Effect of Environmental Flow on Health of Dammed Rivers

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Abstract India is a water stressed country and therefore it has increased its storage capacity from 15 Billion Cubic Meter (BCM) to 200 BCM in last 60 years by constructing more than 4000 dams. Majority of rivers have been dammed. Large water storage potential has paid a lot to the country in the form of food security and economic strength. But ecological issues are becoming critical with the passage of time and the downstream flows are diminishing posing a serious threat against the lives of the rivers. This situation has brought the environmentalists and the water managers to the loggerhead. The fact that dams are not meant to break the rivers but to modulate the floods and to store a portion of the monsoon waters that could be used in the non-monsoon period for productive purposes is somehow not taken in the right spirit. Overall health of river including ecology depends on flow in the downstream of dam during non-monsoon season. Computation of environmental flow is very complex and requires some actual trials such that it can be effectively released in a planned manner and the river health can be sustainably maintained. The paper focusses on the importance of the health of the rivers with discussion of an actual case study.

Keyword Dam, Environmental flow, Food security, River

Effect of Dam on Hydraulic System, Water Chemistry and Eco System: An Overview

Rainfall that reaches the soil is either infiltrated in to the soil or it flows on the surface of the soil. A part of precipitation infiltrates in to the soil out of which some is percolated to the groundwater storage and balance is the interflow which flows through the soil to the river or drain. The part of precipitation that flows on the surface of the soil is called run-off which goes to river or drain.

Rivers and groundwater are intimately connected across multiple scales. River water infiltrates into the surrounding bed and banks, travels along short groundwater flow paths, and returns to the channel. These flow paths define the hyporheic zone, a critical ecological transition area between fluvial and groundwater ecosystems, which mediates the exchange of water, nutrients, contaminants, and heat [1] . Rivers can receive groundwater contributions or lose water to the surrounding aquifer, and these large-scale flow patterns impact the finer patterns of hyporheic exchange. For example, groundwater discharge to a gaining reach limits the size of the hyporheic zone [2]. Since reaches alternate between gaining and losing conditions over seasons and flood events [3], hyporheic exchange also varies [4]. Some reaches alternate between gaining and losing conditions daily in response to stage fluctuations. The penetration distance of river water into the surrounding aquifer prior to flow-path reversal determines the size of the hyporheic zone. The frequency of flow-path oscillations determines hyporheic residence times. The hyporheic zone functions as a reservoir for solutes and energy in rivers and facilitates important biogeochemical reactions. Hyporheic exchange therefore affects water quality at the watershed scale [5]. Some aquafers nearby the river channel are connected to the river channel have a tendency to receive some water from the river channel, hold it and then to release in the river when gravity permits. All such water contributions to the river channel which are transient in nature and form i.e. surface water and ground water at different locations and instances are generally known as base-flow once they appear in the river channel to be the part of the river flow.

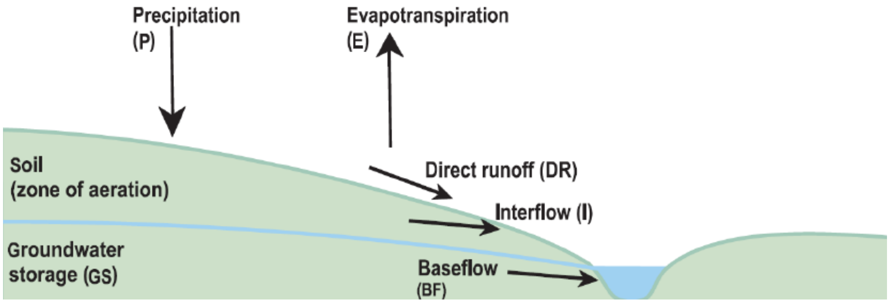

Fig. 1 River flow ingredients

Hyporheic phenomena in case of dam are different from otherwise. The residence times (hours) and path lengths (centimeters to meters) of dam induced hyporheic exchange are similar to hyporheic exchange induced by natural processes [6]. The difference between them is that the 'dam-induced' hyporheic exchange is intrinsically transient because unsteady pressures at the sediment–water interface cause the exchange and the 'natural' hyporheic exchange is rather steady because time-averaged pressure gradients at the sediment–water interface cause the exchange.

A natural river-groundwater system dominated by base-flow indicates how groundwater flows steadily through the riparian aquifer in one direction like water through a gill during most of the year. In such cases, groundwater discharge to the river limits the size of the hyporheic zone. On the other hand, a river-groundwater system downstream of a dam indicates how river water flows in and out of the riparian aquifer like air flowing in and out of lungs due to frequent stage fluctuations. Thus, behavior of river-groundwater system in base-flow dominated river differs from that in case of dam dominated river.

Dam operations fundamentally change the hydrological, thermal, and geochemical dynamics of riparian aquifers and their hyporheic zones. In the absence of dam operations, groundwater would flow steadily towards the river through the riparian aquifer like water flowing through gills. The steady discharge of groundwater would limit lateral hyporheic exchange. In contrast, dam operations induce stage fluctuations that drive river water in and out of the riparian aquifer. The unsteady, reversing flow of water through the riparian aquifer is like the flow of air through lungs [7].

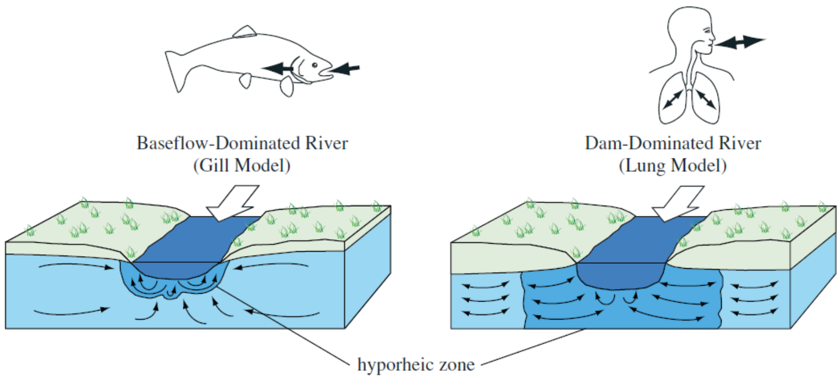

Fig. 2 Conceptual models of base-flow-dominated river and dam-dominated river [7]

The result of dam on the downstream stretch of the river is gradual decline in the base-flow and over a period of some years the base-flow evanesces and the river dries up. Several perennial rivers of India have dried up after getting broken by dams. This process is slow and therefore it is difficult to appreciate the same.

River-groundwater system once affected, base-flow is consequently affected. With decline in base-flow, water chemistry fluctuates in the river. The specific conductivity of river water is greatest in between dam releases during base-flow periods and lowest during dam releases when reservoir water dominates the flow. In the absence of dam operations, river and riparian aquifer chemistry fluctuates less. The specific conductivity of river water consistently resembles values measured during base-flow periods. Steady groundwater discharge to the river limits lateral hyporheic exchange and therefore the specific conductivity of pore water near the channel consistently resembles the specific conductivity of groundwater. Along steady groundwater flow paths, a ladder of redox conditions also regulates nitrogen, sulfur, and organic carbon inputs to the river. Thus, alterations in river-groundwater system lead to changes in quantity and quality of surface and ground water in the downstream of the dam.

Changes occur in hyporheic zone characteristics and river and aquifer chemistry due to dam operations. Biological life of the river also undergoes changes especially in the downstream. Because reservoirs require changes in land use pattern, plant, animal or human being settlement areas change. Forests, agricultural areas may be submerged. As the water level differentiates periodically, some species begin to live under water from time to time, in the tide zone [8]. This area may turn to marshy land or reed bed depending on the soil structure. Water-soil-nutrient relationship which is established after floods in the downstream of the dam, change after a long period. This also trigger changes in soil and water quality.

Table 1 Difference between base-flow-dominated river and dam-dominated river [7]

Variable	**The Gill model: Base-flow-dominated rivers**	**The Lung model: Dam-dominated rivers**
Water-table variation	Moderate to small	Rapid, large fluctuations
Hydrologic link to river	Steady groundwater flow towards river	Flow directions regularly reverse over short timescales
	Flood events can temporarily perturb flow paths and rates	
Hyporheic zone characteristics	Laterally limited by groundwater discharge to the river	Laterally extensive
	Flows driven by bed form topography, river morphology, and in-stream structures	Flows driven by river stage fluctuations downstream of dams
	Flows are generally steady but may vary in response to floods, seasons, and morphodynamics	Flow are unsteady and reverse at time-scales of hours to days
Effects on river temperature	Hyporheic and groundwater inputs steadily influence river temperatures	Hyporheic and groundwater inputs only influence river temperatures when flow direction is towards river
Effects on river chemistry	Riparian aquifer is a sink for NO_3 and SO_4 and a source for DOC	Uncertain but likely a function of competition between hyporheic residence times and reaction kinetics
Effects on riparian aquifer chemistry	Variation in redox conditions with distance along groundwater flow paths	Uncertain but likely variable in both time and space

A dam reservoir is required to be operated sensibly such that the dam does not become a threat for the aqua-life especially in the downstream stretch. Tail end dams require more sensible reservoir operations as the estuarine stretch of river is the most sensitive and the most active zone for the aqua-life. Some sea fishes come to fresh water and swim up to the spring in order to lay eggs. Later on, they return to sea with new young fishes. A dam in tail stretch of river causes interruption to the life cycle of these creatures and cause deaths in a mass. By-pass flows are designed for this purpose in some rivers as a mitigating measure to allow bilateral passage for such creatures. As various fishes tend to travel in different seasons in different directions and they travel in large number at a time, design of the fish pass does matter.

Development of Holistic Perception for Water and Ecology

Construction of dams remained a major activity for several years to meet the ever-increasing demand of the human civilization. Severe flow regulations and diversion of surface water had no consideration for the health of the downstream stretches of the rivers and livelihood concerns of the riparian people for a long as the ill-effects were not known to the planners and engineers. In Europe and U.S.A., severe effects on biodiversity came to the notice in the mid of the twentieth century and the concept of the environmental flow emerged.

In 1990 the Global Consultation on Safe Water and Sanitation for 1990s was held at Delhi, India it was emphasized on protection of the environment and safeguarding of health through the integrated management of water resources and liquid and solid waste. Integrated Water Resource Management conventionally addresses the conservation, utilization, management, etc. but this event emphasized the environment as a perspective of the Integrated Water Resource Management which was a very important dimension of viewing the water management.

In 1992, International Conference on Water and Environment was held at Dublin which concluded that fresh water is finite and vulnerable resource, essential to sustain life, development and the environment. Thus, life, development and environment were viewed holistically.

In 1992, United Nations Conference on Environment and Development was held at Rio de Janeiro from where which an important guiding principle emerged that protection of water resources, water quality and aquatic ecosystems should be essential objective of water resource management.

In March, 2000 the Second World Forum and Ministerial Conference was held in Hague where The World Water Vision was presented with three primary objectives: (1) to empower people and communities to decide how to use water, (2) to get more crops and jobs per drop and (3) to manage use to conserve fresh water and terrestrial ecosystems. This was a major thrust on preservation of ecosystems amongst growing demand of fresh water for the needs of human beings.

In August, 2013, at the Stockholm World Water Week the most important achievement of all deliberation was cultivation of sense that the environment should no longer be seen as “separate” from human spheres. India also passed through the same phase with some delayed sequence of events.

In all the deliberations on water resource management, there had been the central idea of conservation of river ecology. During last 25 years, the science of environmental flow has gained a large-scale support and a significant development of methods of computing environmental flows for rivers has taken place as a result of several dialogues. This changed the water resource management strategies and emphasis on ecosystems and sustainable and perennial flows of rivers became a significant feature of the basin level planning.

In the post-independence era, i.e. after 1947, the main issue was of food security for which creation of storage potential was must and hence India constructed more than 4000 dams in only 40 years. Most of the Indian rivers have now been excessively exploited to fulfil ever-increasing demand from power, agricultural, industrial and municipal sectors. Now the ill-health of the downstream stretches of the rivers and ecosystems have been acknowledged in India and hence some mitigating measures are being taken up. Main thrust is in the form environmental flow like Europe and USA. However, river restoration has been a more popular term in India which includes environmental flow, pollution control, base-flow revival, etc. Environmental flow is being studied for many rivers like Ganga, Yamuna, Satluj, Godavari, Narmada, Tapi, etc. but the implementation needs more serious efforts.

Experiment with Mahi River of Gujarat, India

Mahi is a river in western India. It originates from Vindhyachal Hills, Madhya Pradesh and after flowing through Rajasthan, enters Gujarat and meets in Bay of Khambhat. Its total length is 583 Km. and catchment area is 34,842 Km^2. Bhadar is right bank tributary and Panam, Kun and Goma are left tributaries of Mahi River. A lot of people worship to Mahi River and lot more religious places and temples are situated by its shore. Due to the enormousness of the river, it is also known as a Mahisagar. In Rajasthan, there is a dam near Banswara with reservoir known as Bajaj Sagar. In Gujarat, there is a dam known as Kadana and is a weir known as Wanakbori. In the tail stretch, there has been constructed a small weir known as Sindhrot. Length of river from Wanakbori weir to the ocean is 120 Km approximately and from Sindhrot weir to the ocean is 35 Km. Thus, the flow is highly regulated.

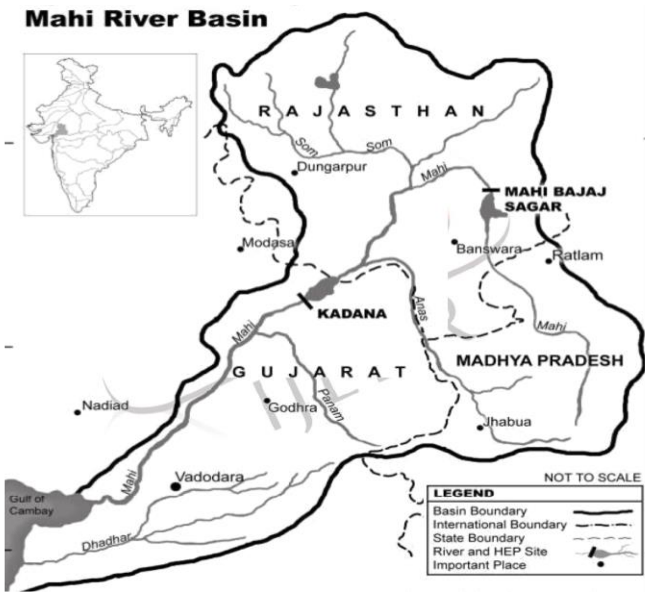

Fig. 3 Basin map of Mahi

Mahi estuaries has been facing serious issues of salinity ingress and rising saline levels in groundwater. According to Comptroller and Auditor General (CAG) Report 2011, salinity ingress area has been increased by 15%. Compared with the data of 1977-1984, there has been an addition of 88,947 hectares to the affected areas. According to the Central Pollution Control Board (CPCB), Government of India, the major reasons for polluted Mahi river stretch in Gujarat are effluents directly discharged by the factories into the water bodies and domestic effluents released by the municipalities. Millions of litres of untreated or semi-treated effluents are dumped in the river.

Table 2 Fish faunal diversity of downstream zone of Mahi river [9]

Sr. No.	**CLASS: PISCES**		**SUB-CLASS: TELEOSTEI**
	Order	**Family**	**Genus and species**
1	Acanthoptergii	Percidae	*Ambassis ranga*
2			*Therapon jarbua*
3		Gobiidae	*Gobius giuris*
4			*Boleophthalmus glaucus*
5		Rhynchobdellidae	*Mastacembelus pancalus*
6			*Mastacembelus armatus*
7		Mugilidae	*Mugil belank*
8			*Mugil corsula*
9		Ophiocephalidae (channa-dae)	*Ophiocephalus marulius*
10			*Ophiocephalus punctatus*
11		Cichlidae	*Oreochromis mossambicus*
12	Ancanthini	Pleuronectidae	*Cynoglossus macrolepidotus*
13	Physostomi	Siluridae	*Macrones seenghala*
14			*Arius nenga*
15		Scombresocidae	*Belone annulata*
16		Cyprinidae	*Labeo boggut*
17			*Labeo rohita*
18			*Cirrhina reba*
19			*Cirrhina fulungee*
20			*Barbus sarana*
21			*Barbus ticto (Puntis ticto)*
22			*Rohtee cotio*
23			*Chela bacaila*
24		Notopteridae	*Notopterus kapirat*
25		Clupeidae	*Engraulis mystax*
26			*Clupea fimbriata*

The downstream zone of river Mahisagar is known for diversity of aqua-life during post monsoon season. This zone has both, fresh water and estuarine regime and hence, fishes of different ecosystems are represented in the survey. Total 26 species were reported from 03 orders and 12 families having diverse food habits and ecosystem as listed in Table 2. However, the diminishing number of fishes became a concern for all during the last two decades.

The primary reason for diminishing number of fishes was restricted release of flow from the dams. From 2006 to 2013, average release per day during post-winter i.e. January to June was only 0.24 Million Cubic Meter (MCM) in the tail stretch of Mahi river. Post-winter flow has the maximum effect in the estuarine zone of a controlled river as immediately after the monsoon, there is base flow and hence the effect of the release from the dam is not exclusive. Continuous deterioration of water quality up to 2104 was alarming and that justified sensible intervention. In 2014, the flow in river remained very high as an exceptional case due to heavy rainfall in the entire basin and dams in the upstream stretch were full and huge hydropower was also generated. But then were systematic and sincere efforts to release some water in to the river in spite of shortage of water in the upstream dams by generating hydropower such that the average daily non-monsoon flow remains 0.75 MCM. It was aimed at improving the subsurface water quality and health of the river in the tail stretch. Hydropower generation was not the primary objective. Prior to construction of dam, average daily river flow was reported as 1.2 MCM but restoring the same condition required some curtailment in present demand and therefore a balancing exercise became necessary.

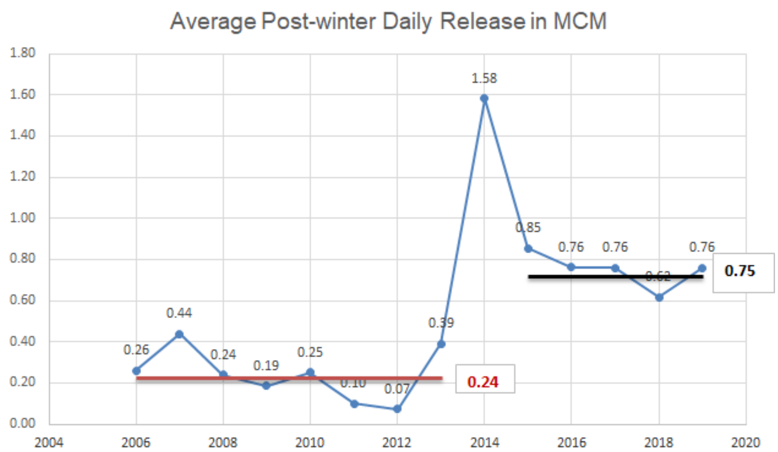

Fig. 4 Average post-winter daily release in Mahi river

Consistent efforts of maintaining enhanced flow in the tail stretch of Mahi river yielded some encouraging results in the form of water quality of the aquifers. Important determinant of the health of the river is the fisheries production. Some water quality parameters have also been studied and the health of the river could be assessed based on the results. Impacts on both the aspects - water quality and fisheries production have been studied and discussed in a nut shell.

An important fact is that the fishermen community had never flourished in the surrounding of the Mahi river as the yield of fish used to decline fast and hence many of them preferred to change the source of livelihood, but whosoever remained in the same profession could not earn sufficient to invest further. In spite of all these limitations they witnessed a big change in the yield of the fishes after 2015. Average annual catch not only got doubled but rare species like Hilsa has been found in large numbers during last three years.

Table 3 Annual Post-winter daily release and fisheries production

Year	**Average Post-winter Daily Release in MCM**	**Annual Estuarine Fisheries Production in MT (Metric Ton)**	**Average Long Term Annual Estuarine Fisheries Production in MT (Metric Ton)**
2006	0.26	394	1235
2007	0.44	444	
2008	0.24	2072	
2009	0.19	1686	
2010	0.25	1760	
2011	0.10	1061	
2012	0.07	1216	
2013	0.39	1342	
2014	1.58	2309	2270
2015	0.85	2246	
2016	0.76	2306	
2017	0.76	2211	
2018	0.62	2280	
2019	0.76	2360 (Provisional)	

It is important to note that quantity of flow and yield of fishes can not be apparently correlated on a small time scale, but two distinct phases of relatively a long time scale with consistently low release and consistently higher release respectively clearly indicate the relationship between the two parameters. Behaviour of fishes is based on long term response of flow pattern and therefore is required to be evaluated with a long term database. The present experiment is going to become the basis for further scientific studies as they require some inputs in the form of results of some experiments without which they would merely remain a theoretical exercise. However, early results of the experiment are encouraging looking to the very objective and the scientific computations for the environmental flow followed by detailed research on ecosystem would certainly help in enhancing the river system as a whole in the coming years. Studies of fisheries along with improvement in water quality linked with release pattern would certainly project better defined principles which would improve the knowledgebase and reservoir operation techniques.

Water quality results on selective parameters obtained from water samples taken from an observation well in the downstream of the Wanakbori weir are shown in Table 4 in representative form such that post-winter variations could be better appreciated and correlated with the release of water. Continuous deterioration of water quality up to 2104 was alarming and that justified sensible intervention.

An important factor for decline in river water quality in tail stretch of Mahi river was sea water intrusion during high tide. As the river flow had reduced in the post-monsoon period, sea water could travel longer in to the tail stretch of the river gorge during high tides. Aquifers in the surrounding were also reported to have deteriorated from water quality point of view. As the surface water was not of right quality, people started extracting groundwater which facilitated sea water intrusion in to aquifers and hence the decline in groundwater quality. Neither surface water, nor the groundwater remained usable and therefore some intervention became necessary.

Release from hydropower was decided and monsoon of 2014 gave a positive boost to the efforts. Water release of 2014 showed clearly that process of deterioration of water quality was effectively stopped and continuing more water release would bring positive changes in the water quality and hence was done so. The results were very encouraging and till date there has been a consistent improvement in the water quality followed by satisfactory maintenance of water quality in both the crucial stages of the water year - beginning of the post-winter phase i.e. January or pre-monsoon i.e. June. Actually the trials were made with an objective of improving water quality so that aqua-life could be restored.

Table 4 Water quality variations in post-winter phases

Month and Year	TDS (Acceptable up to 450 ppm)	Conductivity (Acceptable up to 1000 µS/cm)	Magnesium hardness (Acceptable up to 110 ppm)	Total Hardness as CaCO3 (Acceptable up to 215 ppm)
Feb-13	629	1173	206	390
May-13	748	1396	434	560
Jan-14	1178	2198	818	1022
Feb-15	1170	2182	492	700
May-15	1190	2220	484	700
Jan-16	150	280	84	130
May-16	266	496	118	188
Jan-17	254	473	80	154
May-17	242	451	84	148
Feb-18	265	494	86	150
May-18	270	502	80	160
Feb-19	280	523	100	166
May-19	277	517	80	150

Coherence amongst the data of average post-winter release of water, estuarine fisheries production and water quality variations suggests that the endeavors made to improve the downstream river health have brought welcoming results. Even species like Hilsa which had gone extinct for many years are found after 2017 which is a sign of restoration of aqua-life. Water quality improvement to a noteworthy extent suggests success of the experimental work. Since the tail stretch of the river receives the tide effect, weekly scheduling of release was attempted so as to optimize the benefits out of given releases from the reservoir.

Further Scope and Conclusion

Ecology of rivers with dams are susceptible to dangers if dam operations are not carried out sensibly and sensitively. Diminishing base-flow in the downstream of a dam is the most serious threat for any river which is mainly attributable to the over-emphasized objective of dam as conservation of water. With proper operations of a dam to ensure necessary release in the downstream, it becomes possible to maintain the ecology of the river and water quality of aquifers which are very essential for the overall health of the river besides its objective of conservation of water.

Health of endangered tail stretch of Mahi river could be improved by persistent efforts in the form of enhanced release of flow which was based on a mix of mathematical, *ad hoc* and experimental exercise. After an elaborated attempt of about four years, data has been sufficient to validate the mathematical models for computation of the ecological flow for the Mahi river in different stretches and in different seasons on weekly basis. Unlike depending on purely theoretical or *ad hoc* approach to computation of ecological flow, validation of data based on actual experiments *a priori* could certainly lead to a more rational approach for any river as computation of ecological flow for any river stretch is neither a stochastic nor a deterministic type of an exercise; it rather depends on several river characteristics which are essentially dynamic in nature and could not be fully taken in to the bounds of mathematical modelling. Ecological flow also varies for different phases of the water year and has direct relationship with the rainfall and dam operation and groundwater parameters, and, therefore, experimental part of the exercise immensely helps in converging to a workable solution with maximum benefits along with a proper balance between the objectives of conservation of water and of maintaining downstream river health.

The tail end structure on the Mahi river is Sindhrot weir whose actual objective is to partially fend the tidal influence has also helped in converging fast to the schedule of release of flow from the upstream dams. All the rivers may not have this kind of situation and hence the efforts for computation of ecological flow for them may require a different strategy. A fish-pass could also be designed provided on the side of the Sindhrot weir considering scientific data on aqua life and biotic characteristics of the same to allow migratory species to venture in the upstream stretches of the river. This could further improve the river health and river ecology. This provision is under consideration.

Country like India can not dismantle the existing dams for restoration of river ecology but can certainly establish a healthy reservoir operation practice conducive to sustenance of aqua-life for all the dammed rivers and wherever feasible, can construct fish passes to ensure ecological sustainability along with water harnessing for human requirements. By doing so, India can avail the benefits of revival and restoration of aqua-life in many of its river basins which is no less important than making water resource management for the mankind. A perceptional change which is required to be subscribed and endorsed widely is that the ecological flow is not a wastage of water but a part of water use pattern.

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