27.27	9.09	16.67	16.67	16.67
Base flow index	77.14	60	16.36	51.17	100	100	100
Date of min	37.14	60	70.91	56.02	65	72	68.5
Date of max	23.81	16.67	39.39	26.62	5	40	22.5
Low pulse count	14.29	16.67	27.27	19.41	100	100	100
Low pulse duration	31.43	80	56.36	55.93	100	100	100
High pulse count	33.33	16.67	3.03	17.68	41.67	12	26.84
High pulse duration	54.29	80	56.36	63.55	6.667	12	9.33
Rise rate	42.86	75	63.64	60.5	12.5	100	56.25
Fall rate	77.14	80	70.91	76.02	28.33	72	50.17
Number of reversals	37.14	60	56.36	51.17	100	100	100
MAVHA	33.81	36.87	35.05		57.24	62.65	

Notes: MAVHA - Mean Absolute Value of Hydrologic Alteration (%); Hydrologic alteration above 67th percentile for different degree of regulations (67th percentile IHA (absolute average value) for the Periyar River is 0.4078, Muvattupuzha River is 1.0);

Explanations for different periods AB, BC,CD,DE, PQ, QR and RS given in section 3.3;

*Periyar River: Unregulated flow regime (AB) is compared with flow regimes after different degrees of regulation during the periods BC,CD and DE and hydrologic alterations were quantified;

+Muvattupuzha River: Unregulatedflow regime (PQ) is compared with flow regimes after different degrees of regulation during the periods QRand RSand hydrologic alterations were quantified.

Table 6 Indicators of hydrologic alteration (IHA) before flow regulations in the Periyar River (1963-1975)

	Mean	Std Dev	Range Limits		RVA Targets		Non-Attainment *
			Lower	Upper	Lower	Upper	
Group-1							
Nov	201.5	165.42	57.78	691.4	36.08	366.09	33.33
Dec	131.9	229.69	40.4	856.7	-97.79	361.5	33.33
Jan	37.44	16.89	14.57	69.84	20.55	54.32	41.66
May	60.64	58.184	15	217.9	2.456	118.8	16.66
Group-2							
7-day min	15.2	6.544	5.1	29.65	8.656	21.73	16.66
30-day min	17.92	7.43	6.633	32.82	10.49	25.35	41.66
BFI	0.06251	0.02921	0.01565	0.1092	0.033	0.09172	33.33
Group-3							
Julian Date*	62.67	57.199	28	284	63	120	50
Group-4							
LPD	12.2	9.484	1	34.75	2.716	21.69	58.33
Group-5							
Rise rate	75.68	18.05	44	102.2	57.63	93.74	50
Fall rate	-57.98	16.65	-86.89	-31.35	-74.63	-41.33	41.66
Number *	181.4	20.5	124	200	160.9	202	8.33

Notes: RVA - Range variability approach; BFI - Base flow index; LPD - Low pulse duration; Number* indicates number of reversals; Julian Date* indicates Julian Date of Annual Min; Non-attainment* indicates values falling beyond the threshold limits expressed as percentage of total number in the data set%(Average non-attainment: 32.69%).

Table 7 Indicators of hydrologic alteration (IHA) before flow regulations in the Muvattupuzha River (1963-1975)

	Mean	Std Dev	Range Limits		RVA Targets		Non-Attainment*
			Lower	Upper	Lower	Upper	
Group-1							
Jan	10.82	5.56	2.54	19.18	5.26	16.38	33.33
Feb	5.96	3.44	1.94	11.39	2.52	9.41	33.33
Mar	4.77	3.33	2.06	11.57	2.06	8.10	22.22
Apr	8.11	5.06	2.19	17.53	3.04	13.17	44.44
May	20.61	14.82	4.76	53.07	5.79	35.43	22.22
Group-2							
3-day min	2.71	2.89	0	8.89	0	5.61	22.22
7-day min	3.03	2.97	0	9.01	0.06	6.01	33.33
30-day min	3.81	3.50	0.07	10.66	0.32	7.31	33.33
90-day min	5.74	3.56	2.13	11.73	2.18	9.30	22.22
BFI	0.04	0.04	0	0.12	0.0001	0.07	22.22
Group-4							
LPC	5.67	3.54	2	14	2.13	9.20	22.22
LPD	23.68	18.01	61	4.67	5.67	41.69	22.22
Group-5							
Number*	120.22	11.62	101	138	108.61	131.84	33.33

Notes: BFI - Base flow index; LPC - Low pulse count; LPD - Low pulse duration; Number* indicates number of reversals; Non-attainment* indicates values falling beyond the threshold limits expressed as percentage of total number in the data set%(Average non-attainment: 28.20%).

4.2 Impacts of inter-basin and intra-basin regulations

4.2.1 Idukki HEP (1976)

The hydrologic alterations in 33 IHA parameters, after commissioning of the Idukki

reservoir in the Periyar and Muvattupuzha Rivers, are detailed in column 2 & 5 of Table 5. Water transfer from the Periyar River to the Muvattupuzha River under this project caused considerable hydrologic alteration in the Muvattupuzha River compared to the Periyar River. The average hydrologic alteration in the

Table 8 Non-attainment* for different degree of regulations: Periyar River

Parameter	Reference Period			
	AB	BC	CD	DE
Jan	41.66	77.77	20	53.84
May	16.66	11.11	20	30.76
Nov	33.33	11.11	10	7.69
Dec	33.33	0	0	0
7-d min	16.66	88.88	90	69.2
30-d min	41.66	55.55	90	92
Base flow index	66.66	66.66	80	53.84
Date of min	55.55	55.55	80	84.62
Low pulse duration	55.55	55.55	85	53.38
High pulse duration	0	0	0	0
Rise rate	50	50	0	0
Fall rate	41.66	41.66	20	30.76
No of reversals	8.33	8.33	50	69.2
Average non-attainment	32.90	40.16	41.92	41.94

Notes: Non-attainment* indicates values falling beyond the threshold limits expressed as percentage of total number in the data set (%).

Table 9 Non-attainment* for different degree of regulations: Muvattupuzha River

Para*	Reference Period			S1	S2
	PQ	QR	RS		
Jan	33.33	100	100	88.88	77.77
Feb	33.33	100	100	100	94.44
Mar	22.22	100	100	94.44	88.88
Apr	44.44	100	100	100	94.44
May	22.22	100	100	88.88	55.55
3-d min	22.22	100	90.9	83.33	61.11
7-d min	33.33	100	100	83.33	66.66
30-d min	33.33	100	100	94.44	88.88
90-d min	22.22	100	100	100	77.77
BFI	22.22	100	100	72.22	55.55
LPC-	22.22	100	91.66	83.33	77.77
LPD	22.22	-	-	60	81.25
Number*	33.33	100	83.33	94.44	94.44
Ave. non-attainment	28.20	100	97.158	87.94	78.03

Notes: Para*: Parameters; Non-attainment*, see Notes in Table 8; S1 (Scenario 1): After MVIP (Full Commissioning); S2 (Scenario 2): Additional diversion during January-May (Refer table 10 last row); BFI - Base flow index; LPC - Low pulse count; LPD - Low pulse duration; Number* indicates number of reversals; Muvattupuzha River: Average water deficit (Jan-May) is Nil for Scenario 1 and 0.219 Mm³/day for scenario 2.

Muvattupuzha River was 57.34% compared to an average hydrologic alteration value of 33.81% in the Periyar River. The monthly flows during January, May November and December, 7-day

minimum, 30-day-minimum, base flow index, date of minimum, low pulse duration, high pulse duration, rise rate, fall rate and number of reversals showed greater than 67th percentile hydrologic alteration values in the Periyar River. In the Muvattupuzha River, receiving inter-basin water transfer at a rate more than 50 m³/sec after power generation under the Idukki HEP, non-monsoon monthly flows (January-May), 3-day minimum, 7-day minimum, 30-day minimum, 90-day minimum, base flow index, low pulse count and duration and number of reversals showed 100% hydrologic alteration indicating that the impact of Idukki HEP was much more pronounced, especially for low flow IHA parameters in the Muvattupuzha River.

Non-attainment analysis was done for ranked IHA parameters. For the Periyar River the non-attainment increased from 32.9 to 40.16% after commissioning of the Idukki HEP, whereas for the Muvattupuzha all selected IHA parameters except low pulse duration showed 100% non-attainment. Since low pulse count in the Muvattupuzha River was zero after commissioning of Idukki HEP the pulse duration value was not available.

4.2.2 Idamalayar and Lower Periyar HEPs (Periyar River)

Hydrologic Alterations after commissioning of Idamalayar and Lower Periyar HEPs were 36.87 and 35.05 respectively (Table 5, Column 3 & 4). The reduction in hydrologic alteration after Lower Periyar HEP (1997) may be because of increase water utilization for meeting water demand in various sectors, especially domestic water supply and irrigation. Several water supply schemes were commissioned upstream during the period after 1997 to meet urban and rural domestic water supply needs. The irrigation demand for summer crops also increased after 1997. The non-attainment rate was almost stable (42%) after the Idamalayar and Lower Periyar intra-basin regulations (Table 8, column 4 & 5).

4.2.3 Muvattupuzha Valley Irrigation Project (MVIP, Muvattupuzha River)

The hydrologic alteration showed an increase to 62.65% from 57.24%, after the major irrigation project (MVIP) was partially commissioned in 1994. This is mainly because the fact that group-5 IHA

Table 10 Water availability, demand and excess water available for diversion in the Muvattupuzha River

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Water availability (m³/sec) [Based on 16 years data(1977-1994)]												
AMS	53.06	53.43	53.3	60.01	75.51	309.7	394.6	294.4	164.3	172.5	126.9	58.89
Water Demand (Present)(m³/sec)												
MVIP	9.285	14.16	19.37	6.092	4.569	0.736 8	0.477	1.96	5.277	6.977	19.02	22.419
IWS	20	20	20	20	20	20	20	20	20	20	20	20
DWS	2	2	2	2	2	2	2	2	2	2	2	2
LIS	2.23	3.459	4.734	2.974	1.116	0.1811	0.1167	0.4797	1.289	1.705	4.65	5.48
Water Demand (Future)(m³/sec)												
FR	11.58	11.58	11.58	11.58	11.58	11.58	11.58	11.58	11.58	11.58	11.58	11.58
TWD	45.37	38.20	42.65	42.65	39.27	34.50	34.17	36.02	40.14	42.26	57.25	61.48
MWDP	7.695	15.23	10.65	17.45	36.25							

Notes: AMS - Average monthly streamflow (m³/sec); MVIP - Muvattupuzha Valley Irrigation Project; IWS - Industrial water supply; DWS - Domestic Water supply; LIS - Lift irrigation schemes; FR - Future Requirements [Domestic & Industrial sectors]; TWD - Total water demand (present + future); MWDP - Max water diversion possible (January-May)

factors (rise rate and fall rate) showed increased hydrologic alteration. The non-attainment rate during this period reduced from 100% to 97.15%.

Abe et al. (1997) used the modified tidal prism method to study the probable changes in the mixing and exchange processes in the Muvattupuzha estuary, after the full commissioning of MVIP project. The analysis shows that reduction of fresh water discharge in the estuary from 45 m³/sec to 25 m³/sec may cause a remarkable increase in salinity levels during non-monsoon months. A minimum discharge level of 30m³/sec has to be maintained in the lower reaches of the Muvattupuzha River to keep off salinity, so that water dependent sectors downstream will not suffer due to water diversion for irrigation under MVIP.

The monthly water availability and demand (present and future) in the Muvattupuzha River downstream of the gauging site are detailed in Table 10. If a 50% return flow from irrigation sector (CGWB 2009) and 80% return flow from domestic and industrial sectors (NIUA 2005) is assumed, these return flows will be sufficient to meet the instream flow requirements of 30 m³/sec in the estuary portion of the Muvattupuzha River to prevent the salinity intrusion.

Two scenarios were analyzed for calculating non-attainment: (1) The scenario after full commissioning of MVIP (2) The scenario of diverting excess fresh water available in the basin during January to May, after meeting present and future demands. The analyses show that the non-attainment rate for scenario (1) (after full

commissioning of MVIP) will be 87.94% and for scenario (2) (diversion of excess fresh water to adjacent basin after meeting present and future needs in the Muvattupuzha River basin) will be 78.03%. The corresponding water deficit for the period (January-May) for scenario (1) is nil and for scenario (2) is 0.219 million m³/day (Table 9).

Groundwater studies in the basin by Gopinath G (2003) reveal that the groundwater condition in the basin is highly satisfactory and the southwestern part of the basin has a very good prospect zone with high optimum yield, a low recuperation time and a high storage coefficient. Through conjunctive use of surface, groundwater and scientific reservoir operations, the water deficit in the basin and hydrologic alterations in the Muvattupuzha River can be minimized.

5 Conclusions

The influences of inter-basin and intra-basin water transfers in the flow regimes of the Periyar and Muvattupuzha Rivers in the humid Western Ghat region of Kerala State due to commissioning of three HEPs (Idukki (1976), Idamalayar (1987) and Lower Periyar (1997)) were systematically studied using IHA framework. Conclusions are summarized as follows.

- The impacts of the Idukki project on the downstream flows in the Periyar River were considerable. The inter-basin diversion of water after power generation to the adjoining Muvattupuzha River basin caused substantial alterations in several of the 33 factors compared to

intra-basin regulations in the Periyar River due to commissioning of the Idukki HEP.

- Even though the subsequent development of the Idamalayar and Lower Periyar schemes helped in flood moderation and fair weather flow augmentation due to intra-basin regulations, the hydrologic alterations in the Periyar River also increased due to increased degree of regulations.

- In both the Periyar and Muvattupuzha Rivers, the low flow indicators were sensitive to regulations and showed considerable alterations when the degree of regulations changed.

- The diversion of excess fresh water from the Muvattupuzha River will reduce the value of non-attainment, but several other factors like the of water deficit and duration of the deficit period, the possibility of conjunctive use of groundwater and surface water to meet future demands etc. have to be looked into before such diversions are attempted.

- Construction and operation of reservoirs with multiple purposes i.e, power generation, flood reduction, irrigation etc. invariably induces high hydrologic alteration in the flow regime. These alterations may have affected the aquatic and riparian flora and fauna. Indiscriminate sand mining and pollution added negatively to such alterations (Sreedharan et al. 2010). A recent fish survey conducted by Kurup et al. (2004) in the Periyar and Muvattupuzha Rivers indicates that more than 50% of the ornamental/food fish species are critically endangered. Studies show that 56% of the endemic fishes of Kerala, classified under 32 species, are from Periyar River which makes the river basin a unique one in southern India (Arun 1998), Kurup et al. (2001). The construction of 15 dams has almost closed the river system to movement of the biota through the basin. Percentage of the basin closed to the movement of aquatic biota by structures is more than 70% (Smakhtin et al. (2007). Degree of flow regulation (calculated as the ratio of total storage capacity (3.27 Billion Cubic Meters (BCM)) to long-term mean annual flow volume at the outlet (12.3 BCM), is 25% (KSEB 2005).

- Application of the Habitat Suitability Index (HIS) model to study selected endangered and endemic fish species of Periyar River shows that construction of reservoirs under HEPs caused fragmentation of Periyar River (Manoj 2013).

Many endemic and rare fish in this river occur as fragmented populations, isolated in headwater tributaries. The strong positive correlation with bedrock and negative correlation with cobbles indicate that species abundance will decline with changes in flow regime and the reduction in the size of the riverbed material. With the construction of reservoirs, the change of substratum to a muddy type adversely affects the species. The study reports that the level of dissolved oxygen, the most important parameter affecting this species, was reduced with the construction of the dam. The typical microhabitats in flowing water ecosystems such as riffle and glide, which have a strong influence on the species, are vanishing as a result of flow regulations by reservoirs. The typical hiding places such as large and small woody debris piles are also decreasing in number as a result of construction of large storage structures. Multiple dams reduced flow downstream leading to decline in fish numbers, and extinction of fish species, prawns and shrimps in the lower reaches (Joseph 2004). Periyar being a relatively small river, the sensitivity to further flow reduction is high. Large-scale fish mortality and algal blooms between Idamalayar and Eloor industrial sites located in the downstream of Periyar River were also reported (Joseph 2004).

- It is necessary to further quantify and address the uncertainties in ongoing research. The current research has shed light on the impacts of HEP on hydrological regimes, and regional water resources management in humid tropics will greatly benefit from the research results. There is a scope for further investigations on the hydrological alterations resulting from reservoir operations and its impact on the aquatic environment.

- The analysis stresses the need for formulating more sustainable policy of operation for HEPs taking into consideration hydrologic alterations and water demand downstream. Such a policy revision may considerably improve the sustainability of aquatic and riparian environments in river basins of the humid tropics.

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