

## Chapter 4

### Results And Discussion

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#### 4.1 Identification of Pharmaceutical Pollutants (PPs) of Concern in River Waters

Zhou et al. (2019) presented a list of the 45 most frequently analyzed pharmaceuticals in European surface waters. For river health assessment, the PPs of concern in our study are those whose  $MEC > PNEC$  and  $RQ > 1$  for any aquatic organisms in the river environment.

##### 4.1.1 Indian Rivers

Based on literature review and information available in public domain, this study observed that around 17 PPs divided under four classes of pharmaceuticals, namely, antibiotics, NSAIDs, anticonvulsants, and stimulant have been reported in Indian rivers. Among these 17 reported pharmaceutical compounds, 11 are within acceptable limits for any biotic indicator, and the remaining six are present at concentration levels above PNEC. As per the decided objectives of the present study, such compounds are likely to affect the river health condition adversely and need due attention. Table 4.1 gives a summary of this observation, with six pharmaceutical compounds divided in three classes reported from six Indian rivers.

**Table 4.1: Pharmaceutical compounds detected in Indian River waters**

S.No.	Pharmaceutical Class	Pharmaceutical compounds reported in the river	Name of river and Reference
1	Antibiotics	i. Azithromycin	<b>River Ahar, Udaipur</b> (Williams et al., 2019)
		ii. Norfloxacin	<b>IsakavaguNakkavagu Stream of River Godawari, Hyderabad</b> (Fick et al., 2009)
		iii. Naproxen	<b>River Akravathi, Bengaluru</b> (Gopal et al., 2020)
		iv. Sulfamethoxazole	<b>River Yamuna, Agra</b> (Jindal et. al., 2015)

2	Non- Steroidal Anti-Inflammatory Drugs (NSAIDs)	v. Diclofenac	<b>River Yamuna, Agra</b> (Jindal et. al., 2015)
3	Stimulants	vi. Caffeine	<b>River Ganga, Patna</b> (Sharma et al., 2019) <b>River Brahmaputra, Guwahati</b> (Kumar et al., 2019) <b>River Ahar, Udaipur</b> (Williams et al., 2019)

From Table 4.1, it is observed that Caffeine, among the Stimulants is the most frequently recorded pharmaceutical compound in Indian rivers. Azithromycin, Caffeine, Diclofenac, Naproxen, Norfloxacin, and Sulfamethoxazole are the six pharmaceutical compounds whose reported concentrations are above their PNEC values for algae, MI, or fish.

#### 4.1.2 Rivers beyond India, across the world

Within a limited survey of rivers beyond India, from across the world, 7 rivers were selected in which the reported concentrations of pharmaceutical compounds have been found above their PNEC values for aquatic organisms. Details of 5 pharmaceutical compounds, divided under two classes are summarized in Table 4.2.

**Table 4.2: Classification of PPs detected in world river waters**

S.No.	Pharmaceutical Class	Pharmaceutical compounds reported in the river	Name of river and Reference
1	Antibiotics	i. Amoxicillin	<b>River Lambro, Milan, Italy</b> (Riva et al., 2019)
		ii. Ofloxacin	<b>River Wangyang, China</b> (Jiang et al., 2014)
		iii. Sulfamethoxazole	<b>River Ravi, Lahore, Pakistan</b> (Khan et al., 2013)
			<b>River Nairobi Basin, Kenya</b> (Ngumba et al., 2016)
	<b>River Wangyang, China</b> (Jiang et al., 2014)		
	<b>River Mitheu, Ghana</b> (Kairigo et al., 2020)		
	<b>River Brisbane, Australia</b> (Watkinson et al., 2009)		
	iv. Triclosan	<b>River Lambro, Milan, Italy</b> (Riva et al., 2019)	
2	Non- Steroidal Anti-Inflammatory Drugs (NSAIDs)	v. Acetaminophen	<b>River Altamaha, USA</b> (Vidal Dorsch et al., 2012)

From the Table 4.1 and Table 4.2, our analysis indicates 10 PPs, namely azithromycin, acetaminophen, amoxicillin, caffeine, diclofenac, naproxen, norfloxacin, ofloxacin, sulfamethoxazole, and triclosan are the pollutants found most frequently above PNEC affecting the biotic indicators of river health world across. Moreover, among the 10 pharmaceutical compounds selected, sulfamethoxazole among antibiotics and caffeine among the stimulants are more frequently recorded in rivers.

## 4.2 Ecological Risk Assessment of Pharmaceuticals in River Water

For the purpose of the present study, pharmaceutical compounds whose observed MEC are found above their PNEC values are considered as Pharmaceutical Pollutants (PPs) for river waters. High Risk Quotient ( $RQ_h$ ) has been calculated based on MEC and PNEC to assess the ecological risk level for vulnerable biotic group.

Table 4.3 presents the summary of analyses for 13 rivers selected in the present study from across the world, including India.

**Table 4.3: High Risk Quotient ( $RQ_h$ ) due to PPs in selected rivers across the world**

S.No.	Pharmaceutical compounds observed in river waters.	Name of River	MEC ( $\mu\text{g/L}$ )	PNEC ( $\mu\text{g/L}$ )			$RQ_h$ , and the most vulnerable biotic
				Algae	MI	Fish	
i.	Azithromycin <sup>*1</sup>	<b>River Ahar, Udaipur</b> (Williams et al., 2019)	0.410	<b>0.18</b>	0.44	460	$RQ_h = 2.27$ for <b>Algae</b> .
ii.	Acetaminophen <sup>*2</sup>	<b>River Altamaha, USA</b> (Vidal Dorsch et al., 2012)	11	13	<b>9.2</b>	38	$RQ_h = 1.2$ for <b>MI</b> .
iii.	Amoxicillin <sup>*1</sup>	<b>River Lambro, Milan, Italy</b> (Riva et al., 2019)	51	<b>5</b>	182.7	-	$RQ_h = 10.2$ for <b>Algae</b>
iv.	Caffeine <sup>*3</sup>	<b>River Ganga, Patna</b> (Sharma et al., 2019)	0.743	<b>0.15</b>	182	87.5	$RQ_h = 4.95$ for <b>Algae</b>
		<b>River Brahmaputra, Guwahati</b> (Kumar et al., 2019)	0.410				$RQ_h = 2.73$ for <b>Algae</b>
		<b>River Ahar, Udaipur</b> (Williams et al., 2019)	3.680				$RQ_h = 24.5$ for <b>Algae</b> .
v.	Diclofenac <sup>*2</sup>	<b>River Yamuna, Agra</b> (Jindal et. al., 2015)	0.994	<b>0.2</b>	20	0.05	$RQ_h = 4.97$ for <b>Algae</b> ; and <b>19.88</b> for <b>Fish</b> .

vi.	Naproxen <sup>*2</sup>	<b>River Akravathi, Bengaluru</b> (Gopal et al., 2020)	4.334	31.8	<b>2.62</b>	115.2	RQ <sub>h</sub> = <b>1.65</b> for <b>MI</b> .
		<b>River Altamaha, USA</b> (Vidal Dorsch et al., 2012)	13.1				RQ <sub>h</sub> = <b>5</b> for <b>MI</b> .
vii.	Norfloxacin <sup>*1</sup>	<b>IsakavaguNakkavagu Stream of River Godawari, Hyderabad</b> (Fick et al., 2009)	470	<b>1.6</b>	<b>12</b>	<b>1.4</b>	RQ <sub>h</sub> = <b>293</b> for <b>Algae</b> . <b>39</b> for <b>MI</b> and <b>335</b> for <b>Fish</b> .
viii.	Ofloxacin <sup>*1</sup>	<b>River Wangyang, China</b> (Jiang et al., 2014)	11.8	<b>5</b>	31.75	101	RQ <sub>h</sub> = <b>2.36</b> for <b>Algae</b> .
ix.	Sulfamethoxazole	<b>River Yamuna, Agra</b> (Jindal et al., 2015)	0.733	<b>0.27</b>	25	506	RQ <sub>h</sub> = <b>2.71</b> for <b>Algae</b> .
		<b>River Ravi, Lahore Pakistan</b> (Khan et al., 2013)	2.7				RQ <sub>h</sub> = <b>10</b> for <b>Algae</b> .
		<b>River Nairobi Basin, Kenya,</b> (Ngumba et al., 2016)	13.8				RQ <sub>h</sub> = <b>51.1</b> for <b>Algae</b> .
		<b>River Wangyang, China</b> (Jiang et al., 2014)	13.8				RQ <sub>h</sub> = <b>51</b> for <b>Algae</b> .
		<b>River Mitheu, Ghana</b> (Kairigo et al., 2020)	2.8				RQ <sub>h</sub> = <b>10.37</b> for <b>Algae</b> .
		<b>River Brisbane, Australia</b> (Watkinson et al., 2009)	2				RQ <sub>h</sub> = <b>7.40</b> for <b>Algae</b> .
x.	Triclosan <sup>*2</sup>	<b>River Lambro, Milan, Italy</b> (Riva et al., 2019)	0.27	<b>0.014</b>	0.39	0.26	RQ <sub>h</sub> = <b>17.14</b> for <b>Algae</b>

\*1- Antibiotics; \*2- NSAID/ Analgesic; \*3- Stimulant

It is observed from Table 4.3, the high-risk quotient ( $RQ_h$ ) ranges from 2.27 to 293 for algae, 1.2 to 39 for MI, and 19.88 to 335 for fish. A higher  $RQ_h$  value indicates a high MEC of PPs in the river near the city of observation. The population of the town, the general public consumption rate of pharmaceutical compounds, and the degree of treatment/ diversion or disposal of HWW stream reaching the river may affect the observed MEC, resulting in high  $RQ_h$ .

#### **4.3 Threshold High Risk Condition and Threshold High Risk Concentrations ( $RC_T$ )**

The scientific background for arriving at PNEC values suggests that it is calculated by dividing the lowest no observed effect concentration (NOEC), lowest observed effect concentration (LOEC), or expected lowest concentration to kill 50% of the test population  $E(L)C_{50}$  values of the most sensitive species by an appropriate assessment factor (AF). This AF is used to overcome the uncertainty of raw toxicity data and derive the PNEC (Vryzas et al., 2011). According to the EU guidelines (European Commission, 2003), (i) an AF of 1000 is used in the cases where at least one short-term  $E(L)C_{50}$  from each of the three evaluated trophic levels is available; (ii) an AF of 100 is used when one long-term assay is available for either algae, crustaceans or fish; (iii) an AF of 50 is used in the case of existing two long-term assays in two different trophic levels; and (iv) an AF of 10 is used when three long-term assays in three different trophic levels are available. Thus, it appears that at  $MEC/PNEC = 10$ , the high concentration of PPs may start causing ecological imbalances to the aquatic species. Accordingly,  $RQ_T (=10RQ)$  has been defined as the 'threshold high risk condition' beyond which the ecological condition of the river may be considered 'impaired'. Correspondingly,  $RC_T$  equal to 10 times the PNEC may be taken as the upper limit for risk assessment. This limit has been decided and used in the present river health risk index assessment study.

#### 4.4 RQ<sub>h</sub>-Based Classification of Ecologically High Risk Conditions

Under ‘high-risk’ conditions, from RQ<sub>h</sub> = 1 to RQ<sub>h</sub> = RQ<sub>T</sub> = 10 RQ, the present study has proposed a classification of ‘high risk conditions’ as given below:

RQ<sub>h</sub> = 1 - 3: indicating ‘moderately’ high risk.

RQ<sub>h</sub> = 3 – 5: ‘significantly’ high risk

RQ<sub>h</sub> = 5 – 8, ‘critically’ high risk,

RQ<sub>h</sub> = 8- 10, ‘severely’ high risk,

RQ<sub>h</sub> > 10, ‘impaired conditions.’

#### 4.5 Ecological Risk Conditions (ERCs) due to PPs in Rivers

Based on RQ<sub>h</sub> values determined for different rivers selected for this study (Table 4.3) and classification of ‘ecologically high-risk conditions’ the ERC for different rivers is found as given in Table 4.4. It is observed that the ERC varies from ‘moderately high’ to ‘impaired conditions,’ and all three biotic indicator groups are affected due to the presence of PPs in river water.

**Table 4.4: Ecological risk conditions (ERC) in rivers having PPs above PNEC.**

S.No.	Name of the river	Pharmaceutical compound of concern with MEC>PNEC for algae, MI, or fish in river water	ERC (based on RQ <sub>h</sub> ) and most vulnerable trophic level
1	River Lambro, Milan, Italy (Riva et al., 2019)	Amoxicillin	‘Impaired Conditions’ for Algae.
		Triclosan	‘Impaired Conditions’ for Algae.
2	River Ahar, Udaipur, India (Williams et al., 2019)	Azithromycin	‘Moderately’ high risk for Algae.
		Caffeine	‘Impaired Conditions’ for Algae.
3	IsakavaguNakkavagu Stream of River Godawari, Hyderabad, India. (Fick et al., 2009)	Norfloxacin	‘Impaired Conditions’ for all Algae, MI and Fish.

4	River Akravathi, Bengaluru, India (Gopal et al., 2020)	Naproxen	‘Moderately’ high risk on MI.
5	River Yamuna, Agra, India (Jindal et. al., 2015)	Sulfamethoxazole	‘Moderately’ high risk for Algae.
	River Yamuna, Agra, India (Jindal et. al., 2015)	Diclofenac	‘Significantly’ high risk for Algae, and ‘Impaired conditions’ for Fish.
6	River Ravi, Lahore, Pakistan (Khan et al., 2013)	Sulfamethoxazole	‘Severely’ high risk for Algae.
7	River Nairobi Basin, Kenya (Ngumba et al., 2016)	Sulfamethoxazole	‘Impaired Conditions’ for Algae.
8	River Wangyang, China (Jiang et al., 2014)	Ofloxacin	‘Moderately’ high risk for Algae.
		Sulfamethoxazole	‘Impaired Conditions’ for Algae.
9	River Mitheu, Ghana (Kairigo et al., 2020)	Sulfamethoxazole	‘Impaired Conditions’ for Algae.
10	River Brisbane, Australia (Watkinson et al., 2009)	Sulfamethoxazole	‘Critically’ high risk for Algae.
11	River Altamaha, USA (Vidal Dorsch et al., 2012)	Acetaminophen	‘Moderately’ high risk for MI.
		Naproxen	‘Significantly’ high risk for MI.
12	River Ganga, Patna, India (Sharma et al., 2019)	Caffeine	‘Significantly’ high risk for Algae.
13	River Brahmaputra, Guwahati, India (Kumar et al., 2019)	Caffeine	‘Moderately’ high risk for Algae.

( $RQ_h = 1 - 3$  indicate ‘moderately’ high risk,  $3 - 5$ , ‘significantly’ high risk,  $5 - 8$ , ‘critically’ high risk,  $8 - 10$ , ‘severely’ high risk and  $RQ_h > 10$ , ‘impaired conditions’).

It is also observed that the reported concentrations of amoxicillin in River Lambro; caffeine in River Ahar; diclofenac in River Yamuna; norfloxacin in IsakavaguNakkavagu Stream of River Godavari; triclosan in River Lambro; and Sulfamethoxazole in River Ravi, River Nairobi Basin, River Wangyang, and River Mitheu create ecologically impaired conditions because of unacceptably ‘high risk’ for biotic indicators. Algae are at the most vulnerable

biotic level due to PPs, followed by macroinvertebrates and fishes. Such high-risk conditions are reflected in poor river health at the given site.

#### **4.6 River Health Assessment, Including the Effects of PPs**

##### **4.6.1 Framework for calculating River Health Index (RHI)**

In the present study, river health assessment has been done using a unified river health index (RHI) as defined by Eq. 3.1. This includes an additional indicator group of Emerging Pollutants (EPs) in the RHI calculation framework.

##### **4.6.2 Calculation of RHI in river Ganga near Varanasi, including the Effects of PPs**

To check the applicability of the framework for calculating RHI and classification of river health conditions, the water quality data for the river Ganga upstream of Varanasi City (India) during the spring season (March 2018) (Saxena, 2020) has been used. In addition, as representative of EPs class, concentrations of PPs reported in the river Ganga near Varanasi (Jindal et al., 2015 and Sharma et al., 2019) have been used to understand their possible impacts, assuming that PPs being persistent pollutants will have their presence on the same level at the time of monitoring of other parameters.

Table 4.5 presents the data set of water quality characteristics used to demonstrate the applicability of the framework developed in the present study.

**Table 4.5: Water quality characteristics of the river Ganga near Varanasi city (India)**

S. No.	Indicator Group	Weightage	Parameters	MEC	Source
1.	Dissolved oxygen-related parameters (DORPS)	$w_1 = 0.10$	i. EC ( $\mu\text{mhos/cm}$ )	332	Saxena and Singh, 2020
			ii. DO (mg/L)	6.3	
			iii. BOD (mg/L)	4.0	
			i. COD (mg/L)	52	
2.	Nutrients (NT)	$w_2 = 0.20$	i. $\text{NH}_3\text{-N}$ (mg/L)	0.31	Saxena and Singh, 2020
			ii. TN (mg/L)	0.78	
			iii. TP (mg/L)	0.125	
3.	Emerging Pollutants (EPs)	$w_3 = 0.20$	i. Caffeine ( $\mu\text{g/L}$ )	0.743	Sharma et al., 2019
			ii. Diclofenac ( $\mu\text{g/L}$ )	0.994	Jindal et al. (2015) for river Yamuna at Agra in the Ganga Basin
			iii. Sulfamethoxazole ( $\mu\text{g/L}$ )	0.773	
4.	Algal Bacterial (AB)	$w_4 = 0.20$	i. APPI	13	Saxena and Singh, 2020
			ii. FC (MPN/100 mL)	1200	
5.	Macroinvertebrate (MI)	$w_5 = 0.20$	i. MSW	1.65	Saxena and Singh, 2020
			ii. MBMWP	4.8	
6..	Fish (F)	$w_6 = 0.10$	i. FS	70	Saxena and Singh, 2020
			ii. FSW	2.23	

Based on water quality characteristics reported, the normalized scores, indicator group scores, and RHI have been calculated, as summarized in Table 4.6.

**Table 4.6: Normalized Scores, Indicator Group Scores, and RHC of the river Ganga near Varanasi**

S.No.	Indicator Group	Parameters	Normalized Score (0-5)	IGS (0-100)	Indicator Group/River Health Condition
1.	Dissolved oxygen-related parameters (DORP) ( $w_1=0.10$ )	i. EC ( $\mu\text{mhos/cm}$ )	5	75	Very Good
		ii. DO (mg/L)	4		
		iii. BOD (mg/L)	4		
		iv. COD (mg/L)	2		
		$\Sigma$ Normalized score	15		
		No of parameters considered	4		
2.	Nutrients (NT) ( $w_2=0.20$ )	NH <sub>3</sub> -N (mg/L)	4	80	Very Good
		TN (mg/L)	4		
		TP (mg/L)	4		
		$\Sigma$ Normalized score	12		
		No of the parameters considered	3		
3.	Emerging Pollutants (EPs) ( $w_3=0.20$ )	Caffeine	0	27	Critical
		Diclofenac	0		
		Sulfamethoxazole	4		
		$\Sigma$ Normalized score	4		
		No of the parameters considered	3		
4.	Algal Bacterial (AB) ( $w_4=0.20$ )	APPI	3	60	Stressed
		FC (MPN/ 100 mL)	3		
		$\Sigma$ Normalized score	6		
		No of the parameters considered	2		
5.	Macroinvertebrates (MI) ( $w_5=0.20$ )	MSW	2	50	Over Stressed
		MBMWP	3		
		$\Sigma$ Normalized score	5		
		No of the parameters considered	2		
6.	Fish (F) ( $w_6=0.10$ )	FS	4	70	Good
		FSW	3		
		$\Sigma$ Normalized score	7		

		No of the parameters considered	2		
			<b>RHI (0-100)</b>	58	<b>Stressed</b>

Fig. 4.1 shows the colored pictorial map of river health conditions based on IGSs and overall RHI calculated for the river Ganga at Varanasi (India).

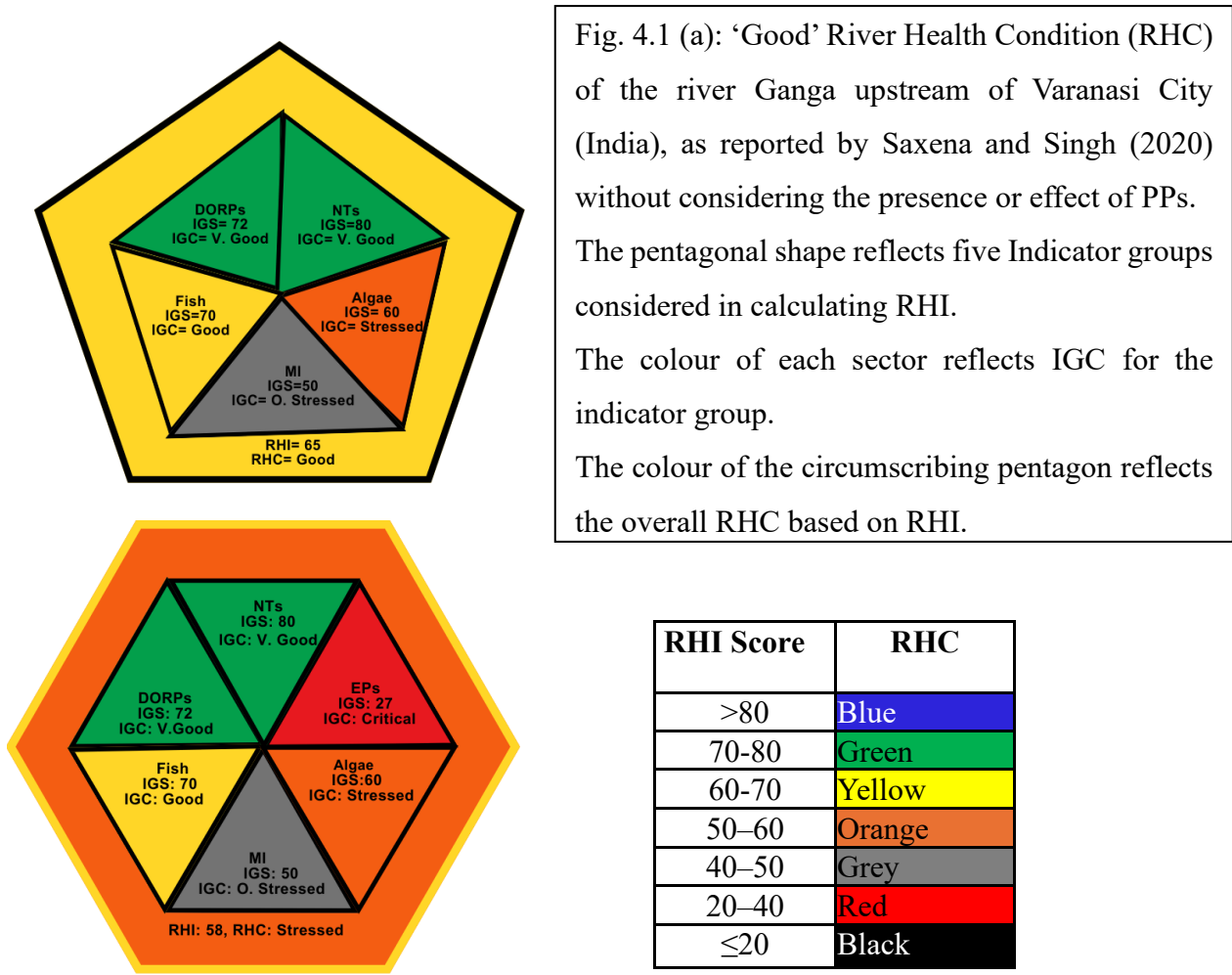


Fig. 4.1 (b): ‘Stressed’ River Health Condition (RHC) of the river Ganga at upstream of Varanasi city (India), considering the presence of PPs as reported by Jindal et al (2015) and Sharma et al. (2019) in rivers of Ganga basin in addition to water quality characteristics reported by Saxena and Singh (2020) at Varanasi. The hexagonal shape indicates six groups of indicators considered in formulating RHI. The colour of each sector inside the hexagon reflects the IGC for the indicator group. The colour of the circumscribing hexagon reflects the overall RHC based on RHI.

It is observed that based on RHI calculated without including effects of PPs, the RHC is indicated as 'Good' in the river Ganga near Varanasi. Once the presence of PPs is considered to coexist with other measured physicochemical and biological parameters, the RHC is found under the 'Stressed' condition. The apparent reason for the decrease in RHI from 65 (indicating 'Good' river health condition) to 58 (indicating 'Stressed' condition) is the inclusion of PPs whose concentrations have been reported above PNEC for aquatic organisms in the river environment. The algae and the MI groups are the worst biotic indicators affected. This sufficiently indicates the need of appropriate treatment and management of PPs before mixing with river water.

### **4.6.3 Case Studies of other Indian rivers for RHC with PPs above PNEC**

#### **4.6.3.1 River Arkavati, Bangalore**

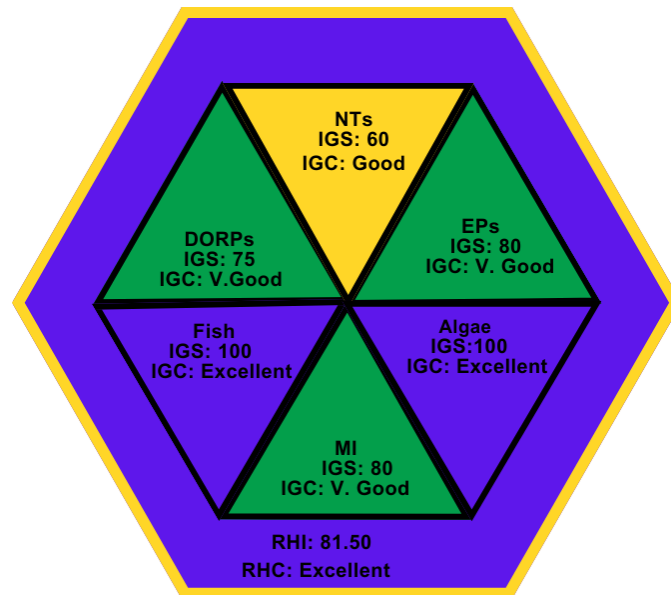
The Arkavati River originates from the Nandi Hills in the Chikkaballapur district of Karnataka and flows through Bengaluru Rural and Ramanagara districts. It flows southwards to finally join River Cauvery at Sangam near Mekedatu, after flowing 190 km and 34 km downstream of two Kanakapura. Kumudvathi and Vrishabhavathi Rivers are the two tributaries of River Arkavathi, in which four man-made reservoirs are constructed across the Arkavathi River for water supply to nearby towns of Bengaluru. The river supports agriculture, drinking water needs, and biodiversity in the basin, which are now being degraded over the years due to reduced flow over-extraction and pollution from industrial and domestic waste. The water quality parameters used to assess the RHC has been summarized in Table 4.7. Within the river catchment, 2 STPs are available to treat the wastewater based on MBBR and Aerated Lagoon technologies before discharging it into the river waters.

**Table 4.7: Reported water quality parameters of river Akravathi, Bangalore**

S. No.	Indicator Group	Weightage	Parameters	MEC	Source
1.	Dissolved oxygen-related parameters (DORP)	$w_1 = 0.10$	i. EC ( $\mu\text{mhos/cm}$ )	115.9	Kumar et al., 2020
			ii. DO (mg/L)	6.5	
			iii. BOD (mg/L)	3.90	
			i. COD (mg/L)	50	
2.	Nutrients (NT)	$w_2 = 0.20$	i. $\text{NH}_3\text{-N}$ (mg/L)	0.21	
			ii. TN (mg/L)	0.74	
			iii. TP (mg/L)	2.32	
3.	Emerging Pollutants (EPs)	$w_3 = 0.20$	Naproxen ( $\mu\text{g/L}$ )	4.334	Gopal et al., 2020

**Table 4.8: Normalised Scores, IGS and RHI for river Akravathi, Bangalore**

S.N.	Indicator Group	Parameters	Normalised Score
1.	Dissolved oxygen-related parameters (DORPs)	EC ( $\mu\text{mhos/cm}$ )	5
		DO (mg/L)	4
		BOD (mg/L)	4
		COD (mg/L)	2
<b>IGS for DORPs</b>			75
2.	Nutrients (NTs)	$\text{NH}_3\text{-N}$ (mg/L)	5
		TN (mg/L)	4
		TP (mg/L)	0
<b>IGS for NTs</b>			60
3.	Emerging Pollutants (EPs)	Naproxen	4
<b>IGS for EPs</b>			80
<b>Ecological Risk for biotic indicators due to Naproxen</b>			
	Algae	MI	Fish
Normalized Score (0-5)	5	4	5
IGS	100	80	100
<b>RHI</b>			81.50

**Fig. 4.2: Coloured hexagonal map of RHC for river Akravathi based on IGC and RHI**

#### 4.6.3.2 River Brahmaputra, Guwahati

The Brahmaputra River is one of the major rivers of the Indian subcontinent and holds immense significance for the city of Guwahati, Assam. It originates from the Tibetan Plateau as the Yarlung Tsangpo and enters India through Arunachal Pradesh before reaching Assam. The average width of the Brahmaputra in this region is around 10 km, making it one of the most expansive rivers in the world. Urbanization and industrial growth in Guwahati have increased pollution in the Brahmaputra. Sewage Treatment Plant based on ASP and UASB are the two existing treatment technologies for reducing pollutants from wastewater before discharging it into river waters. According to the Directorate of Health Service, 84 major hospitals and healthcare centers, including 16 government and 68 private, reside in the River Brahmaputra catchment near Guwahati, which directly or indirectly discharges their wastewater (approx. 7.59 MLD) into the river catchment daily.

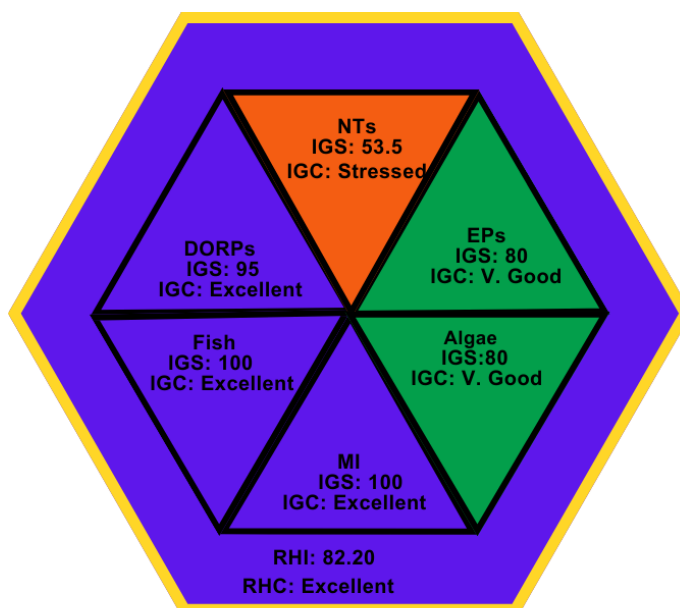
**Table 4.9: Reported water quality parameters of river Brahmaputra, Guwahati**

S. No.	Indicator Group	Weightage	Parameters	MEC	Source
1.	Dissolved oxygen-related parameters (DORP)	$w_1 = 0.10$	ii. EC ( $\mu\text{mhos/cm}$ )	86.09	Das et al., 2022 and Meena et al., 2023
			ii. DO (mg/L)	6.6	
			iii. BOD (mg/L)	1.75	
			ii. COD (mg/L)	5.81	
2.	Nutrients (NT)	$w_2 = 0.20$	i. $\text{NH}_3\text{-N}$ (mg/L)	0.19	
			ii. TN (mg/L)	0.94	
			iii. TP (mg/L)	7.9	
3.	Emerging Pollutants (EPs)	$w_3 = 0.20$	i. Caffeine ( $\mu\text{g/L}$ )	0.410	Kumar et al., 2019

**Table 4.10: Normalised Scores, IGS and RHI for river Brahmaputra, Guwahati**

S.No.	Indicator Group	Parameters	Normalised Score
1.	Dissolved oxygen-related parameters (DORPs)	EC ( $\mu\text{mhos/cm}$ )	5
		DO (mg/L)	4
		BOD (mg/L)	5
		COD (mg/L)	5
<b>IGS for DORPs</b>			95
2.	Nutrients (NTs)	$\text{NH}_3\text{-N}$ (mg/L)	5
		TN (mg/L)	3
		TP (mg/L)	0
<b>IGS for NTs</b>			53.5
3.	Emerging Pollutants (EPs)	Caffeine	4
<b>IGS for EPs</b>			80
Ecological Risk for biotic indicators due to Caffeine			
	Algae	4 MI	5 Fish
Normalised Score (0-5)		4	5
IGS		80	100
RHI			82.2

**Fig. 4.3: Colored hexagonal map of RHC for river Brahmaputra based on IGC and RHI**



#### 4.6.3.3 River Ganga, Patna

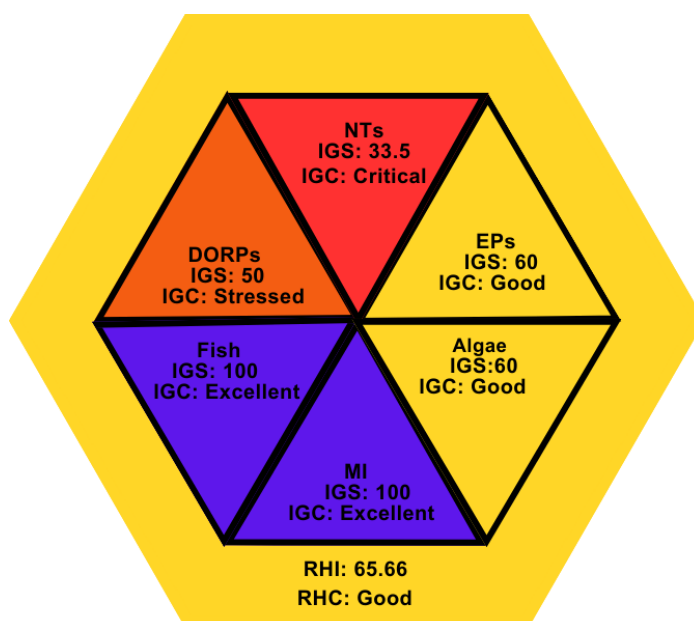
The river Ganga originates from the Gangotri Glacier in the Indian state of Uttarakhand at Gaumukh, where it is called the Bhagirathi River and travels Approximately 2,525 kilometres. The river empties into the Bay of Bengal, forming the Sundarbans Delta, the largest delta in the world. In the middle stretch, the river Ganga travels through Patna, which has 162 hospitals in the river Ganga catchment, contributing 10-15 MLD of hospital wastewater containing pharmaceuticals.

**Table 4.11: Reported water quality parameters of river Ganga, near Patna**

S. No.	Indicator Group	Weightage	Parameters	MEC	Source
1.	Dissolved oxygen-related parameters (DORP)	$w_1 = 0.10$	iii. EC ( $\mu\text{mhos/cm}$ )	587.14	Saurabh et al., 2021 Saxena & Singh 2020 Sharma et al., 2019
			ii. DO (mg/L)	5.87	
			iii. BOD (mg/L)	6.16	
			iii. COD (mg/L)	68	
2.	Nutrients (NT)	$w_2 = 0.20$	i. $\text{NH}_3\text{-N}$ (mg/L)	0.90	
			ii. TN (mg/L)	1.39	
			iii. TP (mg/L)	0.26	
3.	Emerging Pollutants (EPs)	$w_3 = 0.20$	i. Caffeine ( $\mu\text{g/L}$ )	0.743	

**Table 4.12: Normalised Scores, IGS and RHI for the river Ganga near Patna**

S.N.	Indicator Group	Parameters	Score
1.	Dissolved oxygen-related parameters (DORPs)	EC ( $\mu\text{mhos/cm}$ )	4
		DO (mg/L)	3
		BOD (mg/L)	2
		COD (mg/L)	1
<b>IGS for DORPs</b>			50
2.	Nutrients (NT)	NH <sub>3</sub> -N (mg/L)	2
		TN (mg/L)	2
		TP (mg/L)	1
<b>IGS for NTs</b>			33.3
3.	Emerging Pollutants (EPs)	Caffeine	3
<b>IGS for EPs</b>			60
Ecological Risk for biotic indicators due to Caffeine			
	Algae	MI	Fish
Normalised Score (0-5)	3	5	5
IGS	60	100	100
<b>RHI</b>			65.66

**Fig. 4.4: Colored hexagonal map of RHC for river Ganga near Patna based on IGC and RHI**

#### 4.6.3.4 River Yamuna, Agra

River Yamuna is the fifth largest river in India, with a vast drainage system of 366,224 km<sup>2</sup>. The river originates from Yamunotri and merges with the river Ganga at Prayagraj. The River Hindon and Hindon Canal meet near Agra, carrying a high pollution load from industries and locally populated areas. The generation of hospital wastewater is a major concern in Agra City, as it has a total of 693 hospitals in the River Yamuna Catchment with a total hospital wastewater generation of 18-21 MLD (Sharma et al., 2008). Total sewage generation is approx. 286 MLD having 4 STPs based on UASB and SBR technologies in Agra city (NGT, 2014).

**Table 4.13: Reported water quality parameters of river Yamuna, Agra**

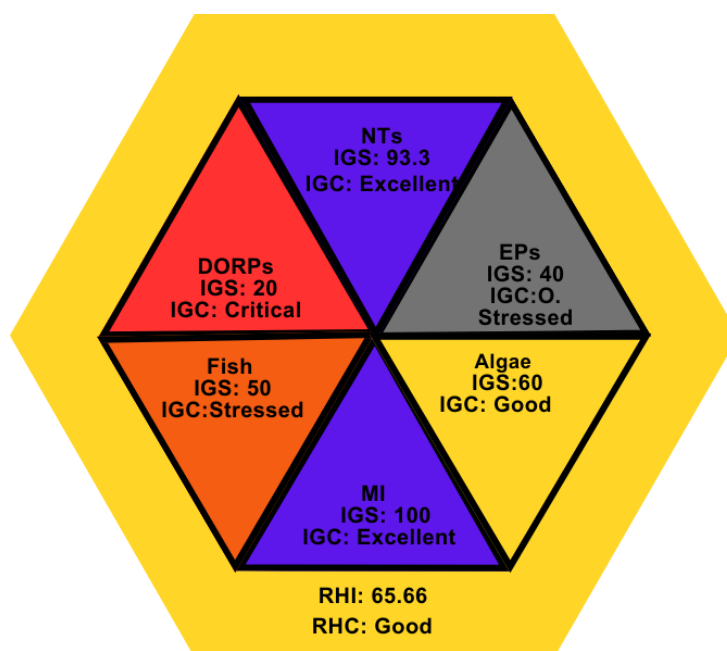
S. No.	Indicator Group	Weightage	Parameters	MEC	Source	
1.	Dissolved oxygen-related parameters (DORP)	$w_1 = 0.10$	iv. EC ( $\mu\text{mhos/cm}$ )	1029	Mishra et al., 2020	
			ii. DO (mg/L)	3.5		
			iii. BOD (mg/L)	21		
			iv. COD (mg/L)	79		
2.	Nutrients (NT)	$w_2 = 0.20$	i. NH <sub>3</sub> -N (mg/L)	0.5		
			ii. TN (mg/L)	0.23		
			iii. TP (mg/L)	0.06		
3.	Emerging Pollutants (EPs)	$w_3 = 0.20$	ii. Diclofenac ( $\mu\text{g/L}$ )	0.994		Jindal et al., 2019
			iii. Sulfamethoxazole ( $\mu\text{g/L}$ )	0.773		

**Table 4.14: Normalised Scores, IGS and RHI for the river Yamuna near Agra**

S.N.	Indicator Group	Parameters	Normalised Score
1.	Dissolved oxygen-related parameters (DORP)	EC ( $\mu\text{mhos/cm}$ )	2
		DO (mg/L)	1
		BOD (mg/L)	0
		COD (mg/L)	1
<b>IGS for DORPs</b>			20
2.	Nutrients (NTs)	NH <sub>3</sub> -N (mg/L)	4
		TN (mg/L)	5
		TP (mg/L)	5
<b>IGS for NTs</b>			93.3
3.		Diclofenac	0

	Emerging Pollutants (EPs)	Sulfamethoxazole	4
<b>IGS for EPs</b>			40
Ecological Risk for biotic indicators due to EPs			
	Algae	MI	Fish
Normalised Score for Diclofenac	2	5	0
Normalised Score for Sulfamethoxazole	4	5	5
<b>IGS</b>	60	100	50
<b>RHI</b>			65.66

**Fig. 4.5: Colored hexagonal map of RHC for river Yamuna near Agra based on IGC and RHI**



#### 4.6.3.5 Isakavagu-Nakkavagu Stream of River Godawari, Hyderabad

Isikavaku stream is the tributary of River Godavari, Hyderabad, contributes 1.5 MLD of Drugs of high concentration from prone pharmaceutical manufacturing industries, which finally reaches River Godavari. The stream carries waste from 90 bulk drug manufacturers from a location near Hyderabad, Telangana and meets River Godavari, increasing the pollution load to surface water resources. Patancheru effluent treatment plant

was installed to reduce the pollution load, although after limitations in treatment technology active pharmaceuticals ingredients reaches the water resource (Fick et al., 2010).

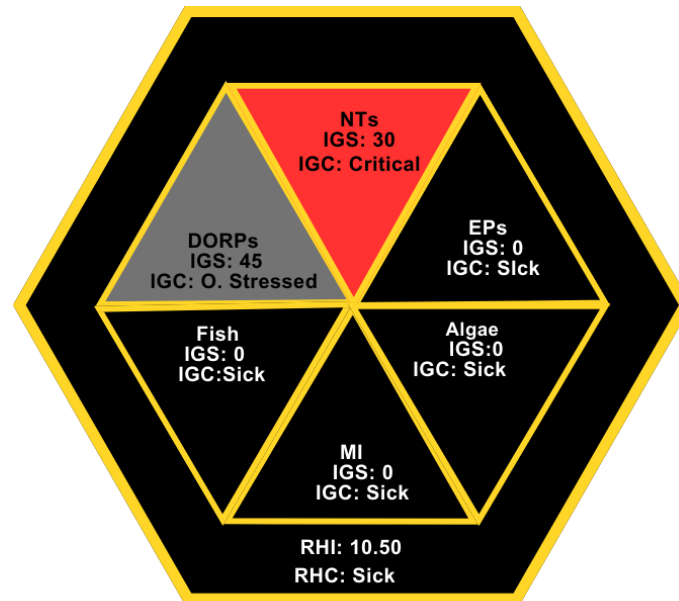
**Table 4.15 Reported water quality parameters of the Stream**

S. No.	Indicator Group	Weightage	Parameters	MEC	Source
1.	Dissolved oxygen-related parameters (DORPs)	$w_1 = 0.10$	v. EC ( $\mu\text{mhos/cm}$ )	270	Chavan et al., 2009
			ii. DO (mg/L)	3.06	
			iii. BOD (mg/L)	9	
			v. COD (mg/L)	44	
2.	Nutrients (NTs)	$w_2 = 0.20$	i. $\text{NH}_3\text{-N}$ (mg/L)	0.66	
			ii. TN (mg/L)	0.98	
			iii. TP (mg/L)	1.2	
3.	Emerging Pollutants (EPs)	$w_3 = 0.20$	i. Norfloxacin ( $\mu\text{g/L}$ )	470	Fick et al., 2009

**Table 4.16: Normalised Scores, IGS and RHI for the Stream**

S.No.	Indicator Group	Parameters	Normalised Score
1.	Dissolved oxygen-related parameters (DORPs)	EC ( $\mu\text{mhos/cm}$ )	5
		DO (mg/L)	1
		BOD (mg/L)	0
		COD (mg/L)	3
<b>IGS for DORPs</b>			45
2.	Nutrients (NTs)	$\text{NH}_3\text{-N}$ (mg/L)	3
		TN (mg/L)	3
		TP (mg/L)	0
<b>IGS for NTs</b>			30
3.	Emerging Pollutants (EPs)	Norfloxacin ( $\mu\text{g/L}$ )	0
<b>IGS for EPs</b>			0
Ecological Risk for biotic indicators due to EPs			
	Algae	MI	Fish
Normalised Score for	0	0	0
Norfloxacin			
IGS	0	0	0
RHI			10.50

**Fig. 4.6: Colored hexagonal map of Isakavagu-Nakkavagu Stream of river Godawari, Hyderabad based on IGC and RHI**



#### 4.6.3.6 River Kshipra, Ujjain

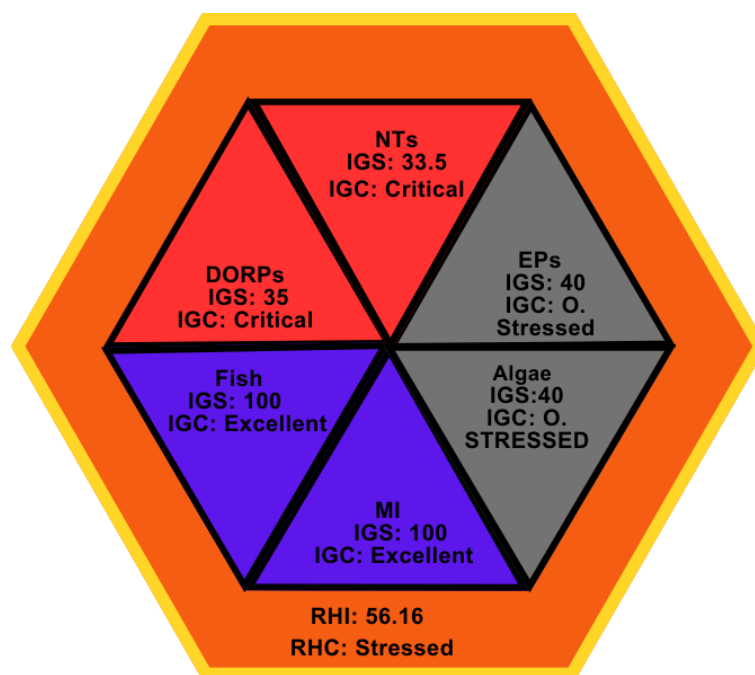
River Kshipra originates from Kokri Bardi Hills, about 11 km southeast of Indore, and flows through the city of Ujjain in the western part of Madhya Pradesh with a catchment area of 5600 km<sup>2</sup>. The holy river water quality maintains bathing standards (CPCB 2012), which gets contaminated by the tributary River Kahn, and 11 drains reach into the water with high domestic and hospital wastewater (Gupta et al., 2013). A report by the Comptroller and Auditor General of India on the degradation of the Kshipra River (CAG, 2021) states the total urban sewage generation in the catchment in a year lies approx. 14813 ML, out of which 670 ML gets treated and discharged into river water. However, the hospital wastewater generation is 2365 ML in urban areas from 29 hospitals, with STPs of SBR technology in the catchment area of River Kshipra.

**Table 4.17: Reported water quality parameters of river Kshipra, Ujjain**

S. No.	Indicator Group	Weightage	Parameters	MEC	Source
1.	Dissolved oxygen-related parameters (DORP)	$w_1 = 0.10$	vi. EC ( $\mu\text{mhos/cm}$ )	324.8	Raghuvanshi and Reddy 2018
			ii. DO (mg/L)	3.5	
			iii. BOD (mg/L)	22.92	
			vi. COD (mg/L)	65.42	
2.	Nutrients (NT)	$w_2 = 0.20$	i. $\text{NH}_3\text{-N}$ (mg/L)	0.9	
			ii. TN (mg/L)	1.5	
			iii. TP (mg/L)	3.35	
3.	Emerging Pollutants (EPs)	$w_3 = 0.20$	i. Norfloxacin ( $\mu\text{g/L}$ )	1.98	
			ii. Sulfamethoxazole ( $\mu\text{g/L}$ )	4.66	

**Table 4.18: Normalised Scores, IGS and RHI for the river Kshipra, Ujjain**

S.No.	Indicator Group	Parameters	Normalised Score
1.	Dissolved oxygen-related parameters (DORPs)	EC ( $\mu\text{mhos/cm}$ )	5
		DO (mg/L)	1
		BOD (mg/L)	0
		COD (mg/L)	1
<b>IGS for DORPs</b>			<b>35</b>
2.	Nutrients (NTs)	$\text{NH}_3\text{-N}$ (mg/L)	3
		TN (mg/L)	2
		TP (mg/L)	0
<b>IGS for NTs</b>			<b>33.33</b>
3.	Emerging Pollutants (EPs)	Norfloxacin ( $\mu\text{g/L}$ )	4
		Sulfamethoxazole ( $\mu\text{g/L}$ )	0
<b>IGS for EPs</b>			<b>40</b>
<b>Ecological Risk for biotic indicators due to EPs</b>			
	Algae	MI	Fish
	Normalised Score for Norfloxacin	4	5
	Normalised Score for Sulfamethoxazole	0	5
	<b>IGS</b>	40	100
			<b>RHI</b> 56.16

**Fig. 4.7: Colored hexagonal map of RHC for river Kshipra, Ujjain based IGC and RHI**

#### 4.6.4 Case Studies of representing RHC for other world rivers with PPs above PNEC

Estimating the actual density of aquatic life based on field identification is sometimes hard and more time-intensive. Considering such situations, the ecological risk to aquatic organisms is discussed based on PNEC and  $RC_T$ . With such ecologically ‘high risk’ condition, assuming that IGS for DORPs and NTs groups of indicators are in good condition ( $IGS \geq 60$ ) and concentrations of PPs are as reported, it was attempted to calculate RHI to know the RHC. The results of such analyses are shown in Table 4.17.

It is observed from Table 4.17 that River Lambro, Italy (RHI= 47), River Mitheu, Ghana (RHI= 48), River Nairobi Basin, Kenya (RHI= 48), and River Ravi, Pakistan (RHI= 48) are under ‘Poor’ category and mostly ‘overstressed’. This is primarily due to the presence of PPs above PNEC in the aquatic environment and needs improvement. On the other hand, River Wangyang, China, River Brisbane, Australia and River Altamaha, USA are found in ‘Acceptable’ health conditions ranging from Good to Excellent category.

**Table 4.19: Prediction of RHC based on RHI with reported concentrations of PPs and their effects on biotic indicators**

S.N.	Name of the River Studied	Name of Pharmaceutical Compounds and MEC ( $\mu\text{g/L}$ )	Normalized Score (0-5 scale)	(IGS) of PPs (0-100 scale)	Normalized Score on (0-5) scale for Biotic Indicators			Indicator Group Score (IGS) (0-100)			RHI	RHC
					Algae ( $W_4$ : 0.20)	MI ( $W_5$ : 0.20)	Fish ( $W_6$ : 0.10)	Algae	MI	Fish		
1	River Lambro Milan, Italy	Amoxicillin (51)	0	0	0	5	5	0	100	100	48	Overstressed
		Triclosan (0.27)	0		0	5	4					
2.	River Ravi, Lahore, Pakistan	Sulfamethoxazole (2.7)	0	0	0	5	5	0	100	100	48	Overstressed
3.	River Nairobi Basin, Kenya	Sulfamethoxazole (13.8)	0	0	0	5	5	0	100	100	48	Overstressed
4.	River Wangyang, China	Ofloxacin (11.8)	4	40	4	5	5	40	100	100	64	Good
		Sulfamethoxazole (13.8)	0		0	5	5					
5.	River Mitheu, Ghana	Sulfamethoxazole (2.8)	0	0	0	5	5	0	100	100	48	Overstressed
6.	River Brisbane, Australia	Sulfamethoxazole (2)	2	40	2	5	5	40	100	100	64	Good
7.	River Altamaha, USA	Acetaminophen (11)	4	60	5	4	5	70	90	100	72	Excellent
		Naproxen (13.1)	2		2	5	5					

### 4.6.5 Ecological Risk Condition (ERC) and RHC of rivers with high PPs

For rivers outside India, it is assumed that based on DORP and NTs group parameters of water quality, the river health is in ‘Good’ conditions.

Based on classification of ecologically high risk conditions, and RHI based RHC, colored maps for the rivers under study have been presented in Fig. 4.8 (i to vii).

**Fig. 4.8 (i-vii): Colour-coded depiction of ecologically high-risk group of biotic indicator and hexagonal RHC based on IGC and RHI.**

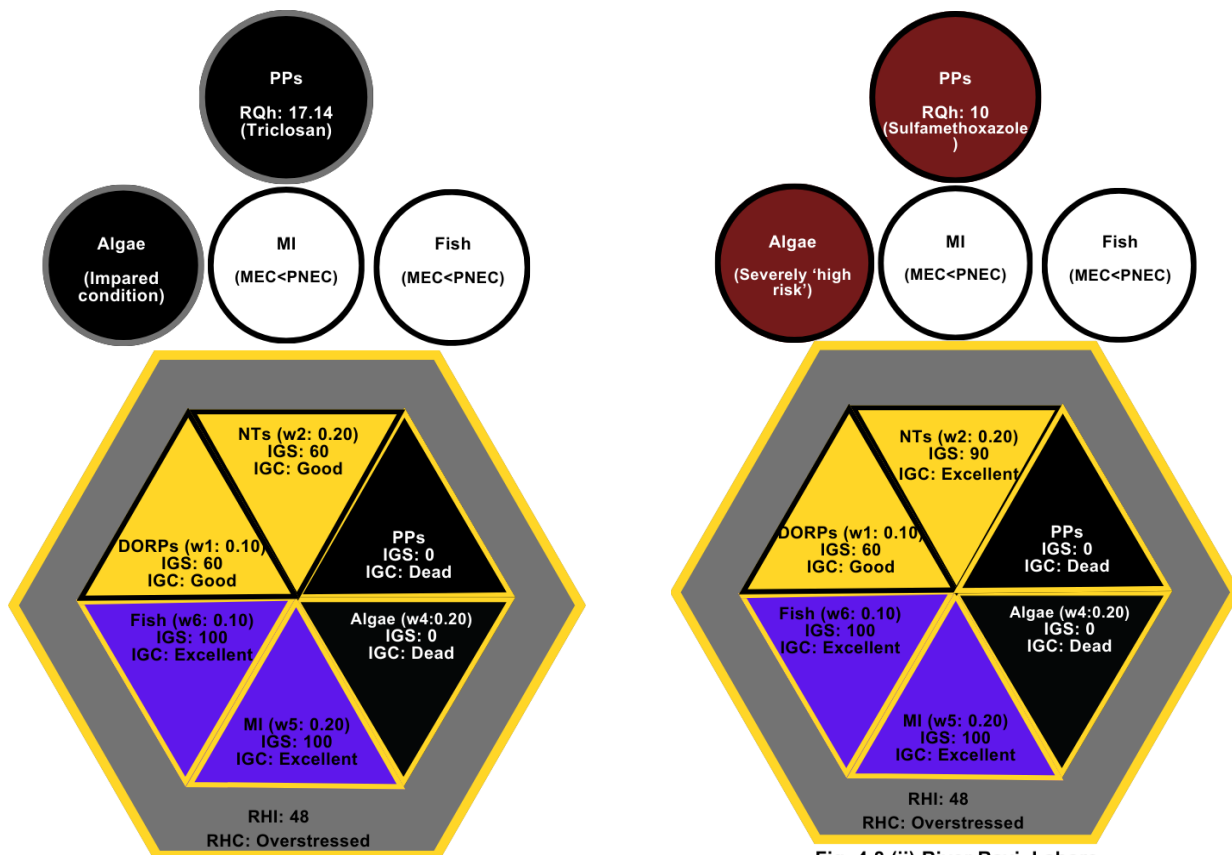
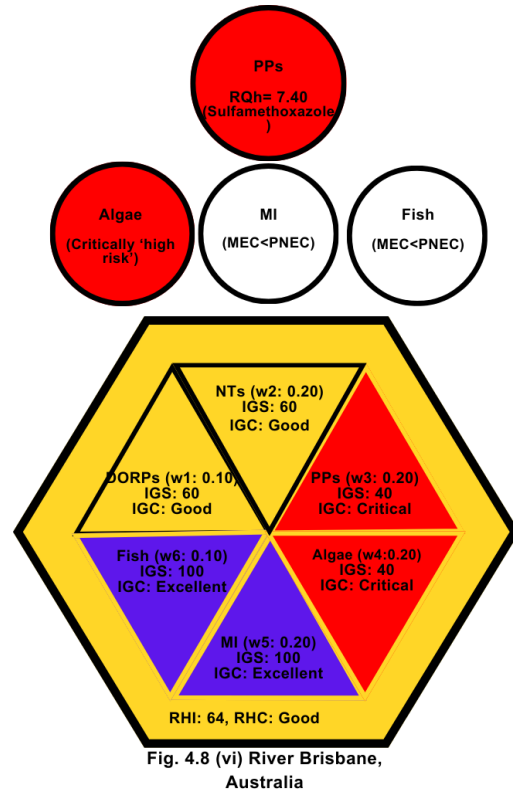
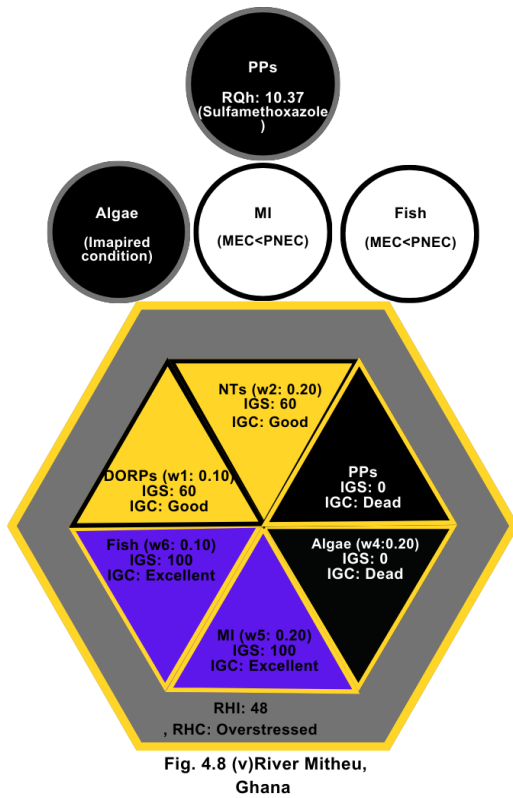
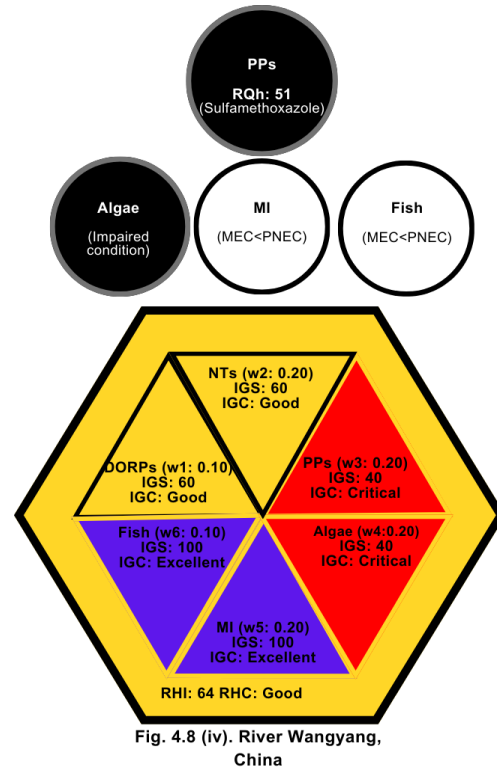
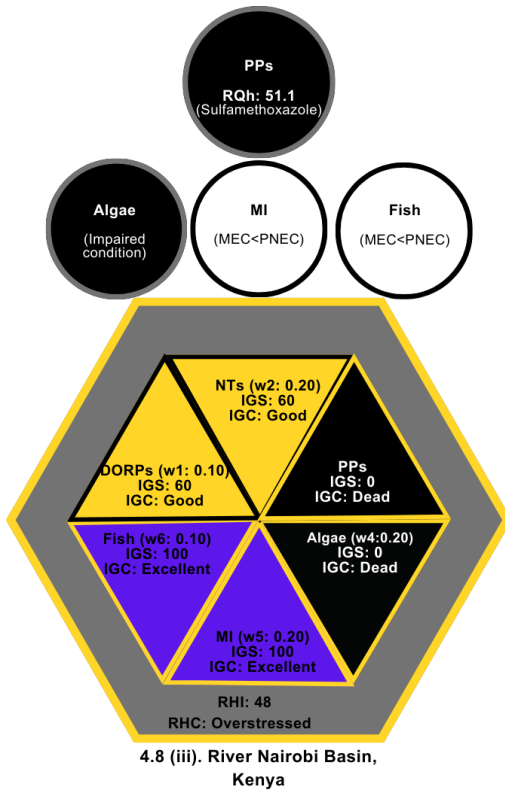


Fig. 4.8 (i) River Lambro, Milan, Italy

Fig. 4.8 (ii) River Ravi, Lahore, Pakistan



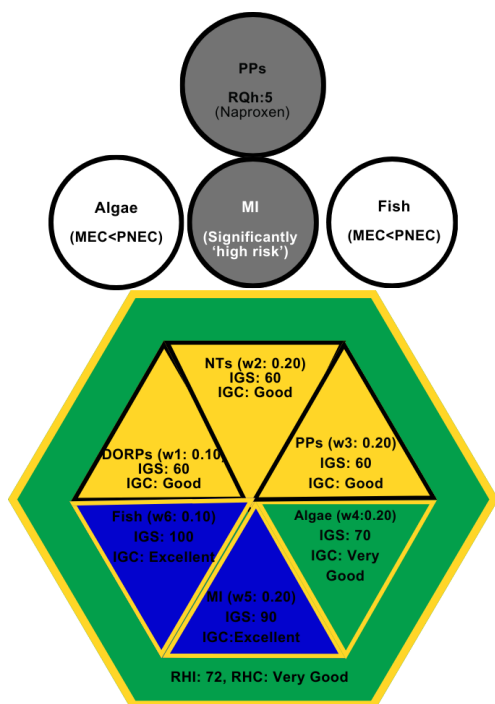


Fig. 4.8 (vii) River Altamaha, Georgia, USA

#### 4.7 Options for River Health Improvements: Treatment Technologies Effective for PPs

Overall, the condition analyses suggest that in order to improve in IGS and make RHC under the 'Acceptable' category, there seem to be three possible approaches:

- i. Augmentation of Existing Treatment Technology: It is encouraging to observe that a growing number of STPs in India and across the world are following chlorination/ ozonation/ UV radiation to disinfect treated effluent to meet biological water quality requirements before discharging to natural water bodies. In addition to its intended objectives, augmentation of treatment systems with such advanced oxidation processes (AOPs) as a tertiary unit also helps in oxidising organic substances of calcitrant nature, including pharmaceutical compounds, which effectively reduces the concentrations of PPs, thereby reducing the ecologically high-risk conditions towards a safer side for biotic indicators of river health.
- ii. Suggestion for new technology: For new installations near the outfall from pharmaceutical industry or hospital wastewater discharges, treatment systems based on MBR or MBBR have been

reported to have high efficiencies for removing PPs. Such units will substantially reduce the outgoing concentrations and risks associated with biotic indicators.

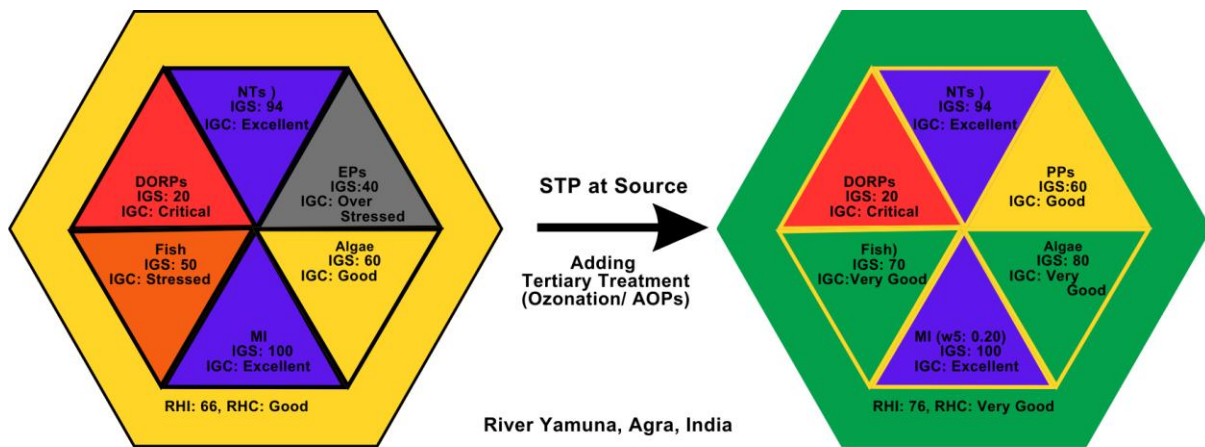
iii. A more fundamental and new innovative approach to reduce the risk due to PPs is to separate the urine stream from human waste at the source itself. Urine carries around 70-80% of pharmaceutical compounds and more than 50% of nutrients discharged into the water environment. As an example, assuming that around 1 L of urine is separated from 10000 population of a city, likely nutrients load reduction is given in Table 4.20

**Table 4.20: Nutrient load reduction from source-separated urine of a 10000 population**

Nutrients	Approx. rate (g/p/d)	Daily Removal Potential (Kg)
N	7.87	78.70
P	0.67	6.70
K	2.96	29.60

From Table 4.20 it is observed that an estimated amount of **78.7 kg/d** of nitrogen and **6.7 kg/d** of Phosphorus can be reduced for every 10000 population. This will not only improve the IGS for NTs group but will also increase the EPs group score as 70-80% of consumed pharmaceutical compounds are excreted through urine. Thus, source separation of urine and diversion from mixing with domestic wastewaters reduces more than 50% of PPs and NTs load, and is likely to create improved IGS, RHI, and better RHC.

Using the option of adding tertiary treatment units such as ozonation on STPs at Agra whose effluents discharge in the River Yamuna (India) as an example, the scenario analysis suggests that the IGC for PPs is likely to change from 'Over Stressed' to 'Good', thereby improving the RHI from 66 to 76 and RHC from 'Good' to 'Very Good' (Fig 4.9).



**Fig.4.9: Possible health conditions improvement plan for River Yamuna at Agra (India)**

Suggestive Augmentation or New Installation Treatment Technologies at STPs in Indian Cities has been given in Table 4.21:

## 4.21 Suggestive Augmentation or New Installation Treatment Technologies at STPs in Indian Cities

S.No	Name of the river	Critical PPs of Concern	(MEC) (µg/ L)	(PNEC) (µg/ L)	(RQ <sub>h</sub> )	(Removal Required (%)	Existing STPs Technology	Suggestive Technology for Augmentation	New Installation
i.	River Kshipra, Ujjain	Norfloxacin	1.98	1.4 (Fish)	1.4	30	SBR	SBR+ UV	MBBR+ CL*
		Sulfamethoxazole	4.66	0.27 (Algae)	17.25	96	SBR	SBR+ Ozonation	MBR+ H <sub>2</sub> O <sub>2</sub>
ii.	IsakavaguNakkavagu , Stream reaches River Godavari near Hyderabad, India	Norfloxacin	470	1.4 (Fish)	335	99	SBR	SBR+ O <sub>3</sub> +UV	MBR+O <sub>3</sub> +CL*
iii.	River Akravati, Bengaluru, India	Naproxen	4.334	2.620 (MI)	1.65	40	MBBR/A2O	MBBR+ H <sub>2</sub> O <sub>2</sub>	MBBR+ CL*
iv.	River Yamuna, Agra, India	Sulfamethoxazole	0.773	0.27 (Algae)	2.86	65	UASB/SBR	SBR+ O <sub>3</sub>	MBR+ CL*
		Diclofenac	0.994	0.050 (Fish)	19.88	50	UASB/SBR	SBR+ CL*	MBR+CL*
v.	River Ganga, Patna, India	Caffeine	0.743	0.15 (Algae)	4.95	80	ASP/SBR	ASP+ UV+CL*	MBBR+O <sub>3</sub>
vi.	River Brahmaputra, Guwahati, India	Caffeine	0.410	0.15 (Algae)	2.73	64	ASP/UASB	ASP+ O <sub>3</sub>	MBR+ CL*

\*CL: Chlorination