CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This Chapter deals with advancement in understanding of quality assessment and monitoring of surface water bodies such as rivers and streams. Initially, the process started with the water quality measurements using some physical, chemical and bacteriological parameters such as turbidity, Biochemical Oxygen Demand (BOD) and Total Coliform (TC). Subsequently researchers came up with biological quality of streams using biotic species as indicators and now the practitioners are coming up with the concept of River Health, combining the effect of water quality, biotic parameters, hydrology, riparian vegetation etc. This sections deal with water quality indexing, different biological indices and concept of River Health.

2.2. Stream Condition Assessment and Monitoring

The rivers, being the major source of water have been the backbones of civilization. However, water quality of rivers is found to be degrading by anthropogenic activities in many parts of the world. The excessive water extraction and dumping of waste in the river are the major causes of damage to fresh water systems (Jain and Singh, 2006). According to the hydrologic flow health analysis of river Ganga the health of the river in terms of low flows is mostly moderate to good. Hence, the water quality problems during the low flows are not due to hydrologic conditions, but they are mainly due to overloading of pollutants beyond the assimilation capacity of the river

(GRBMP, 2014). To protect the rivers from such degradation, river health assessment and monitoring is needed.

2.2.1. Physico-Chemical Parameters Based Approach for Stream Condition Assessment

Earlier, water quality was assessed solely on the chemical analyses of water samples. The concept of indexing water quality with a numerical value based on physical, chemical and biological parameter measurements was first developed in 1965 by US based National Sanitation Foundation (NSF). Horton (1965), Prati et al. (1971), Brown et al. (1972), Harkins (1974) etc. are the early workers towards development of Water Quality Index (WQI). The National Sanitation Foundation Water Quality Index (NSFWQI) used Dissolved Oxygen (DO), Fecal Coliform (FC), pH, Biological Oxygen Demand (BOD), Temperature Change, Total Phosphate (TP), Nitrate (NO_3^-), Turbidity and Total Solids (TS) as water quality parameters. Oregon Water Quality Index (OWQI), developed in 1970 used Temperature, DO, BOD, pH, (NH_4^+ + NO_3^-)-Nitrogen, TP, TS and FC as variables. Bhargava (1983) developed a simplified model for WQI and applied to the stretches of river Ganga and Yamuna in India to identify the pollution status. In 1995, the Canadian Ministry of Environment, developed British Columbia Water Quality Index (BCWQI) for water quality evaluation. In 1996 Florida Stream Water Quality Index (FWQI) used eight parameters such as Turbidity, TS, DO, BOD, COD, Total Organic Carbon (TOC), Nutrients (Phosphorus and Nitrogen) and Bacteria (Total and Fecal Coliform). Swamee and Tyagi (2000) developed a mathematical formulation for an aggregate index by using nine parameters. A new index was developed by Said et al. (2004) to provide a simpler method for describing water quality. Jha and Singh (2008) used entropy to evaluate the water quality at different locations of six rivers such as Baitarani, Brahmani, Malprabha, Pachin, Gomti and Yamuna in India. Dash et al. (2018) used multivariate statistical tools for monitoring and assessing the water quality of Deepor Beel river a part of Brahmaputra River in N-E India. Singh et al. (2019) used Shannon entropy for water quality assessment of the Beki river, Assam (India).

In India the water quality management is done under the provision of Water (Prevention and Control of Pollution) Act, 1974. The main objective of this Act is maintaining and restoring the wholesomeness of national aquatic resources by preventing and controlling the pollution. The level or degree of wholesomeness to be maintained or restored is not mentioned in this Act. The wholesomeness in terms of protection of human uses has been defined by Central Pollution Control Board (CPCB), and thus, human uses of water have been taken as base for identification of water quality objectives for different water bodies in the country. As the natural water bodies are used for various competing and conflicting demands, the objective is restoring and/or maintaining natural water bodies to such a quality as needed for their best uses.

Thus, a concept of “Designated Best Use” (DBU) was developed in 1978. A water source is put to many beneficial purposes, but the source is classified according to the use which demands highest quality and this is termed as “DBU”. The water bodies are classified under five different classes (A to E) as shown in **Table 2.1.**

Table 2.1: Designated Best Use (DBU) of Inland Waters

S	Designated Best Use (DBU)	Class of Water	Primary Water Quality Criteria
1	Drinking Water Source without conventional treatment but after disinfection	A	1.Total Coliform (TC) Organism (MPN/100ml) ≤ 50 2. pH: 6.5- 8.5 3. Dissolved Oxygen (DO) ≥ 6mg/l 4. Biochemical Oxygen Demand (BOD) (5 days at 20^0C) ≤ 2mg/l
2	Outdoor bathing (Organized)	B	1. Total Coliform (TC) Organism (MPN/100ml) ≤ 500 2. pH: 6.5-8.5 3. Dissolved Oxygen (DO) ≥ 5mg/l 4. Biochemical Oxygen Demand (BOD) (5 days at 20^0C) ≤ 3mg/l
3	Drinking water source after conventional treatment and disinfection	C	1. Total Coliforms (TC) Organism (MPN/100ml) ≤ 5000 2. pH: 6 - 9 3. Dissolved Oxygen (DO) ≥ 4mg/l 4. Biochemical Oxygen Demand (BOD) (5 days at 20^0C) ≤ 3mg/l
4	Propagation of wild life and & fisheries, recreation & aesthetic	D	1. pH : 6.5 - 8.5 2. Dissolved Oxygen (DO) ≥ 4mg/l 3. Free Ammonia (as N) ≤ 1.2 mg/l
5	Irrigation, Industrial Cooling, Controlled Waste disposal	E	1. pH: 6.0 - 8.5 2. Electrical Conductivity (EC) ≤2250 µmhos/cm 3. Sodium Absorption Ratio (SAR) ≤ 26 4. Boron ≤ 2mg/l

Source: CPCB, ADSORBS/3: 1978–1979, Scheme for Zoning and Classification of Indian Rivers: Estuaries and Coastal Waters, and CPCB (2002), ADSORBS/32: 1999–2000, 'Water Quality Status of Yamuna River, Assessment and Development of River Basin'.

2.2.2. Biological Indicators Based Approach for Stream Condition Assessment

In recent years the focus has shifted from measuring only physical and chemical parameters to biological indicators to assess stream condition (Karr, 1991; Norris and Norris, 1995; Resh et al., 1996; Wright, 1995). In Australia, the United States and the United Kingdom there is much emphasis on rapid biological assessment using indices such as the Index of Biotic Integrity (IBI) (Karr, 1981) and the benthic-IBI (B-IBI) (Plafkin et al., 1989; Kerans and Karr, 1994). There has been a realization that more accurate picture of the condition or health of waterways can be assessed by the structure of plant and animal communities present in the river. As the stresses imposed by human became more complex and pervasive due to changes in knowledge and societal values, biological monitoring evolved rapidly during the twentieth century (Karr, 1999). The assemblage structure of a broad taxonomic group such as, water birds (Kingsford, 1999), macroinvertebrates (Kay et al., 1999; Marchant et al., 1999; Smith et al., 1999; Turak et al., 1999) or diatoms (Chessman et al., 1999) are the focus of such biological aspects. The habitats in aquatic ecosystems have different biological organisms such as macroinvertebrates, algae, fish etc. residing in it which conveys the integrative and continuous characters of water quality. In biological processes macroinvertebrates plays a key role such as nutrient recycling, transmission of energy through food webs, metabolism of pollutants and dispersion of secondary products (Covich et al., 1999; Lu, 2005). Therefore macroinvertebrates, algae, fish etc. have been considered as suitable indicators (Reavie et al., 2010; Whitton and Kelly, 1995; Allan, 1995; Hawkes, 1979; Hellawell, 1986; Rosenberg and Resh, 1993; Sladecek, 1979; Tittizer and Koth, 1979). The concept of biomonitoring approaches and bioindicators used for river ecosystems was reviewed by Li et al. (2010) for their current use and anticipated future direction. The common indicators are periphyton, benthic macroinvertebrates and fish. These can be used separately or contemporaneously.

The diversity indices such as Margalef Index, Shannon – Wiener Index, Simpson Index etc, biotic indices such as Trent Biotic Index (TBI), Chandler's Score System, Chutter's Index, Hilsenhoff's Biotic Index (HBI), Biological Monitoring Working Party Score System (BMWP), Average Score per Taxon (ASPT), multimetric approaches such as Index of Biotic Integrity (IBI) for fish assemblages, multivariate approaches such as RIVPACS, AUSRIVAS, BEAST, ANNA, Functional Feeding Groups (FFGs) as Index of Trophic Completeness are different biomonitoring approaches to evaluate the stream's health. Out of these, biotic indices and multimetric approaches are most frequently used approaches. The functional measures reflect the ecological integrity and are applied as a complementary approach. The molecular techniques of biomonitoring are efficiently used for enhancing the taxonomic resolutions and detecting the genetic diversity in river. A benthic diatom-based index of biotic integrity (BD-IBI) for analyzing benthic algae assemblages was developed by Tan et al. (2015) using multivariate and multimetric approaches for the assessment of the aquatic environment in the upper Han River (China).

In the past few decades, two major approaches using such indicators have been developed. First approach, viz., the multimetric index approach arose as an offshoot of basic research in aquatic ecology (Karr, 1981, 1991; Karr et al., 1986) and second approach, called predictive model, relies on multivariate statistical methods to discern pattern in taxonomic composition. The 'multimetric' approach is used in many countries including greater than 85% of water-quality programs in the U.S.A. (Southerland and Stribling, 1995) for assessing condition of the river. The multimetric index approach (Karr and Chu, 1999) reduces the complexity and presents the data in a form that can be easily understood by non-experts (Barbour et al., 1999; Plafkin et al., 1989). The U.S. EPA Rapid Bioassessment Protocols (RBP) for the multimetric approach suggests that reference sites and the test sites (Barbour et al., 1999) should be within the eco-regions (Omernik, 1987). According to Karr and Chu (2000) the multimetric approach is superior to the predictive model approach in several ways. However, Norris and Hawkins (2000) argued that the currently practiced multimetric approach is compromised by circularity in choice of metrics, lack of independence in sub-indices and crude methods for matching reference sites with test sites. They suggested that to resolve these arguments the approach used in marine bioassessment should be adopted.

Predictive models quantify river health as, the degree to which a site supports the biota that would be expected to occur there in the absence of alteration by humans. From predictive model approach, River Invertebrate Prediction and Classification System (RIVPACS) is used nationally in the United Kingdom (Wright, 1995), Australian River Assessment System (AUSRIVAS) is used nationally in Australia (Simpson and Norris, 2000) and Benthic Assessment of Sediments (BEAST) is used in Fraser River basin in Canada (Reynoldson et al., 1997). RIVPACS and its derivative, AUSRIVAS are empirical statistical models that predict the aquatic macroinvertebrate fauna that would be expected to occur at a site in the absence of environmental stress (Simpson et al., 1996). In the predictive model approach, assessments are made on a site-specific basis by comparing observed taxa with those predicted to occur at that site by the model. Predictive model assessments are based on changes in taxonomic composition, they may serve as both early warning and compliance indicators (Cairns and McCormick, 1992). Many predictive models compare the quality of an impacted site with a reference site on the basis that biological species which share a similar habitat at different sites, are more alike than species which belong to different habitats but are found at the same site (Parsons and Norris, 1996). RIVPACS is used for estimating and monitoring the ecological quality of river sites using standardized protocols to compare a wide range of sites (Clarke et al., 2003). Index of Biotic Integrity (IBI), RIVPACS and Australian River Assessment System (AUSRIVAS) models utilize macroinvertebrate and fish assemblage data for making site specific predictions (Barmuta et al., 2002; Wright, 1995; Karr, 1991). In Australia, many composite river health approaches such as Australian Rivers Assessment System (AUSRIVAS), National Framework for the Assessment of River and Wetland Health (FARWH), Tasmanian Index of River Condition (IRC), Sustainable River Audit (SRA) and systematic river health assessment for the Murray Darling Basin consider the state of pristine condition or pre-European reference conditions to assess the health of river systems at state and national levels (Askey-Doran et al., 2009; Norris et al., 2007; Peter et al., 2008).

Historically the work in the direction of assessment of biological quality of rivers started in 1977 in UK with the development of RIVPACS (River InVertebrate Prediction And Classification System) a software package by the Institute of Freshwater Ecology (IFE), UK. This RIVPACS software offers site-specific predictions of the macroinvertebrate fauna to be expected in the absence of major environmental stress. Further versions of RIVPACS as RIVPACS II was used in 1990 for River Quality Survey. RIVPACS III was developed for Great Britain and Northern Ireland in 1995 for General Quality Assessment Survey and RIVPACS III+ is a development of new procedures for detecting statistically significant temporal and spatial changes. In 1992, Australia developed Australian River Assessment System (AUSRIVAS) as a nationally standardized approach for biological assessment of stream condition using macroinvertebrate under National River Health Program (NRHP). The predictive modeling approach used in RIVPACS forms the basis of AUSRIVAS. In 1995 Canada used the same predictive technique of RIVPACS and AUSRIVAS for developing Benthic Assessment of Sediment (BEAST) predictive models for rivers and lakes and for the prediction of macroinvertebrate composition using microhabitat features (Evans and Norris, 1997; Reynoldson et al., 1997). Stockwell and Faith (1996) developed a model called Assessment of Nearest Neighbor Analysis (ANNA) for calculating an observed/expected ratio of taxa richness. The approach is very similar to RIVPACS/ AUSRIVAS with a fundamental difference that in RIVPACS/AUSRIVAS, classification and analysis of discriminant function is required which is not needed in ANNA. ANNA uses Euclidean distance (ecological distance) for describing differences between habitats, which is the oldest and the simplest method (Washington, 1984) and is widely used as a similarity coefficient in ecological studies (Faith et al., 1987; Hruby, 1987). In ANNA model, similar sites are found by calculating the ecological distance between the set of reference sites and the test site based on number of environmental variables. Then these similar sites are used to establish the reference condition. ANNA's robustness and accuracy of prediction was tested by Linke et al. (2005) and it was concluded that AUSRIVAS and ANNA both are equally good in performance but ANNA is more accurate when applied on the trace metal gradient sites and is more robust for Observed (O) versus Expected (E) regressions.

In South Africa, a biological index named South African Scoring System (SASS) is used for assessing aquatic invertebrate fauna. This index is based on the presence of families of aquatic invertebrates and their perceived sensitivity to water quality changes (Chutter, 1998). SASS results are expressed both as an index score (SASS score) and the Average Score Per recorded Taxon (ASPT value) (Vos et al., 2002).

The health condition of river Keum-Ho located in South Korea was evaluated by An et al. (2002) by applying the Index of Biological Integrity (IBI). Qualitative habitat evaluation index (QHEI) was used for the assessment of habitat condition. It was observed that the river health was rapidly degrading due to the combined effect of chemical contaminations and habitat modifications. Initiatives have already been taken in South Africa, Australia, China and Singapore to monitor and maintain the health of rivers. Various indices that apply to certain attributes of river are being used to describe the overall state of the river.

2.3. Concept of River Health

In order to express the status and condition of the river ecosystem, river health (Karr, 1999; Norris and Thoms, 1999) has been introduced into the field of eco-hydrology based on the concept of ecosystem health. According to Karr (1999) the river health means the ability of the aquatic ecosystem to support and maintain the ecological integrity and process. Due to degradation of the ecosystem, the research in the area of river health assessment has increased in recent years (Norris and Thoms, 1999; Zhao and Yang, 2005; Vugteveen et al., 2006).

The ecological and human values both are incorporated in the concept of River Health. Rapport (1989) suggested that efforts to protect ecological health must consider the human uses and amenities derived from the system. The main objective of river management is restoration and maintenance of ‘healthy’ river ecosystem (Gore, 1985;

Karr, 1991; Rapport, 1991). Many researchers such as Regier (1993) and Meyer (1997) agree that the societal values are important in defining and protecting health. According to Haskell et al. (1992) an ecosystem is healthy if it is resilient to stress, is active and maintains its organization and autonomy over time. According to Karr (1999) 'the river health means the ability of the aquatic ecosystem to support and maintain the ecological integrity and process.' Broadly a river is healthy when it can sustain its ecological integrity (Bond et al., 2012).

2.3.1. Approaches of River Health Monitoring

River health monitoring is undertaken to protect and improve the health of ecological assets of river which are impaired by human actions. The goal of river management may be to maintain the current status, to improve on the current status or achieve a target state of river health.

The United States Environmental Protection Agency (U.S. E.P.A) Study Group on Environmental Monitoring (National Research Council, 1977) categorized environmental monitoring relevant to pollutants into three categories: **source monitoring**, **ambient monitoring** and **effects monitoring.** ***Source monitoring*** informs about type of pollutants, their source and in what amounts; the concentration of pollutants present in the physical and biological environment are measured in ***Ambient monitoring***, and the consequences of the pollutants on the biota or living things is measured in ***Effects monitoring***. These categories are not readily transferable to holistic river health monitoring. Metcalfe-Smith (1996), Barbour et al. (1999) and ANZECC and ARMCANZ (2000a; 2000b; 2000c) have reviewed different approaches to monitor the river condition.

In line with U.S.E.P.A. Study Group, the European Union (EU) Water Framework Directive (Kallis and Butler, 2001) describes three types of monitoring: **surveillance, operational and investigative monitoring.** ***Surveillance monitoring*** is carried out for large river basins to provide a coherent and comprehensive overview of current health status, and an assessment of long-term changes. The ***operational monitoring*** is for water bodies upto 10 km² that are identified to be at risk of failing to meet environmental objectives, and for monitoring changes in the status after rehabilitation measures are adopted. The ***investigative monitoring*** is done to ascertain the magnitude and impacts of accidental pollution, or for those water bodies that have failed, or are likely to fail to meet the environmental objectives for unknown reasons. Surveillance monitoring is referred to as **trend monitoring** or **routine monitoring**, operational monitoring is referred to as **restoration assessment** or **campaign monitoring** (MDBC, 2003), and the investigative monitoring is referred to as **impact assessment** (Kallis and Butler, 2001). Thus, various approaches of river health monitoring may be summarized as given in **Fig 2.1**.

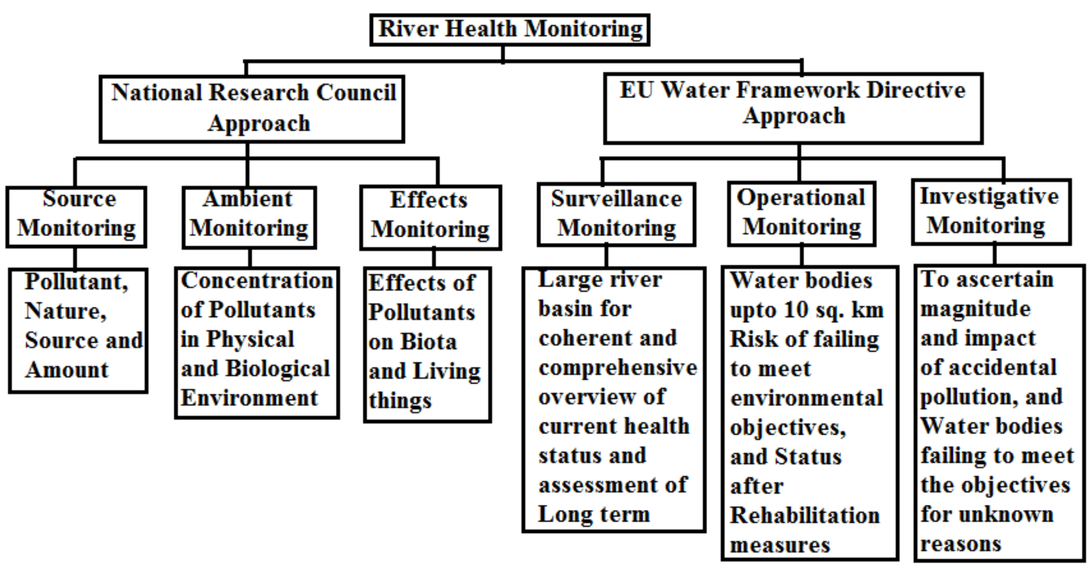


Fig 2.1: Approaches of River Health Monitoring

In addition, **Snapshot assessment** is a one-off effort designed to rapidly obtain a picture of the current state of river health over a given area. The spatial patterns in the data are emphasized (Norris et al., 2001; National Water Commission, 2007).

2.3.2. Approaches of River Health Assessment

River health assessment is a way of examining the waterway, using water quality, habitat descriptions, biological monitoring and flow characteristics to create an overall picture of the ecological health. River health assessment provides information to help in management decisions thus, it is an evaluation tool for river management. In river health assessment, analysis and interpretation of the data is carried out to objectively and timely assess the river health condition. This helps for coordinating and monitoring sustainable utilization of water and sustainable development of economy. The river health assessment methods may be classified in two ways : (i) Based on **Content of Evaluation** and **(ii)** Based on **Principle of Evaluation** as shown in **Fig 2.2.**

Based on the Content of Evaluation, the *indicator species* method is one in which the fish, diatoms and microinvetebrates are used as indicators to assess the soundness of river ecosystem whereas *Comprehensive index* method integrates effects of physical, chemical, biological and socio economic indicators for assessment of river health (Huaibin and Jianping, 2014). The Index of Biological Integrity (IBI) (Karr, 1981); the Riparian, Channel and Environmental (RCE) inventory (Petersen, 1992); and the Index of Stream Condition (ISC) (Ladson et al., 1999) are examples of this category.

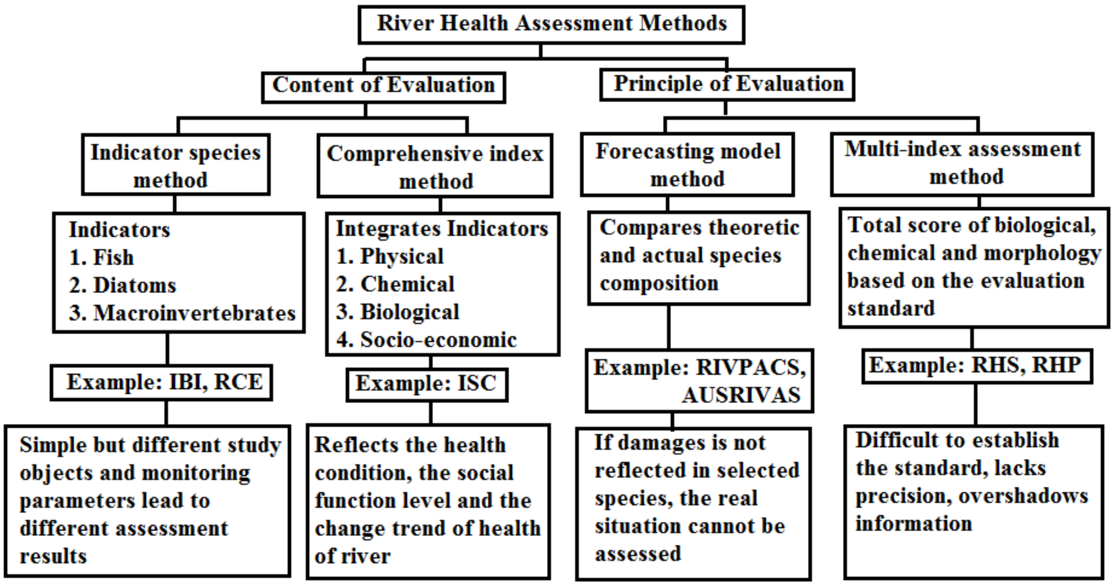


Fig 2.2: River Health Assessment Methods

Based on Principle of Evaluation, **forecasting model** method and **multi-index assessment** method are used as predictive models for the forecast of river health. In forecasting model natural species composition of the reference (undisturbed) site is compared with actual species composition, to assess the condition of the river health (Xia et al., 2014). The River Invertebrate Prediction and Classification System (RIVPACS) (Wright et al., 2000), the Australian River Assessment System (AUSRIVAS) (Simpson and Norris, 2000) and the Benthic Invertebrate Community Structure (BEAST) (Reynoldson et al., 1997) are forecasting models. In forecasting models, the evaluation of river health is done by comparing a single species, and it is assumed that any change in the river is reflected by the changes in selected species (Huaibin and Jianping, 2014). The drawback of this method is that if changes or damages of river health are not reflected in the changes of selected species, it cannot reflect the real situation.

In multi-index assessment method such as River Habitat Survey (RHS), River Health Programme (RHP), the total score is used to evaluate the river health. The total score is calculated based on the individual scores of chemical, biological, morphological characteristics of the river based on the evaluation standard. In this method many factors are used which makes it difficult to establish the evaluation standard. This method is less precise and to some extent overshadows the information of a single parameter.

From ecological perspective, 'River Health' is a recognizable and increasingly acceptable term now, but its comprehensive definition is still evolving. Broadly, it is understood to include integrity, stability and sustainability of biotic life in riverine environment, but it is still difficult to measure it in precise scientific terms. The term was initially proposed in the US, Water Pollution Control Act (Amendments 33 US Code 1251), now known as Clean Water Act (CWA) 1972. The main objective of this act was to restore, and maintain the physical, chemical and biological integrity of waters. The term '**river health**' is often equated with '**biological integrity**' which has been defined by Frey (1977) as:

> "*the capability of supporting and maintaining a balanced, integrated, adaptive community of organisms having a composition and diversity comparable to that of the natural habitats of the region*"

Guo et al., (2009) have summarized various definitions of river health as given by researchers. An updated version of this summary is presented in **Table 2.2**. It is obvious that various terms have been used to express the concept of river health.

Table 2.2: River Health Definition by Different Researchers
(modified from Guo et al., 2009)

Researcher	Term Used	Definition of River health
Meyer (1997)	Stream Health	A healthy stream is an ecosystem that is sustainable and resilient, maintaining its ecological structure and function over time while continuing to meet societal needs and expectations.
Norris and Thoms (1999)	River Health	Healthy river ecosystem is biological integrity in terms of relationship of geomorphological, hydrological and chemical indicators with aquatic biota and sustainability.
Fairweather (1999)	River Health	River health is transdisciplinary and must include various measurements of riverine attributes and characteristics.
Karr (1999)	River Health	Health is equated to integrity. Evaluation of health through indicator of biological integrity.
An et al. (2002)	River Health	Health is equated to integrity. Evaluation of biological integrity, habitat conditions and chemical parameters.
Dong (2005)	River Health	River health is not a precise scientific term but an evaluation tool of river management.
Vugteveen et al. (2006)	River Ecosystem Health	An expression of a river's ability to sustain its ecological functioning in accordance with its organization while allowing social and economic needs to be met by society.
Liu and Zhang (2006)	River Health	River health is a description of river condition with social traits. The standard of river health in the different background is a choice of society in reality.
Schofield and Davies (2007)	River Health	River health can be referred to as the degree of similarity in biological diversity and ecological functioning to a river without any interventions
Liu and Liu (2009)	River Health	Healthy river is a river whose social and natural functions can be balanced or compromised in terms of the socio-economic, ecological and environmental values associated with the river.
Ying et al. (2009)	Water Health	Water Health is described as environmental, ecological, landscape and social service functions of the water based on ecological health degradation of aquatic ecosystems in relation to human-induced watershed alterations.
Agouridis et al. (2015)	Stream Health	A healthy stream is one that is able to support a variety of biological and ecological functions such as filtering and processing of nutrients, organic carbon recycling, sediment transport, and habitat provision.
Kannan et al. (2018)	Stream Health	A healthy stream is one that supports the full complement of structure and functions that are possible in the absence of anthropogenic influences.
Shinde and Babel (2018)	River Health	River health comprises of biological, physical habitat, water quality and socioeconomic dimensions.

Rivers and streams have a wide range of functions including irrigation, domestic water supply and biodiversity conservation despite the fact that the flows are varying for different seasons throughout the year (GRBMP, 2014). Many researchers have attempted to develop an integrated or holistic mathematical approach where the river condition can be expressed as a string of sub-index values, or as a single integrated index without concern for mixing causes and effects. The causes in the rivers are abiotic drivers or pressures such as physical habitat availability, hydrology, riparian vegetation, physical form and process, and water quality (Ladson and White, 1999; Parsons et al., 2002). The resultant effect in the river system due to changes in abiotic factors come as biotic response. In practice, river health is measured using indices that vary along a gradient of environmental disturbance, so that there is a scale of deviation from the healthy state. The degree of deviation from a healthy state is described by the term 'River Condition'. The Australian river health monitoring programs for the state of Victoria (Ladson et al., 1999); the Ecosystem Health Monitoring Programme (EHMP) (Bunn et al., 2010) for the South East Queensland region, the Sustainable Rivers Audit (SRA) for the Murray-Darling Basin (Davies et al., 2010) (now discontinued) and National Framework for the Assessment of River and Wetland Health (FARWH) to cover the entire nation are good examples in this direction.

In **Australia**, the Index of Stream Condition (ISC) has been applied for assessing the condition of stream. Different key aspects such as hydrology, water quality, physical form, streamside zone, and aquatic life were considered and the stream condition was categorized as Excellent, Good, Moderate, Poor and Very Poor (Ladson and White, 1999; Ladson et al., 1999). The main aim of the Ecosystem Health

Monitoring Programme (EHMP) for the South East Queensland region was to identify the priority areas, inspire action and access the effectiveness of management actions. The river was classified as Excellent (near Reference Condition), Good, Fair, Poor, Fail (Fail to meet the ecosystem health objective) (Bunn et al., 2010). In Australia**,** Pinto and Maheshwari (2014) developed a simple four-step (Understand, Identify, Develop, and Apply) River Health Assessment framework to assess ecohydrology and hydrobiology of Hawkesbury– Nepean River (HNR), a peri-urban river systems in New South Wales (NSW).

In 1994 **South Africa** initiated the River Health Programme (RHP) for monitoring and evaluating the river health using instream and riparian biological communities (fish, invertebrates, vegetation). In 2016 RHP was updated and replaced by River Eco-status Monitoring Program (REMP), a component of the National Aquatic Ecosystem Health Monitoring Program (NAEHMP). The objective was to measure, assess and report the ecological state, spatial and temporal trends in the ecological state, emerging problems regarding aquatic ecosystems and provide scientifically relevant information to create public capacity and environmental awareness. The indices used were Index of Habitat Integrity (IHI) for loss of habitat, Fish Assemblage Integrity Index (FAII) to know size class and health of fishes, South African Scoring System (SASS) for macroinvertebrates and Riparian Vegetation Index (RVI) for the modification of riparian zone from its natural state. The health of river is categorized as Natural (N), Good (G), Fair (F) and Artificial.

In **China**, the Australia-China Environment Development Partnership (ACEDP), an Australian AusAID initiative, has undertaken pilot studies in three catchments: the Gui River, a subcatchment of the Pearl River (Bond et al., 2011); the lower Yellow River (Gippel et al., 2012; Liu et al., 2016); and the Liao River (Leigh et al., 2011; Zhang et al., 2013; Qu et al., 2016). Collaboration between Australia and China shaped the preliminary framework for a National River Health Assessment Program (Gipple et al., 2017). The main objective was to develop a national approach to: (a) Know the current health of rivers; (b) Monitor programs and management actions; (c) Develop and implement river health monitoring programs. The features of the river health assessment program of China are given in **Table 2.3.**

Table 2.3: Features of Three Pilot Studies in China

	Pearl & Liao River	Yellow River
Area covered	Health within whole catchment	Only in lowland mainstem of Yellow River
Indicators	Biotic (fish, MI & algae), WQ, Physical Form & Vegetation	Physical Form, Vegetation, Hydrology, WQ & Social
Gradient	Catchment disturbance & hydrological changes	Not followed

In Pearl river the Indicator groups and parameters used are given in **Table 2.4**

Table 2.4: Indicator Groups and Parameters in Pearl River, China
(Bond et al., 2011)

Group	Parameters
WQ	pH, Cond, DO, NH4, NO3, TN
Algae	Chl-a, δ15N, Biological Diatom Index (IBD), Pollution Sensitivity Index (IPS)
Invertebrates	Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa, EPT ratio, Biotic Index, Ratio Five, SIGNAL, SIGNAL weighted
Fish	Fish richness, Fish abundance, Residual weight
Macrophytes	Riparian Width, Riparian connectivity
Physical Form	Free Flow Interruption, Sediment Transport Interruption, Longitudinal-continuity barrier, Catchment Sediment Risk
Hydrology	Index of Flow Deviation (IFD)

The indicator group score is average of parameters score and the numerical score was classified as:

1	Excellent
0.8	Good
0.6	Fair
0.4	Poor
0.2	Very Poor

The results are reported in the form of report card as shown in **Fig 2.3**.

The Indicator Groups and parameters used in Liao river are given in **Table 2.5.**

Table 2.5: Indicator Groups and Parameters in Liao River, China
(Leigh et al., 2012)

Group	Parameters	Group Score
WQ	EC, DO, BOD5, COD, phenols	(P) Minimum Score
Nutrient	NH4, TP	(N) Average
Algae	A_BI2, A_BP	(A) Average
Invertebrates	M_S,M_EPT, M_BWMP	(M) Average
Fish	F_S, F_BI, F_BP	(F) Average

The Ecosystem health is calculated as follows:

Ecosystem Health = (PC x 2/15) + (N x 2/15) + (A x 3/15) + (M x 4/15) + (F x 4/15)

where PC = Physical and Chemical, N= Nutrients, A= Algae, M= Macroinvertebrates F=Fish

Depending on the Ecosystem Health score, the river is classified as:

>0.8	Excellent
≤0.8	Good
≤0.6	Fair
≤0.4	Poor
<0.2	Critical

And the results are given in the form of report card as shown in **Fig 2.4.**

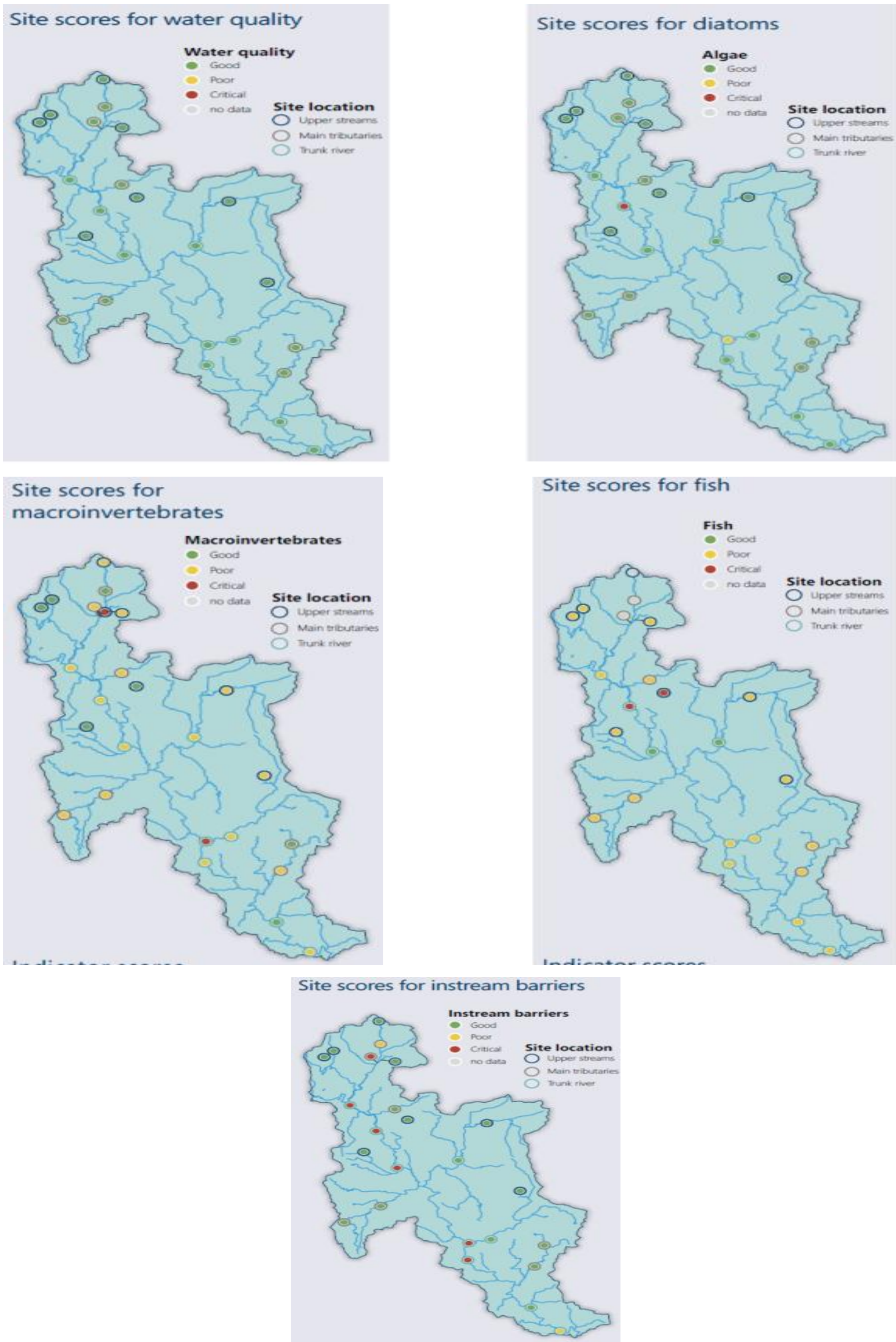


Fig 2.3: Report Card of Pearl River, China

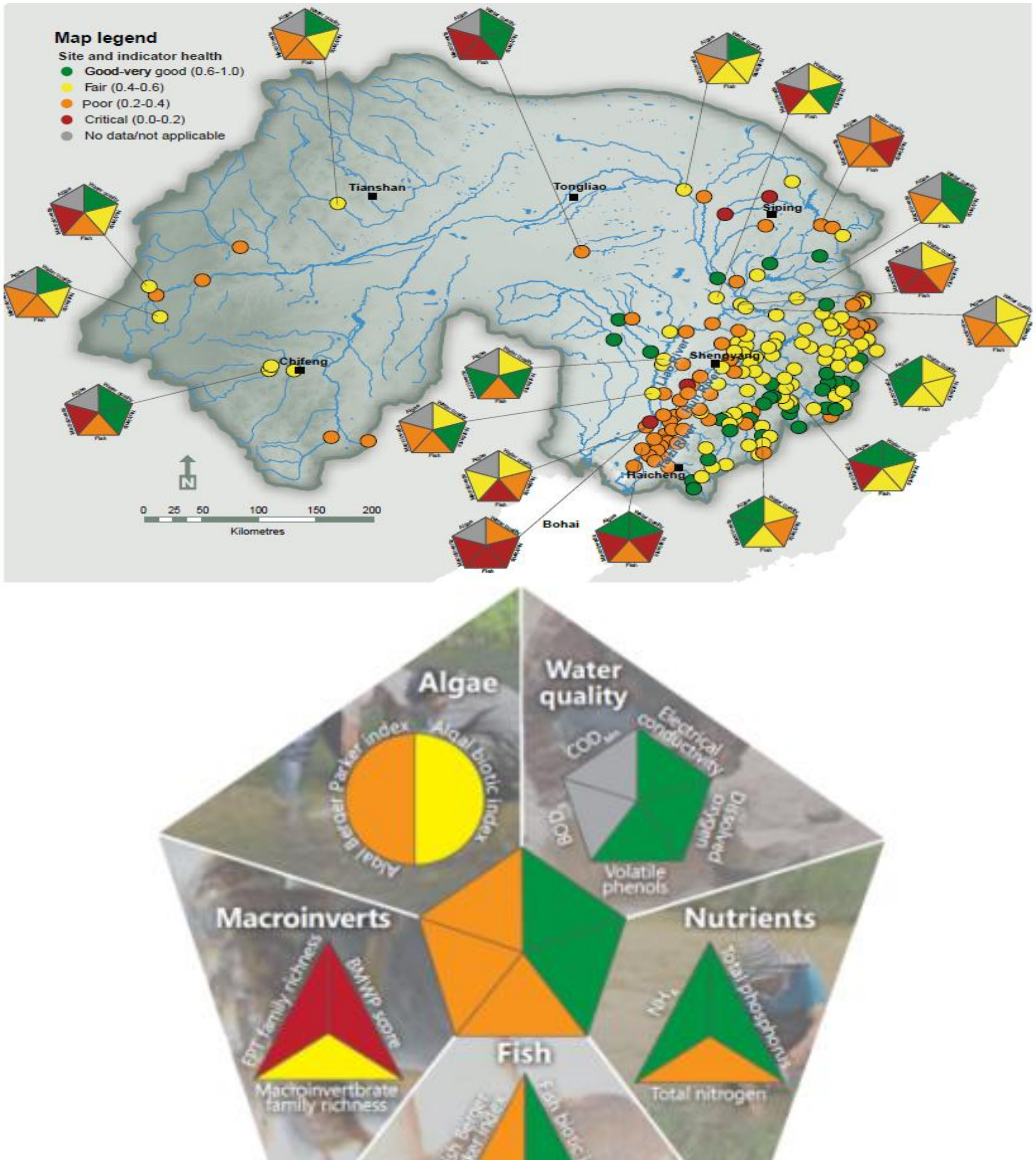


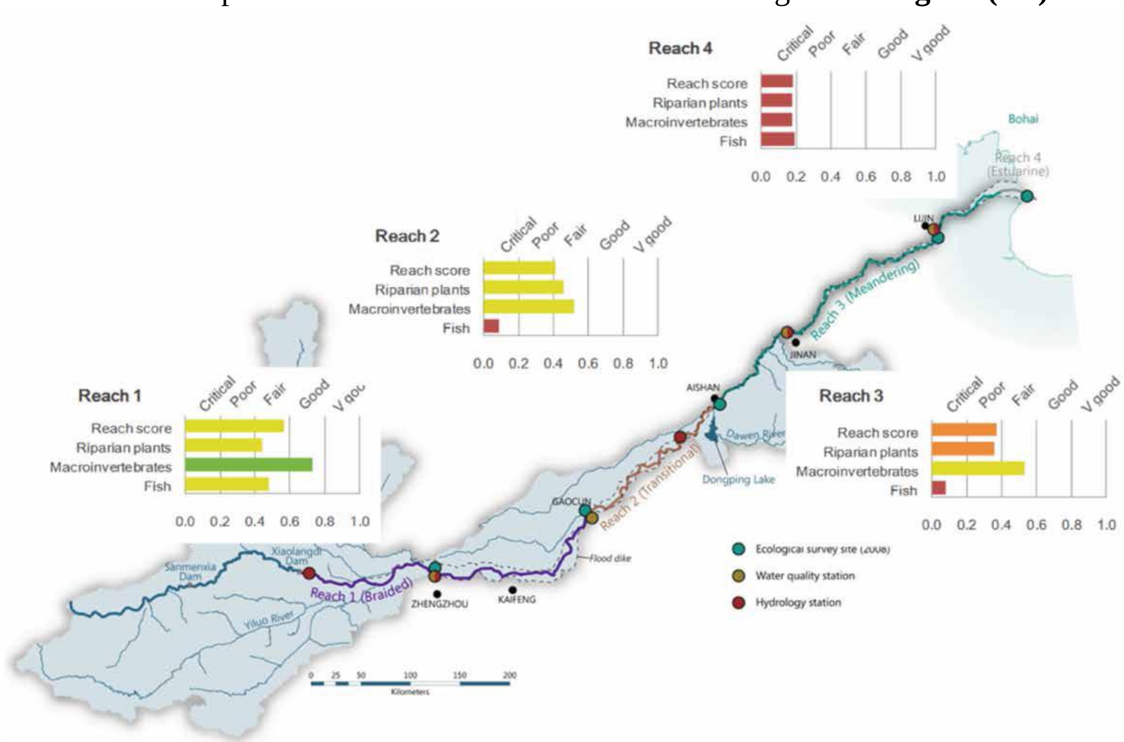
Fig 2.4: Report Card of Liao River, China

In Yellow river, China multimetric approach was adopted. The sites were compared with reference condition. The indicators were divided into two groups: (1) Environmental and (2) Social, and the indicators used under each group are given in **Table 2.6.**

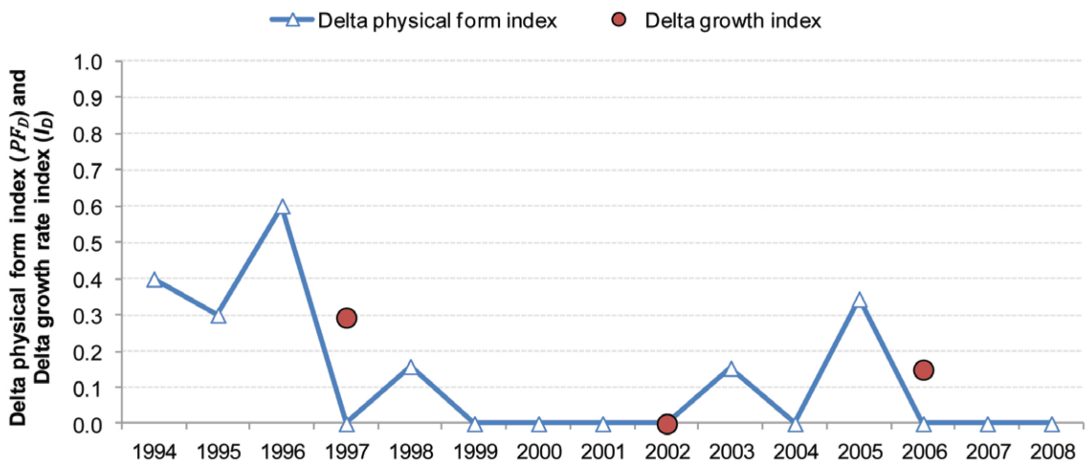
Table 2.6: Groups and Indicators of Yellow River, China
(Gippel et al., 2012)

Group	Indicators
Ecology- Channel	Plants, Macroinvertebrates, Fish
Ecology- Delta	Wetland Vegetation
Hydrology	E-flow component
Water quality	Chinese Standards
Physical Form	Sediment Concentration and Sediment Load
Social	Water Quality
	Flood Risk
	Drought Risk
	Hydropower
	Water consumption
	Recreation
	Navigation

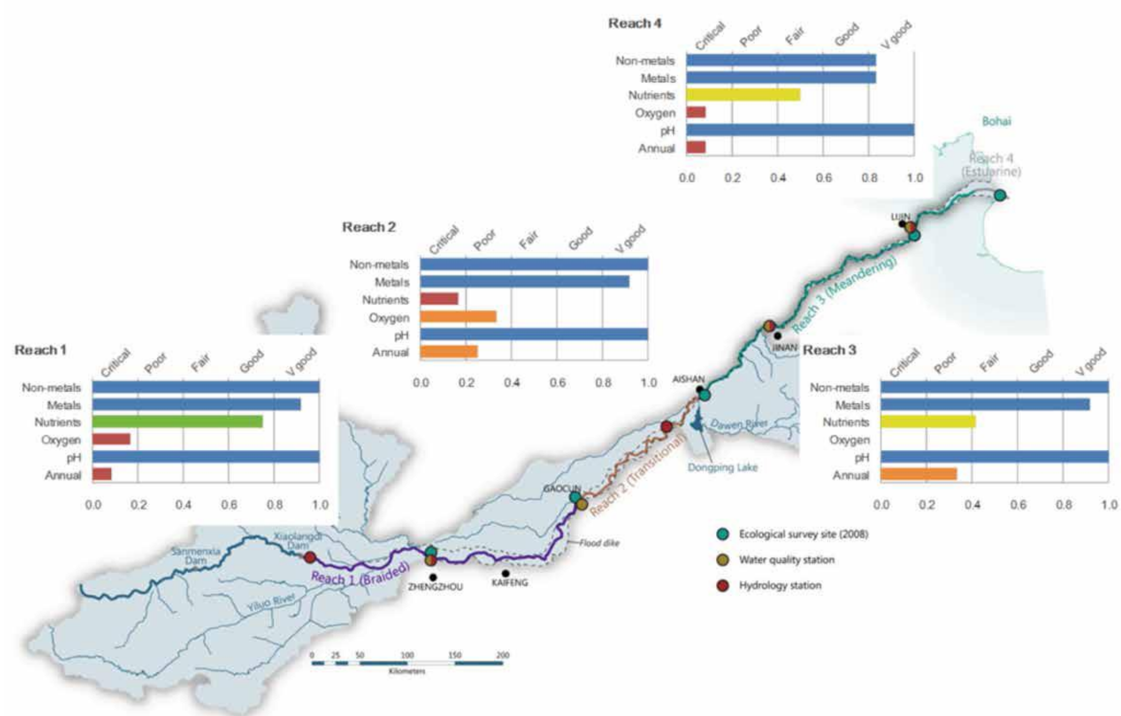
The results are represented as shown below. Few results are given in **Fig 2.5 (a-c).**



(a) Ecological River Health Index



(b) Physical Form Index



(c) Water Quality (aquatic health) Score

Fig 2.5: Report Card of Yellow River, China

The study concluded that hydrology is not a limiting factor to Ecological Health and it appears that water quality limits the ecological health. Methodology adopted in these pilot studies are open to improvement.

In **Thailand,** Shinde and Babel (2018) developed a framework for River Health Assessment for the Mekong River Basin. As conceived, River Health Index (RHI) may be calculated through considerations on three levels: Dimensions, Indicators and Variables. Dimensions and Indicators are the generic part of the framework and can be applied in any river basin. Variables were used to reflect site specific nuances and their choice depends on the local influences or condition. Overall, the framework used 32 Variables, under 10 Indicators, considered in 4 Dimensions. The Indicator scores were averaged to obtain the Dimension score. Further the Dimension score are averaged to arrive at the River Health Index (RHI) value. The RHI value is used to interpret the river condition as:

RHI <1.5	:	Very Poor
RHI 1.5-2.5	:	Poor
RHI 2.5-3.5	:	Good
RHI 3.5-4.5	:	Very Good
RHI > 4.5	:	Excellent

In **India**, after the enactment of Water (Prevention and Control of Pollution) Act, 1974, concern over river pollution has been brought to limelight in a significant way since 1980's (Goldar and Banerjee, 2004). The National Rivers Conservation Program (NRCP) was initiated to monitor various water quality parameters (physicochemical and biological) at some stations on some of the major river systems (Singh et al., 2004; Gurjar and Tare, 2019). Rivers like Ramganga, Kali, and Gomti which are tributaries of Ganga are reported to carry significant pollutant load (Singh et al., 2005; Tare et al., 2003). On national scale, the water quality-monitoring network for inland water bodies is operated under a three-tier programme i.e. Global Environment

Monitoring System (GEMS), Monitoring of Indian National Aquatic Resources System and Yamuna Action Plan. Water samples for 28 parameters consisting of physico-chemical and bacteriological parameters are being analyzed for ambient water samples from the field observations. Biomonitoring is also carried out on specific locations. Water quality data are reported in Water Quality Status Year Book (CPCB, 2013). Ojha and Thakur (2010) applied River Bank Filteration (RBF) technique in parts of North India for the significant removal of Total Coliforms and Fecal Coliform to improve the quality of water.

According to the vision and mission of Ganga River Basin Management Plan (GRBMP) the main goal is to restore the wholesomeness of National River Ganga and her basin. The objective of "Mission-Nirmal Dhara" (MND) is to ensure that the flow in the Ganga River System is bereft of manmade pollution so that the river water quality should not be affected by human activities (GRBMP, 2015). Based on the hydrologic flow health analysis, the health of the river in terms of low flows at the main stem of the river is mostly moderate to good. Hence, the problems in terms of water quality during the low flows are not due to hydrologic conditions, but are due to overloading of pollutants beyond the assimilation capacity of the river. Therefore, the water quality problems in Ganga cannot be addressed by improving the low flow conditions only beyond the current levels. The water quality problems should be addressed by reducing the pollution loading (GRBMP, 2014).

Recently, the Central Pollution Control Board CPCB (2017) has undertaken bio-monitoring of River Ganga from Rishikesh in Uttarakhand to Diamond Harbour (West Bengal) in India. The bio-monitoring was carried out using benthic macro-invertebrates communities emphasizing taxonomic richness and composition. Bio-assessment was done by evaluating Saprobic Score and Diversity Score. Saprobic Score is calculated based on most pollution sensitive (Score 10) and most pollution tolerant (score of 1 or

2) macroinvertebrate family. The intermediate families are placed in between 10 and 1. The Diversity Score is calculated by pair–wise comparison of sequentially encountered individuals. The first observed animal is always different and scored as 1 run and if next observed animal is different from the previous one then a new run starts and if it is same as the previous one then it does not increase the run. Same Run is 0 (organism is the same as the previous) and Next Run is 1 (organism is different from the previous). Based on the range of saprobic and diversity score of the benthic macro-invertebrate families, Biological Water Quality Criteria (BWQC) has been derived to evaluate the Biological Health of water bodies. Accordingly, biological water quality is classified as Clean, Slightly polluted, Moderately polluted, Heavily polluted and Severely polluted, and assigned Class A, B, C, D and E with a colour coding of blue, light blue, green, orange and red respectively **(Table 2.7)**.

Table 2.7: Biological Water Quality with Respect to Range of Diversity and Saprobic Score (CPCB, 2017)

Range of Saprobic Score (0-10)	Range of Diversity Score (0 -1)	Water Quality	Biological Water Quality Class	Indicator colour
7 and more	0.2-1.0	Clean	A	Blue
6-7	0.5-1.0	Slight Pollution	B	Light Blue
3-6	0.3-0.9	Moderate Pollution	C	Green
2-5	0.4-less	Heavy Pollution	D	Orange
0-2	0-0.2	Severe Pollution	E	Red

Most of the locations on the mainstream of river Ganga are in ‘Moderate pollution’ range in ‘Class C’ and none of the locations were found to be Severely polluted. CPCB recommended that efforts must be made to control the pollution so that all locations may comply with at least Class ‘B’ water quality. The study conducted by Sinha et al. (2017) indicates that Ganga river is modified significantly and there is a major change in flow and form of the river due to human interventions. Thus for developing a sustainable rehabilitation strategy, specific geomorphic criteria is to be designed to assess the river health at reach scale based on the assessment of geomorphic diversity.

Table 2.8 presents a summary of analyses indicating parameters used for River Health Assessment.

Table 2.8 Parameters Used for Some Works on River Health Assessment

Country/ Program/ Model	Parameter Considered	Reference
USA, UK Index of Stream Condition (ISC)	Turbidity, EC, pH, TP Macroinvertebrates	Ladson et al. (1999)
USEPA Habitat Score (HABSCORE)	Temp, Conductivity, DO, pH, Turbidity, Odour, Surface oil, Water clarity	Barbour et al. (1999)
South Korea Keum-Ho River	Specific Conductivity, BOD, COD, TN, TP Fish	An et al. (2002)
South Africa KwaZulu-Natal, Mhlathuze River	Temp, pH, TDS, Conductivity, Total Alkalinity, DO,% O_2 Saturation, NH_4^+, NO_2, NO_3, PO_4, Silicon, Chloride, Sulphate, F, K, Na, Ca, Mg	Vos et al. (2002)
Australia AUSRIVAS	Temp, EC, pH, DO, Turbidity Alkalinity Nutrients Ammonium, Air temperature Secchi depth	Parson et al. (2002)
India Monitoring Surface Water Quality	pH, turbidity, color, DO, BOD, hardness, Cl, TDS, SO_4, NO_3,TC, As and F	Sargaonkar and Deshpande (2003)
South Africa River Eco - Classification	pH, Salts, Nutrients, Temp, Turbidity, O_2, Toxics	Kleynhans et al. (2005)
India Surface Water Sources Quality Monitoring	28 parameters consisting of physico-chemical and bacteriological parameters, 9 Trace metals: Hg, As, Cr, Cd, Pb Cu, Ni, Zn, Fe and 15 pesticides: Alpha BHC, Beta BHC, Gama BHC (Lindane), OP DDT, PP DDT, Alpha Endosulphan, Beta Endosulphan, Dieldrin, Aldrin, Carboryl (Carbamat), 2-4 D, Malathion, Methyl parathion, Anilophos and Choropyriphos	Bharadwaj (2005)
China Liao River	pH, TSS, Conductivity, DO, BOD, COD_{cr}, COD_{mn}, FC, TN, NH_4^+, NO_2, NO_3, TP, Pb, Hg,	Meng et al. (2009)

	Cd, Sulphide, Petroleum Hydrocarbons, Volatile phenols	
	Attached Algae, Benthic macroinvertebrates	
NSW, Australia Hawkesbury-Nepean River (HNR) System	pH, Turbidity, DO, Enterococci, E. Coli, Chlorophyll-a, Algal biovolume, Nitrogen, Phosphate, Manganese filtered and phaeophytin	Pinto and Maheshwari (2011)
India River Subansiri	Current flow, Air Temp, Water Temp, Transparency, pH, Hardness, Free CO_2, TS, TSS, TDS, Conductivity, Total Alkalinity, DO, Chloride, Silicates	Baruah et al. (2011)
India Tamirabarani River	pH, Turbidity, EC, TDS, TSS, DO, NH_4-N, NO_3, NO_2, COD, BOD, Na, F and TC	Mophin-Kani and Murugesan (2011)
Australia Georges River Catchment	EC, DO, turbidity, pH, Temp, TN, NO_x, TP alkalinity	Tippler et al. (2012)
	Macroinvertebrates	
China Gui River Catchment	Chl-a, Temp, pH, TDS, Conductivity, DO, TN, NH_4-N, NO_2, NO_3, PO_4-P, TP, As, Pb, Hg, Cr, Al, Zn, Cu	Bond et al. (2012)
	Fishes, Attached Algae, Benthic macroinvertebrates, Riparian and channel condition, Riparian and channel vegetation	
China Yellow River	Water depth, Current flow, Transparency, DO, COD_{mn}, COD_{cr},BOD, NH_4-N, pH, Conductivity, TN, TP	Gipple et al. (2012)
	Fishes, Attached Algae, Benthic macroinvertebrates, Riparian and Channel vegetation	
China Taizi River	Temp, pH, TS, TDS, Conductivity, Total alkalinity, DO, BOD, COD, E-coli, TN, NH_4^+, NO_2, NO_3, PO_4-P, TP, Chlorides, Silicates, Sulphate,, Bicarbonates, As, K, Na, Mg, Ca. Pb, Hg, Cd, Cr, Al, Zn, Cu, Volatile phenols	Leigh et al. (2012)
	Fishes, Attached Algae, Benthic macroinvertebrates	
India Mutha River	Chl-a, Phytoplankton biomass, Transparency, pH, hardness, BOD, TOC, MPN, TN, TP, Chloride	Joshi (2013)
	Fishes, Benthic Invertebrates	
India Urban Rivers and Lakes	Temp, pH, Secchi depth, DO, Alkalinity , Turbidity, TDS, TSS, EC, BOD, COD, TKN, NH_4-N, NO_3-N, TP, Ortho P, TC, FC	Kazmi et al. (2013)
India Satluj River	BOD, DO, pH, COD/BOD, TSS, TN, TP, NH_4-N, SAR, TDS, EC, BOD, Cl, FC, COD/BOD, TN, pH, FC, Cl, NO_3-N, pH, TDS, NH_4-N, EC	Sharma and Reddy (2013)
India Chambal River	Water temp, Transparency, pH, TSS, turbidity, DO, BOD, NO_3, Phosphate	Yadav et al. (2014)
Singapore Lotic Ecosystems	pH, SC, temp, TDS, DO, FC, E Coli, Enterococcus, Cd, Cu, Zn, Pb, Canopy cover	Blakely et al. (2014)

	% , Impervious surface area, Current velocity, Channel stability, Particle size, Wetted width, Stream depth	
	Platyhelminthes, Hemiptera, Polychaeta, Oligochaeta, Hirudinea, Megaloptera, Trichoptera, Mollusca, Lepidoptera, Crustacea, Coleoptera, Odonata (Zygoptera), Diptera, Odonata (Anisoptera), Ephemeroptera, Collembola, Acari, Plecoptera.	
Namibia Orange River	Temperature, Turbidity, DO, pH, Conductivity, Total Phosphorus, Total Nitrogen, TDS and Chlorophyll a.	Munyika et al. (2015)
China Upper Han River	Temp, pH, EC, DO, NH_4-N, NO_3-N, turbidity, Ca_2^+ and SiO_2, Cl^-, SO_4^{2-}, Dissolved organic carbon (DOC), Total organic carbon (TOC), TP, soluble reactive phosphorus (SRP) and TN	Tan et al. (2015)
India Biological Health of River Ganga	Macroinvertebrates	CPCB (2017)
Thailand Mekong River Basin	DO, BOD, TP, TN Heavy Metals	Shinde and Babel (2018)
South Korea Gap River	TP, TN, Heavy Metals	Kim et al. (2019)
	Fish	
India River Ramganga	pH, Temperature, Total Alkalinity, TSS, TDS, DO, BOD_5, COD, NH_3-N, TKN, NO_4, PO_4-P, Sulfates, Chlorides, Zn, Cd, Ni, Cu, Pb, Sr, Ag, Mn, Fe, and Total Coliform	Gurjar and Tare (2019)

River health assessment provides information to help in management decisions. In river health assessment, analysis and interpretation of the data is carried out to objectively and timely assess the river health condition. This helps for coordinating and monitoring sustainable utilization of water and development of economy.

2.4. Research Gaps

An in depth review of the available literature reveals that many methodologies have been proposed towards achieving sustainable river management targets using water quality variables, aquatic species, riparian condition, sediment health and combined indices (Brown et al., 1970; Simpson et al., 2000; ISC, 2006). Several milestones have been covered to reach the current state of understanding for river health assessment. Starting with a few physico-chemical and biological parameters based approach to find Water Quality Indices (WQIs), the scientific community moved to biological indicators based approach of stream condition assessment. Currently, stream health is assessed using several indices such as Index of Habitat Integrity (IHI), Fish Assemblage Integrity Index (FAII), Riparian Vegetation Index (RVI), River Habitat Index, Hydrological Index, Ecosystem Health, Ecological River Health Index, Physical Form Index etc. Thus the following research gap appears to exist particularly in Indian conditions:

1. Currently there is no specific set of physico-chemical and biotic indicators to holistically define and reflect river health.
2. Apparently there is no unified framework to assess, understand and demarcate the stretches of river for varying health conditions.
3. There is lack of clarity in terms of precise reasons for poor river health and approach for scientific intervention to improve river health condition.

Accordingly, following research objectives have been set for the present study:

1. Identification of biological indicators to be considered in conjunction with physico-chemical and bacterial water quality parameters to reflect river health.
2. Development of a Framework for River Health Assessment applicable under Indian conditions.
3. Formation of Indicator Groups to calculate River Health Index (RHI).
4. Classification of River Health Condition (RHC) based on RHI.
5. Colored Pictorial representation of River Health Condition to give a glance.
6. Identification of causative agent(s)/parameters for poor river health conditions so as to help in mitigation/ restoration planning and execution.
7. Suggestive phased planning for river health improvement/restoration.